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Fluidized Bed Combustion for Clean Energy

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ABSTRACT

This paper gives a brief overview of the status and prospects for fluidized bed combustion (FBC) for clean energy, with focus on power and heat generation. The paper summarizes recent development trends for the FB technology and makes an outlook into the future with respect to challenges and opportunities for the technology. The paper also identifies areas related to fluidization, which are critical for the technology and, thus, will require research.

The main advantage with the FBC technology is the fuel flexibility. A compilation of 715 FB boilers (bubbling and circulating) worldwide illustrates the two main applications for the FBC technology: *1.* Small and medium scale heat only or combined heat and power boilers (typically of the order of or less than 100 MW thermal), burning biomass or waste derived fuels, including co-firing with coal and *2.* larger (up to 1,000 MW_{th}) power boilers using coal (black coal or lignite) as fuel. Emerging development includes circulating fluidized beds with supercritical steam data (power boilers) with the first project coming on-line in the near future and research on oxy-fuel fired circulating fluidized beds for CO_2 capture (O_2/CO_2 recycle schemes as well as chemical looping combustion).

Research needs on the topic of fluidization are mainly related to mixing of fuel, solids and gas, including penetration and mixing of secondary air. The larger the cross section of the furnace, the more critical is the fuel mixing, i.e. this is critical for large power boilers. For small and medium scale FBC boilers burning waste and waste derived fuels, there is also a need to understand fuel and gas mixing in order to be able to lower the excess air ratio and, thus, to increase the efficiency.

INTRODUCTION

Fluidized bed combustion (FBC) is today a well established technology for generation of heat, power and a combination of these. Yet, there has been a constant development and refinement of the technology since it reached commercial status in the early 80´s. With respect to the development of the technology, two factors can be mentioned which to a certain extent make the FBC development differ from that of other solid-fuel combustion technologies. First, the fuel flexibility, which is one of the main advantages of the technology, has put focus on different fuels over time since the introduction of the FBC technology. The focus of the development has also been different in different regions of the world, depending on fuel availability. Thus, the various types of fuels yield different demands on the technology (importance of mixing, material issues, heat transfer distribution etc.). Secondly, the two main applications of the FBC technology, smaller heat only or combined heat and power (CHP) boilers burning renewable and waste fuels and large power boilers mainly burning coal yield different problems and challenges, as discussed below.

Two types of fluidized bed boilers dominate the market; bubbling fluidized bed (BFB) boilers and circulating fluidized beds (CFB) boilers, both operated under atmospheric conditions, and these are the focus of this paper. With respect to installed capacity [MW] CFB boilers have by far the greatest market share which is partly due to that large FBC boilers for power generation are large CFB boilers whereas BFB boilers are mainly used in smaller CHP boilers in district heating systems or in industrial applications. Another FBC technology is pressurized fluidized bed combustion (PFBC) for power generation (in a combined cycle arrangement). The PFBC technology was developed in the 80´s and some PFBC power boilers were built, but the development has more or less stopped, partly due to operational problems (e.g. material issues of heat transfer surfaces and problems with high temperature flue gas cleaning for gas turbines) but perhaps also due to “wrong timing” of introducing the technology. The PFBC is not dealt with further in this paper. Neither is gasification processes applying fluidized-bed technology. This, since gasification applied in the energy sector (for production of clean gases such as to be used as transportation fuel and for high efficient gas turbine power generation) is still at an early stage of development, although gasification itself is well proven. In fact, the development of the fluidized bed technology for fuel conversion started within the field of gasification (the Winkler patent of 1922 for gasification of lignite). Recent reviews by Banales and Norberg-Bohm (1) and Koornneef et al. (2) outline the history of the FBC development.

As indicated above, fluidized bed combustion originates from the need to burn difficult low grade fuels of varying quality. One of the main advantages of the fluidized bed technology is its ability to burn various fuels in the same unit. The FBC technology is also characterized by good load following characteristics, possibility for sulphur removal and low NO_x emissions (low combustion temperature) and that without any need for special $DeSO_x$ or $DeNO_x$ equipment.

Fuel flexibility is becoming increasingly important since there is an increased need to burn a broad spectrum of fuels, including CO_2 neutral fuels such as biomass and waste derived biomass fuels. Such fuels are normally burnt in FBC units in CHP schemes. Yet, fluidized beds are also successfully used as power boilers – mostly CFB boilers – with the main competing technology being pulverised coal fired boilers (PC). In addition, the FBC technology is well suited for co-firing in large power boilers as well as in smaller CHP boilers. In a CO_2 constrained future, increasing demands on efficient use of biomass conversion makes it likely that co-firing of biomass with coal become an interesting option as part of the bridge to a more sustainable energy system.

THE BOILER MARKET

This section gives a brief outlook on some trends and problems on the heat and power market as an overall basis for the potential market for the FBC technology in heat and power generation. It is obviously a complex task to analyse in detail the future global market for power and heat generation and such an analysis is outside the scope of this paper. Thus, only some trends from the markets in North America and the European Union are given here.

It can be concluded that there will be a large need for investment in power and heat generation capacity over the next decades and this implies a growing demand for conversion technologies with high environmental performance and high efficiency. With respect to CO_2 emissions, high environmental performance means high efficiency. In addition, there is a growth in demand for small and medium scale combined heat and power plants burning various waste derived fuels in industrial or domestic district heating systems. In the case of power boilers two types of investments can be foreseen; replacement of old boilers in the developed economies and transition economies (e.g. Poland) and investments to meet a strong increase in demand in the developing economies, especially in China and India. Then, there is of course other markets which sooner a later will see a strong increase in investments either due to an increase in demand or due to a need for replacing old generation capacity , e.g in Russia (3). However, also in EU member states in southern Europe there is significant increase in demand for power (4).

