

IEA Fluidized Bed Conversion Programme

Status Report 2010

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IEA Fluidized Bed Conversion Programme

Status Report 2010

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Ein Projektbericht im Rahmen der Programmlinie



Impulsprogramm Nachhaltig Wirtschaften

Im Auftrag des Bundesministeriums für Verkehr, Innovation und Technologie

Vorbemerkung

Der vorliegende Bericht dokumentiert die Ergebnisse eines Projekts aus dem Programm FORSCHUNGSKOOPERATION INTERNATIONALE ENERGIEAGENTUR. Es wurde vom Bundesministerium für Verkehr, Innovation und Technologie initiiert, um Österreichische Forschungsbeiträge zu den Projekten der Internationalen Energieagentur (IEA) zu finanzieren.

Seit dem Beitritt Österreichs zur IEA im Jahre 1975 beteiligt sich Österreich aktiv mit Forschungsbeiträgen zu verschiedenen Themen in den Bereichen erneuerbare Energieträger, Endverbrauchstechnologien und fossile Energieträger. Für die Österreichische Energieforschung ergeben sich durch die Beteiligung an den Forschungsaktivitäten der IEA viele Vorteile: Viele Entwicklungen können durch internationale Kooperationen effizienter bearbeitet werden, neue Arbeitsbereiche können mit internationaler Unterstützung aufgebaut sowie internationale Entwicklungen rascher und besser wahrgenommen werden.

Dank des überdurchschnittlichen Engagements der beteiligten Forschungseinrichtungen ist Österreich erfolgreich in der IEA verankert. Durch viele IEA Projekte entstanden bereits wertvolle Inputs für europäische und nationale Energieinnovationen und auch in der Marktumsetzung konnten bereits richtungsweisende Ergebnisse erzielt werden.

Ein wichtiges Anliegen des Programms ist es, die Projektergebnisse einer interessierten Fachöffentlichkeit zugänglich zu machen, was durch die Publikationsreihe und die entsprechende Homepage www.nachhaltigwirtschaften.at gewährleistet wird.

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Bundesministerium für Verkehr, Innovation und Technologie

ABSTRACT - German

Dieser Bericht gibt einen Überblick über den weltweiten Stand der Technik der Wirbelschichttechnologie hinsichtlich des Einsatzes im Bereich der Energietechnik und ist im Rahmen der Teilnahme Österreichs in der Internationalen Energieagentur – Wirbelschichttechnologie (IEA-FBC) entstanden.

Wirbelschichtanlagen zeigen ein exzellentes Stoff- und Wärmetransport – Verhalten. In Wirbelschichtanlagen können Brennstoffe aus einem weiten Bereich (mit geringen Heizwerten und schwierige Brennstoffe) effizient und emissionsarm verbrannt werden. Limitierungen gibt es hinsichtlich dem Korngrößenband, der Brennstoffchemie und Emissionen sowie der Fluidisierung und der Ascheeigenschaften

Stand der Technik ist die Nutzung eines breiten Brennstoffmixes (Holzabfälle, Rinde, Schlämme, Kohle) in relativ kleinen zumeist blasenbildenden Wirbelschichtanlagen (< 50 MWth). Ein aktueller Trend ist die Nutzung von Klärschlamm und kleine Wirbelschichtanlagen mit Holz als Hauptbrennstoff (< 50 MWth) und größere Anlagen (100 MWth), sowie die Nutzung von kommunalem Abfall und Gaserzeugung.

Auf der Basis von Kohle werden immer größer werdende zirkulierende Wirbelschichtanlagen gebaut (Scale-up), mit dem Ziel sich im Leistungsbereich 600 – 800 MWe und mit netto Wirkungsgraden zwischen 45 -50% neben der Kohlestaubfeuerung zu etablieren (siehe auch Hotta 2009). Ein wichtiger Schritt in diese Richtung stellt die zirkulierende Wirbelschichtanlage als derzeit weltweit größte mit 460 MWe in Lagisza, Polen dar. Diese wurde 2009 in Betrieb genommen.