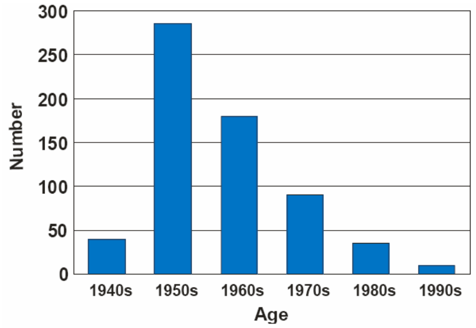


Figure 1. Age distribution of US coal fired power plants (Black Coal). From (5).

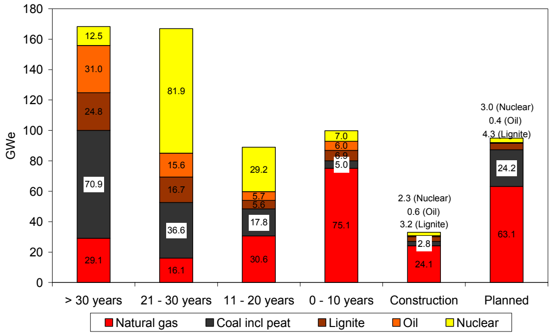
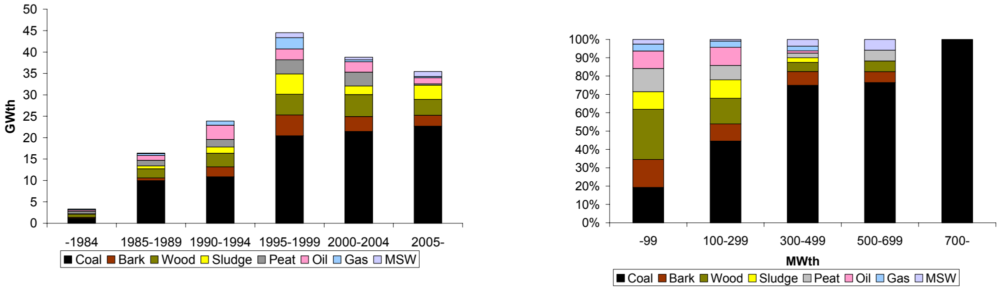


Figure 2. Net capacity of thermal power plants in EU-25 in operation, under construction and planned, distributed by fuel and age and as of May 2006 (thermal plants fuelled on biomass or waste not shown). As in (4), but for January 2007.

Figure 1 shows the age structure of US coal plants plotted as number of boilers (5). As can be seen there is a large number of old boilers built in the 50´s and 60´s. Figure 2 gives the corresponding picture of the European power plant park (EU25), but this figure includes all thermal plants and it is plotted as installed capacity (4). The figure shows that there is a considerable amount of old generation capacity also in the EU. In addition, there has been a considerable shift towards natural gas based power generation during the last decades. This has resulted in that EU has become strongly dependent on natural gas which has shown to be problematic from a security of supply perspective (4, 6). Especially since EU has abundant reserves of coal. The two rightmost bars in Figure 2 indicate that the trend towards an increased use of gas continues in the near future, although the bar representing planned plants in Figure 2 is associated with uncertainties and only gives an indication of the current trend (new projects will come on line as well as some planned projects will not be commenced). It can be concluded that an increased use of solid fuels will enhance security of supply for the EU. An increased use of coal is obviously problematic from a CO_2 perspective. Yet, replacing old and low-efficient coal fired power plants with new high efficient coal power plants contributes to the decarbonisation of the power generation sector. If, on the other hand, CO_2 Capture and Storage (CCS) prove feasible, it will allow an increased use of coal under strict CO_2 emission targets, which will enhance security of supply, but CCS will hardly diffuse significantly on a commercial scale before the year 2020. It is worth noting that the EU aims at requiring coal plants to be equipped with capture technology from 2020 and onwards and that coal plants should be capture ready from around 2015 and on, although the meaning of capture ready is vague[1]. Assuming that the climate threat continues to be increasingly higher up on the political agenda one can conclude that for all coal combustion technologies R&D work must be initiated to investigate the feasibility of CO_2 capture applied to these technologies, i.e. this is also valid for the FBC technology for power boilers (CCS is cost efficient for large power boilers, i.e. large point sources of CO_2 emissions). The technologies to which CO_2 capture can be applied in a cost efficient way is likely to take market shares in a CO_2 constrained world. As mentioned below, such R&D work has started in recent years. CO_2 capture in connection to Enhanced Oil Recovery (EOR) can be an early mover for initiating the technology at large scale (i.e. some of the cost for capture can be offset by the value of the CO_2 for the EOR scheme).



a. b.

Figure 3. Compilation of the FBC reference lists from Alstom, Foster Wheeler and Metso Power, as per February 2007 (715 units in total, including plants under construction) a. Age distribution and fuel mix. b. Unit capacity and fuel mix.

As for small and medium scale CHP units and heat only boilers the FBC technology should have a great chance to take market shares due to good environmental performance and the ability to burn a large range of fuels. As waste flows increase and landfilling will be associated with stricter regulations or banned entirely (e.g. the EU landfill directive[2] which gives a time plan of reduction of biodegradable municipal waste going to landfills), there will be a need for boilers which can incinerate municipal waste under environmentally acceptable conditions and which can reach high efficiency, such as in CHP schemes.

For large power boilers, the FBC technology has to compete with PC boilers and the choice between the two technologies is not obvious. Yet, also for large power boilers there may be an increased demand for fuel flexibility including the above mentioned

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[1] Capture readiness could mean that the site/boiler island has room for extra equipment associated with CO2 capture, while the entire boiler has to be replaced to be able to introduce capture, but a more strict definition would be that the boiler itself (including furnace) should be capture ready.

[2] Council directive 1999/31/EC of 26 April 1999 on the landfill of waste.

co-firing option and this should be in favour of the CFB technology. The CFB boiler technology may also be beneficial for supercritical steam data due to a rather even heat release up through the furnace. The first supercritical CFB boiler is currently under construction and planned to be commissioned in 2009. Rather than competing with the largest PC boilers for lignite (~1,000MW_e), it is probable that the CFB technology will take important niche markets, where fuel flexibility is or can be foreseen to be of future importance. In addition, the outcome of development of CO_2 capture applied to the FBC technology will influence the future FBC market, including new concepts such as chemical looping combustion.

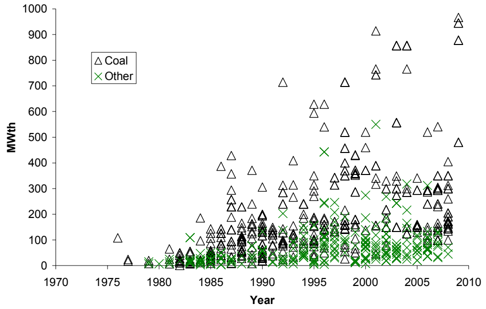

Figure 4. The 715 FBC units in Figure 3 divided by fuel; Δ: units with coal as main fuel, X: units with the one or more of the other fuels indicated in Figure 3 as main fuel.

Figures 3 and 4 illustrate the FBC market until present date with respect to boiler capacity and fuel mix. The figures are a compilation of current (February 2007) boiler reference lists from the three largest boiler manufacturers[3] (included projects built by their previous company constellations); Alstom, Foster Wheeler and Metso Power (until recently Kvaerner). Thus, the plots include all their projects up to present date corresponding to 715 FBC units in total (including those to be commissioned within the next years, but also some units – the oldest ones - which probably have been decommissioned, although these constitute only a small fraction). The two above mentioned FBC applications can be clearly seen in Figures 3b; boilers of a capacity of less than 100 MW_{th} burning waste derived fuels, including biomass and large power boilers mainly burning coal (bituminous coal and lignite, lumped together as coal in the plots). Figure 4 shows the significant increase in unit capacity over the years, especially for power boilers.

It can be concluded that the prospects of the FBC technology for conversion of coal and renewable fuels for heat and power generation are high, both as greenfield plants and as in repowering projects. As for large power boilers there is a great challenge in reducing CO_2 emissions from coal firing. On the short term, increase in thermal efficiency by means of repowering projects and co-firing of biomass can contribute to this, with the latter also to help establishing a biomass market (7). In the longer run, application of CCS should be a prerequisite for firing coal at large scale. However, there will obviously be a great number of coal fired FBC units without capture installed in developing economies such as China over the next decades (including the large number of plants put in operation during the last years). It seems

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[3] This compilation is obviously not covering all FB units worldwide since it is limited to the three manufacturers (although the three major ones). Yet, the number is rather high and in the order of other compilations of FBC units given in literature, see (2) for an overview of such listings. China has a large number of FBC units which are not included in most listings.

clear that the lead in developing CCS technologies will be taken by Europe and North America (and it is the personal opinion by the author that this seems reasonable considering the need to establish credibility of the rich economies in fighting climate change). As briefly indicated below, there are promising capture technologies based on the FBC technology.

THE FBC TECHNOLOGY

This paper assumes the reader to be familiar with the principles of fluidization and fluidization as applied to bubbling and circulating fluidized beds. In short, the principle of the FBC technology is a fluidized bed of inert solids (e.g. sand or ash) which, during start up, is first heated up by start-up burners with oil or gas and when a high enough temperature has been reached – at least 600 °C – solid fuel can be added to the bed and after it ignites, the start-up firing can be shut down. The combustion of the solid fuel can be maintained at a combustion temperature of around 850°C which yields low emissions of NO_x (no thermal NO_x). Depending on fuel the bed may consist of ash or a combination of ash and sorbent and/or inert solids such as silica sand. Large ash particles leave the bed through solids drainage in the bottom of the furnace.

In order to maintain the combustion temperature, the heat balance of the bed is controlled by in-furnace cooling surfaces, which typically are located in the furnace walls (these being membrane tube walls). For BFBs the cooling possibilities are limited to cooling by the furnace wall or in-bed cooling surfaces, such as by means of tube-bundle heat exchangers with horizontal tubes. However, the latter type was only used in the early development of the FBC technology since it soon become evident that such heat transfer surfaces could not withstand the erosion by the bed solids (cf. above mentioned problems with the PFBC technology). Yet, today BFBs are successfully used as waste boilers in the form of heat only boilers or CHP boilers. For these boilers the moisture and volatile content of the fuel (biomass or waste derived fuel) is high enough not too require any in-bed cooling. In fact, such boilers are sometimes designed without any requirement of in-furnace heat transfer surfaces (all furnace walls refractory lined) with most heat extracted downstream of furnace in back-pass. For FBC power boilers only the CFB technology is used today. For large such boilers the wall surface may not be sufficiently large to cool the bed due to the decreasing surface to volume ratio with increased size of the boiler. Thus, the wall cooling surfaces must be complemented with other heat transfer surfaces such as internal or external heat exchangers. Internal heat exchangers are normally in the form of vertical heat exchanger elements protruding from the furnace roof or side walls. For the largest (CFB) power boilers these may extend all the way along the furnace height, i.e. forming internal walls. External heat exchanger elements are in the form of a heat exchanger in the return leg below the cyclone, although heat exchangers in the back pass may also be seen as external heat exchangers. The ratio between the heat extracted within the furnace (included in the primary solids circulation loop in a CFB) and downstream the furnace may vary, mainly depending on fuel (high moisture fuel yields lower such a ratio).

Characteristics of the riser of fluidized bed units applied in combustion are (8, 9):

- A height to diameter (aspect) ratio of the riser (H_0 / D_{eq}) of the order of or less than 10
- A ratio of settled bed height (the bed formed if the solids are not fluidized) to riser diameter of less than 1 ($H_{b,settled} / D_{eq} < 1$)

- Fluidized solids belonging to group B in the Geldart classification
- For CFB units a solids net flux ($G_{s,net}$) typically ranging from 0.5 to 20 kg/m^2·s

Primary operational parameters of the furnace (with respect to fluid dynamics) are the riser pressure drop and the gas flows (i.e. fluidization velocity, secondary gas injection). For CFB boilers there are also the solids net flux ($G_{s,net}$) and the total inventory of solids, but these are normally not known and therefore cannot be considered as operational parameters. This is of importance to realize when it comes to modelling of CFB boilers, i.e. $G_{s,net}$ and solids inventory should not be inputs but outputs in such a model (10).

The above mentioned aspect ratio of an FBC furnace can be seen from Figure 5, which outlines FBC boilers from the above mentioned three boiler manufacturers (Alstom, Foster Wheeler and Metso Power). Figure 5a shows a BFB waste boiler. The boiler furnace has a rather tall freeboard to ensure sufficient burnout time[4]. In addition, the lower part of the furnace has a contraction at the entrance of the secondary air in order to ensure intense mixing of combustion air and volatiles (ACZ; Advanced Combustion Zone). This since the boiler type is used for high volatile waste derived fuels and should be able to handle a variety of fuels, including fluctuations in fuel composition over time. Figure 5b shows an Alstom CFB boiler with an external particle cooler (with the picture, as well as the pictures in Figures 5c-e, showing the entire solids loop with primary cyclone). This specific boiler combines Internal Heat Exchanger (IHE) and External Heat Exchanger (EHE) to widen the range of operation. Figure 5c gives a CFB power boiler from Metso Power. For this particular boiler the size of the in-furnace heat transfer surfaces are large enough not to require any external heat exchanger (pet coke and coal used as fuel), but EHE is optional for the design. The boiler includes a hydration process to ensure sufficient SO_2 reduction (high sulphur fuels) and bottom ash cooler to prevent bed over heating. One of the large lignite CFB power boilers (6 in total) at the Turow power plant in Bogatynia, Poland is given in Figure 5d. The one shown is of the so called compact type (3 of that type on the site), meaning that the primary cyclones are integrated with the furnace yielding a compact and cost efficient design. Figure 5e illustrates the first supercritical CFB boiler planned to be commissioned in 2009 (Lagisza, Poland, 460 MW$_e$ by Foster Wheeler). Also the Foster Wheeler design has the option of EHE in the form of the so called INTREX© heat exchanger (which integrates the EHE with the furnace).

FBC – NEED FOR FLUIDIZATION RESEARCH

The need for research given in this paper focus on the topic of this proceedings, namely problems related to fluidization. For a more general overview of the problems in FBC, see for example a review by Leckner (11) and previous proceedings of this conference and the International Fludized Bed Conference series. What is given below has not the ambition of in any way being complete, but only to point on some topics which the author definitely consider important in the understanding of the processes related to fluidization in FBC units. Such an understanding is important when improving models for design and scale up of FBC boilers. First, a brief overview of the main fluidization characteristics of FBCs is given.

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[4] For waste combustors in EU, there is a requirement of 2 seconds of residence time of the flue gases at a temperature exceeding 800ºC. This is to prevent formation of dioxins. The residence time is taken from the location of the over-fire air.

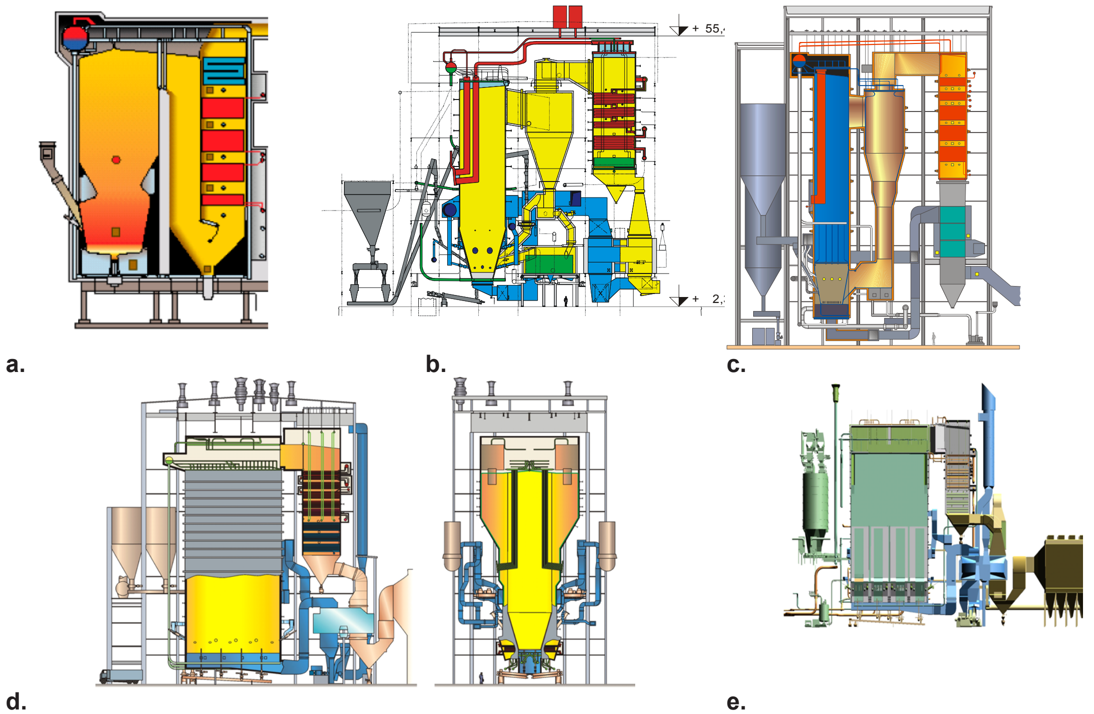

Figure 5. a. Principal outline of FB boilers. a. the Metso Power ACZ$^{\copyright}$ BFB boiler for burning waste (MSW, RDF etc). b. The Alstom Sulcis, CFB power boiler, Italy (340 MWe, 197 bar, 565/580 °C,1026 t/h), start-up 2006. c. The Metso Power CYMIC$^{\copyright}$ CFB power boiler, Manitowoc Public Utilities, Wisconsin USA (160 MWth, 60 kg/s, 103 bar, 541 °C), Petroleum coke, bituminous coal, start up 2005. d. One of three Foster Wheeler compact CFB power boilers at the Turow power plant in Poland (3 x 557 MWth, 195/181 kg/s, 170/39 bar, 568/568 °C), lignite, start-up 2003 (unit #5) 2004 (units #4, 6). e. The Foster-Wheeler supercritical once-through CFB power boiler, Lagisza, Bedzin, Poland (966 MWth, 361/306 kg/s, 275/50 bar, 560/580 °C), start-up 2009.

General fluidization pattern

When it comes to fluidization and mixing of gas and solids a CFB boiler can be divided into the zones shown in Figure 6 whereas a BFB consists only of the (bottom)bed and the freeboard zones in Figure 6. Obviously, the flow in the different zones interacts and depends on each other, as discussed later. A more detailed discussion on the fluidization characteristics of the zones shown in Figure 6 is given elsewhere (10).

The low $H_{b,settled}$ /D_{eq} ratio (< 1) in FBC units yields a non-slugging bed (12,13), whereas tall and narrow risers (with $H_{b,settled}$ /D_{eq} > 1) give a slugging bed ((10) and references therein). With Geldart group B solids, a non-slugging bed in combination with a low primary air-distributor pressure drop results in that a dense bubbling bed can be maintained also at high velocities with bubbles of a so-called exploding character (12, 13). Such a flow results in large fluctuations in the overall gas flow with a high throughflow of gas in the bubbles, leading to high local gas velocities. Thus, the exchange of gas between the bubbles and the emulsion phase is low in relation to the gas flow through the bed. In FBCs, this results in strongly reducing conditions in the bottom bed. In addition, the gas flow becomes highly intermittent (14, 15).

With respect to the freeboard flow in circulating fluidized beds, the above-listed characteristics of fluidized beds applied in CFB combustion were shown to give a flow pattern different from that of the well-investigated tall and narrow laboratory units directed towards chemical engineering applications (e.g. 8, 10). The latter type of units have a higher aspect ratio H_0 /D_{eq} typically ~ 20) and are normally run at a much higher solids net flux ($G_{s,net}$ ~50 kg/m^2 s), i.e. are operated with solids which are finer (d_s typically < 100 μm) and with lower particle density than in CFB units for combustion. The low aspect ratio of the furnace in CFB boilers results in a solids-flow profile developing up through the freeboard (above the bottom bed), i.e. the riser can be seen as an entrance zone with respect to the flow (both solids and gas). This gives a solids flux profile which is fairly flat across the core region, but with pronounced wall layers formed by the solids backmixing at the riser walls (8, 9). Thus, a core/wall-layer structure is present. Tall and narrow risers exhibit a more developed solids flux profile, typically with a parabolic shape (16, 17), depending on operational conditions. Although varying with the solids net flux and the fluidization velocity, these risers also show a more or less pronounced backmixing at the riser walls forming a core-annular structure of the flow, but at high enough gas velocities there may even be up-flow of solids throughout the cross section (e.g. (18)). Considering the low net solids flux in a CFB boiler, the solids loading in the top of the furnace is low, typically ~ 1kg/m^3 (19). As a result, the exit effects on the flow in the top of the riser are rather small (cf. for instance the local increase in solids loading as shown in some laboratory risers at high solids fluxes, see references in (19)).

In summary, the flow pattern in FBC units differs significantly from that of tall and narrow laboratory risers, so the abundant literature on the latter type – especially in CFB applications - is seldom applicable for FBC units. Experimental work which aims at be applicable to FBC should at least have the characteristics given above and laboratory tests under ambient conditions should preferably be operated according to scaling laws given in literature (e.g. (20)).

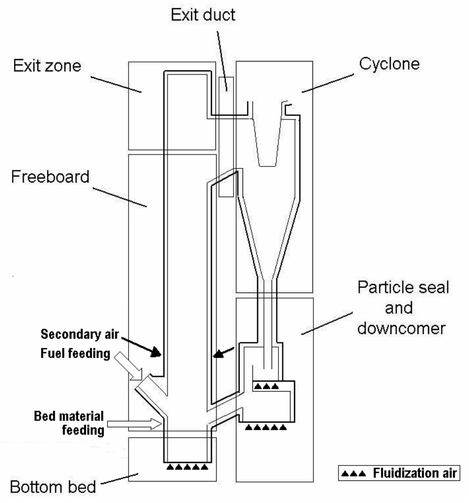

Figure 6. A possible division of zones in the primary circulation loop of a CFB boiler. For a BFB, there is obviously no primary loop and te flue gases leaves the furnace into the back-pass. From (10).

Need for FBC research related to fluidization

Bottom bed and Freeboard (Figure 6): Perhaps the most important area for research on fluidization is to increase the knowledge and modelling capabilities for prediction of mixing of fuel and combustion air, both in the bed (bottom bed in a CFB) and in the freeboard. For the freeboard flow, mixing of secondary and primary air is crucial for control of the burnout process. High enough fuel dispersion is important in order to ensure good mixing of fuel and combustion air, i.e. to obtain a satisfactory burnout while keeping the excess air ratio as low as possible. To what extent a certain fuel mixing behaviour is sufficient or not depends on the fuel conversion time ($\tau_{conversion}$) and the characteristic mixing length (L^*) and a comparison of the characteristic times for fuel dispersion and conversion can be expressed by the Damköhler number (21):

$$Da = \frac{\tau_{dispersion}}{\tau_{conversion}} = \frac{L^* / r_{dispersion}}{\tau_{conversion}} \tag{1}$$

A *Da* number lower than unity (*Da*<1) indicates that the dispersion rate is high enough to ensure a sufficiently homogeneous distribution of the fuel over the cross section of the unit ($r_{dispersion}$ = Mixing rate, $\tau_{dispersion}$= time for fuel dispersion). It should be noted that a certain set of operational conditions yielding a sufficient fuel mixing rate in a certain FBC burning a certain fuel may not be sufficient when changing fuel (*e.g.* to a fuel with a higher volatile content or which is more reactive).

The fuel mixing behaviour is critical since the number of fuel feed points must be kept as small as possible to minimize costs. Consequently, fuel mixing is known to be critical in large FBC units which may have cross sectional areas up to several hundreds of square meters (e.g. the furnace cross sectional area of the CFB boiler shown in Figure 5d exceeds 200 m^2, with this boiler having 6 fuel feeding points, 3 front wall/ 3 rear wall). For smaller FBC units such as BFBs, the fuel often has a high volatile content and therefore understanding of the fuel and gas mixing (release and mixing/burnout) of moisture and volatiles is important in order to design boilers and operational strategies which allow for low excess air ratios for maximizing efficiency.

To evaluate fuel mixing requires modelling of both fuel dispersion and conversion (drying, devolatilization and char burnout). There are semi-empirical models which express the solids mixing in form of dispersion coefficients (e.g. (22)). These models focus mainly on modelling the vertical mixing in laboratory fluidized bed units where, due to their narrow geometry, this is the critical direction for solids mixing, although horizontal solids dispersion coefficients have also been measured in narrow units (e.g. (23)). As mentioned above, in large fluidized bed units such as boilers mixing of solids is critical in the horizontal direction, due to the low bed-height to bed-width ratio. Here, the knowledge is limited, in spite of some work which estimates the horizontal solids mixing in large fluidized bed units (see (24) and references therein). These estimations indicate that large FBC units give solids dispersion coefficients which are an order of magnitude larger than those found in the above-mentioned narrow laboratory CFB units. Although in-bed fuel (and solids) mixing is normally expressed in analogy with a diffusion process it is obvious that the process is highly convective and there is a lack of understanding the fundamental physics behind the fuel mixing. Solids mixing is strongly related to the nature of the bubble flow (21, 24).

The influence of different furnace geometries (such as the ACZ zone shown in Figure 5a) is important and CFD simulations can reveal important information on how such geometries and over fire air influence the gas mixing. Yet, inclusion of solids in CFD simulations for conditions corresponding to boilers is not straightforward. Thus, development of CFD tools for two phase solids flow is of great importance.

Exit zone and exit duct (Figure 6): Here, it is crucial to be able to model the ratio of the solids which leave the furnace and the solids which are internally recirculated, i.e. the back-flow ratio. The solids which are not leaving the furnace turn downwards and form the solids wall layers (There seems to be little back-mixing over the core region, (9)). According to the knowledge of the author, there is no model available which can predict the exit zone flow based on some underlying physics. There are some correlations available (10). For conditions corresponding to those in boilers, it seems as if the exit geometry has little influence on the back-mixing ratio (19), but that is not to say that the net solids flux can be predicted. One way to get more detailed knowledge on the exit effects would be to make CFD simulations of the flow in the exit zone based on equations from first principles. Consequently, there is a need for detailed experiments on the solids flow in the exit zone (to verify such simulations).

Cyclone (Figure 6): In present CFB boiler designs, the primary cyclones normally work rather well (although there were some problems in early designs, e.g. (25)). Yet, for large power boilers cyclones tend to be very large in size (which is costly) and there is an interest to find primary particle separation systems with a more compact design. Thus, this is an area where there is a need for research. One example of a compact particle separator is the compact design shown in Figure 5d, where the cyclones have been integrated with the furnace (26). Also other types of primary solid separators have been proposed such as so called U-beam separators (27). However, the separation efficiency for such separators tends to be too low for finer solids fractions and, therefore require to be followed by additional solids separation device such as multicyclones.

Particle seal and downcomer (Figure 6): When the downcomer is used as an EHE or being linked to such device the solids flow and solid size distribution becomes crucial for the design of the heat transfer surfaces in the EHE, being typically in the form of horizontal tube bundles. To integrate a heat exchanger in the loop seal is advantageous due to the high in-bed heat transfer and since, if correctly designed, the CFB loop will provide a self controlled power output from the EHE; the higher the load the more solids recirculate through the loop seal and the higher the power output from the external heat exchanger. In addition, when burning biomass or co-firing biomass where there is a risk for alkali related corrosion problems on super-heaters located in the flue gas pass downstream the primary cyclone, but an EHE is in a location where the corrosion risk is lower. Yet, the EHE flow becomes complex in that the cooling tubes face a cross flow of solids superimposed on the EHE fluidization flow, which can be characterized as a bubbling bed flow (fluidization velocities are kept low). There is little work on fluidization applied to EHE (28, 29) and this is therefore an area where there is clearly a need for research on fluidization properties (as well as material issues related to high temperature corrosion).

Entire loop in the case of CFB boiler (Figure 6): Integrating the above zones in a model requires knowledge on the particle size segregation, i.e. for a given set of operational parameters (pressure drop and gas velocities), it is the particle size distribution which determines the internal solids backmixing and the net solids flux, the cyclone efficiency (i.e. the design of cyclone) and the solids size (and size distribution) in the loop seal. There is little knowledge on the effect of solids size distribution on the CFB riser flow under conditions relevant for FBCs. A consequence from the above is that if aiming at establishing a gas-solids flow model of the entire CFB loop, the particle size distribution must be included, i.e. in order to model the particle size distribution around the loop. For risers operated at high solids fluxes such as under conditions of FCC crackers, the solids size segregation is less important since these may operate at velocities many times the terminal velocity of all solid fractions in the loop (There may even be upflow of solids at the riser walls as mentioned above). Modeling of solids size segregation also requires that momentum transfer between solids of different size and weight is taken into account (30, 31). Pallarés and Johnsson (10) present a comprehensive model of CFB boiler flow which includes the entire loop and take solids size segregation into account. Yet, this model is not based on first principles and it seems as if there is rather much work to be done before an entire CFB loop can be modelled by means of CFD simulations, taking solids size distribution into account.

In summary, there are several areas where there is a gap in the knowledge which makes it difficult to establish reliable models for design and scale up of FBC units. Of the above listed fields the fuel mixing and the solids segregation are perhaps the two most important fields for which more research is required before a reliable FBC model can be established. It should also be mentioned that a correct modelling of the fluidization process (flow and mixing) is important since the fluidization properties strongly influence the combustion and heat transfer processes (whereas the latter two processes have a rather small influence on the fluidization).

FBC – NEW APPLICATIONS

As indicated above, the global warming problem calls for new and more efficient ways of FBC combustion, including zero (CO_2) emission plants (CCS). CFB power boilers with supercritical steam data (such as the above mentioned Lagisza plant) will contribute to increasing power plant efficiency and thereby to decarbonize electricity production. In addition, co-firing of biomass with coal will make possible further decarbonisation. As for CCS, there are currently two FBC processes being developed, the oxyfuel process and the chemical looping process. Oxyfuel combustion (or O_2/CO_2 recycle combustion) means that the fuel is combusted in a mixture of pure oxygen and recycled flue gas, where the amount of recycled flue gas is adjusted to control the combustion temperature. A schematic principle of the process is illustrated in Figure 7. The oxygen required for the process is produced in an Air Separation Unit (ASU) where the state of the art technology is cryogenic air-separation. The oxyfuel process shown in Figure 7 is being developed both for pulverized coal (PC) fired boilers (e.g. (32)) and for fluidized beds (33). There is presently an intense development of capture processes, including the oxyfuel process (for update information see the IEA Greenhouse gas R&D programme, including an international conference series on Greenhouse Gas Control Technologies, (34)).

The advantage with an oxyfuel scheme applied to FBC is that the oxygen content can be raised to much higher levels than for a PC boiler, while limiting the combustion temperature. Thus, this means that the boiler will be significantly more compact than a corresponding air fired FBC of the same capacity. Figure 8 outlines an oxyfuel fired CFB boiler scheme. Although the principle of FBC oxyfuel technology has been studied in small scale pilot runs, it is too early to say if the technology will be successful. As for oxyfuel fired PC boilers a first larger pilot plant ($30MW_{th}$) is planned to be commissioned in 2008 and the development path may be a bit more straightforward than for oxyfuel fired FBC, but the maximum O_2 concentration in PC boilers is limited to around 30%, at least with the design schemes proposed so far. In the end, it is the electricity generation cost which matters. Economic evaluations based on process analysis on large scale lignite fired PC combustors indicate that the CO_2 avoidance should not be more than 20€/ton CO_2 (32), which is attractive compared to the envisioned future CO_2 price (in EU it seems reasonable to assume that the CO_2 emission cost will be at least 20€/ton CO_2 in 2015.). The oxyfuel process is rather straightforward since all main components are based on commercially available technologies, especially when applied to PC boilers. As indicated, oxyfuel in FBC offers the possibility of a more compact design (boiler volume as well as size of boiler island) which reduces costs (e.g. (33)).

Another process based on fluidized beds is chemical looping combustion. This process is often (somewhat misleading) referred to as oxyfuel combustion. In chemical looping combustion, metal oxide particles are used to transfer oxygen from air to a gaseous fuel. The system consists of two separate reactors, as shown in Figure 9. In the fuel reactor the particles react with the fuel:

$$(2n+m)Me_xO_y + C_nH2_m \rightarrow (2n+m)Me_xO_{y-1} + mH_2O + nCO_2 \qquad (2a)$$

The reduced metal oxide is then transported to the air reactor where oxygen from the air is transferred to the particles:

$$Me_xO_{y-1} + ½O_2 \rightarrow Me_xO_y \qquad (2b)$$

Thus, the reduced metal oxide is oxidized back to the original metal oxide and can be returned to the fuel reactor for a new cycle. Possible metal oxides are some oxides of common transition-state metals, such as iron, nickel, copper and manganese (35). For these oxides reaction (2b) is exothermic with subsequent heat release, and reaction (2a) is most often endothermic. However, the total heat produced in the oxidation and the reduction is the same as in normal combustion where oxygen and fuel are in direct contact. The advantage with performing the combustion in two reactors/steps compared to conventional combustion is that the carbon dioxide is not diluted with nitrogen gas, but is received almost pure without any extra energy demand and without costly external equipment for CO_2 separation, such as the ASU O_2 separation in the above mentioned oxyfuel process. The chemical looping combustion has been successfully applied at laboratory scale (up to 50kW) and small scale (~100kW) pilot testing is under planning, see (35) for an overview on the development work on the process. The process is also being developed for hydrogen production with promising results (35).

With respect to fluidization, the areas of research priority proposed above are more or less valid also for the new applications given here. For oxyfuel fired CFB boilers with high (furnace) inlet oxygen concentrations (e.g. 70%), gas-solids mixing is crucial since it has to be ensured that there are no local excess temperatures causing bed agglomerations. First pilot tests indicate that an oxyfuel fired CFB combustor works at such high oxygen concentrations, but detailed measurement data on the process is not available in open literature. In addition, a large part of the heat has to be taken out from the EHE (Figure 8) and, thus, an oxyfuel fired CFB must have a high net solids flux. The implications of this are not exactly known. For chemical looping combustion, the gas-fuel contact is not as critical as in “normal” combustion, instead the key is to find low cost oxygen carriers with high reactivity, which can withstand the forces in the bed (fragmentation, abrasion) and which will not agglomerate. When scaling up the technology the net solids flux is an important parameter and research is required to find optimal design of the loop. Also, it has to be ensured that there is no gas leakage between the air and fuel reactors. Although, the above mentioned small scale pilot testing indicates that this is not problem it has to be ensured that this is also the case when scaling up the process.

It can be concluded that if the large scale CCS pilot/demonstration projects which are being planned in EU, North America and Australia will prove successful and if the international community will be able to create an institutional framework for accounting and monitoring the stored CO_2, it is likely that when this has happened it will not be possible to build new coal fired plants without CCS. Thus, the future of the FBC technology for large scale coal firing lies in the success of application of CCS schemes to FBC. Within EU, the plan is that CCS should be applied to all coal fired plants from the year 2020 and on (which will depend on that a high enough cost associated with emissions of CO_2 from the power sector can be established).

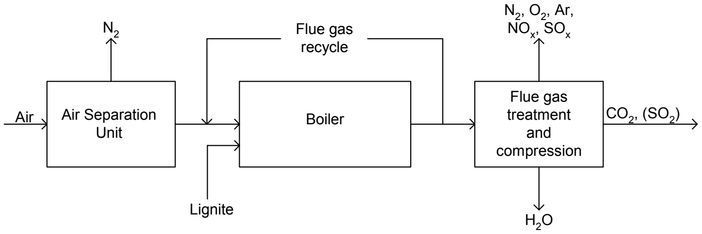

Figure 7. Principle of O_2/CO_2 recycle combustion (oxyfuel combustion).

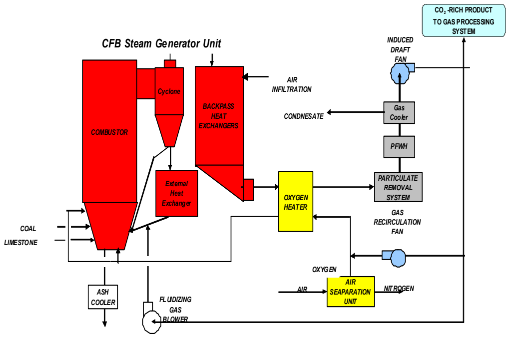

Figure 8. Principal outline of an oxyfuel fired CFB boiler. From Alstom (33).

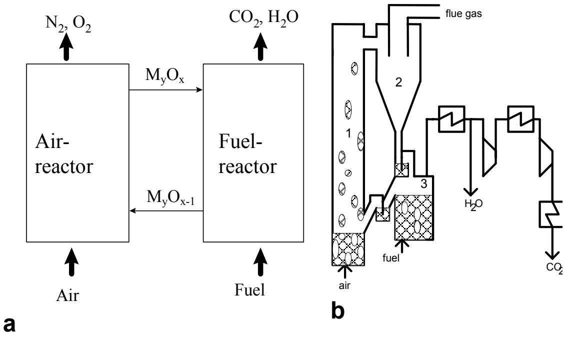

Figure 9. The chemical looping process (35): a. Schematic illustration of the principle (cf Eqns 2 and 3) Me_xO_y/Me_xO_{y-1} denotes recirculated oxygen carrier solids, b. Layout of the process with two interconnected fluidized beds (CFB). 1) air reactor, 2) cyclone, 3) fuel reactor.

CONCLUSIONS

Large investments in the energy system are required over the coming decades, both as a result of an increased demand for heat and power, as well as due to replacement of old plants. The prospects for the FBC technology for clean energy is high, but there are competing technologies (PC boilers when it comes to large scale power boilers and grate fired boilers when it comes to smaller waste boilers). Thus, research and development is required in order to improve the FBC technology. Within the field of fluidization there are several areas which require further research and development in order to establish models for reliable design and scale up of the technology. Fuel mixing is such an area which is of high importance both for power boilers with large cross sections (CFB) and for smaller BFBs for CHP schemes burning difficult fuels of varying quality. New FBC development includes supercritical CFB boilers as well as FBC with CO_2 capture.

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