Weltweit ist ein großer Anstieg an Wirbelschichtanlagen zu verzeichnen. Speziell in China wird ein enormer Zuwachs erfolgen und Anlagen im Leistungsbereich von 600 MWe sind in Vorbereitung. Der Fünfjahresplan (2007 – 2011) sieht 50 zirkulierende Wirbelschichtanlagen im Leistungsbereich 300 MWe vor, sowie Anlagen auf Kohlebasis mit einer Gesamtkapazität von 2000 MWe (Yue et al. 2009).

Weitere Entwicklungen sind der Einsatz von Wirbelschichttechnologie in der Gaserzeugung und Pyrolyse, sowie von Oxyfuel-Verbrennung und Chemical Looping Combustion (CLC) mit dem Schwerpunkt der CO₂ neutralen Kraft- und Wärmeerzeugung aus Biomasse und fossilen Brennstoffen.

Das IEA-FBC unterstützt und stimuliert den Informationsaustausch (siehe www.iea-fbc.org und regional: www.iea-fbc.net) hinsichtlich dem Stand der Technik und den neuesten Entwicklungen zwischen ihren Mitgliedern. Die IEA hat den Bereich Wirbelschichttechnologie für weitere fünf Jahre (2009 – 2014) verlängert und es kann von einer weiteren Verlängerung dieser Periode bis 2019 und darüber hinaus ausgegangen werden.

Die nächsten Schritte sind die Fortsetzung der Unterstützung dieser innovativen Entwicklungen, die Mitgliedschaft Chinas in der IEA-FBC und die stetige Verbesserung und Weiterentwicklung des Informationsnetzwerkes.

ABSTRACT

This report gives an overview of the current status of the fluidized bed technology worldwide in regards to energy technology and is part of the Austrian participation in the International Energy Agency – Fluidized Bed Conversion (IEA-FBC) Implementing Agreement.

Fluidized bed combustors show excellent mixing and heat transfer conditions. They burn efficiently and with low emissions. Due to the high heat capacity of the fluidized bed a wide range of different usually low-quality (with very low calorific values and high moisture contents) or difficult fuels can be used. Limitations exist due to the particle size distribution of the fuel, fuel chemistry and emissions and fluidization characteristics including ash behavior.

State of the art is the utilization of a wide fuel mix (mainly wood wastes, bark, sludges, coal) in relatively small (< 50 MWth) mainly bubbling fluidized bed combustors (BFBC). Current industrial development trends are an increased utilization of sewage sludge, small fluidized bed combustors (< 50 MWth) with wood as the main fuel and large units (> 100 MWth), as well as the utilization of municipal solid waste (MSWth) and gasification.

However, with coal as the main or only fuel (also coal with lower quality) the fluidized bed technology is targeting the size range of pulverized coal (PC) boilers with circulating fluidized bed combustors (CFBCs) in the utility size of 600 – 800 MWe with net efficiencies of 45 -50% (Hotta 2009). A significant step into this size range is the first supercritical and nowadays world's largest CFB boiler (460 MWe) which has been put into operation in 2009 in Lagisza, Poland.

Worldwide there is a significant increase of fluidized bed combustors. Especially in China there is a very strong trend to install large-scale CFBCs in the 600 MWe size range with high efficiencies. During the Five Year Plan (2007 – 2011) 50 units of 300 MWe CFB boilers are to be built and more CFB boilers burning coal waste with total capacity of 2000 MWe are under approval (Yue et al. 2009).

Further developments are focused on novel technologies such as fluidized bed gasification and pyrolysis as well as oxyfuel combustion and chemical looping combustion (CLC) with special respect to CO₂-neutral energy generation both from biomass and fossil fuels.

The International Energy Agency – Fluidized Bed Conversion (IEA-FBC) Implementing Agreement supports and stimulates by information exchange (refer also to www.iea-fbc.org and more regional: www.iea-fbc.net) these very important and significant developments and demonstrations. The IEA has prolonged this very successful Implementing Agreement for the next five year term (2009 to 2014) and it can be well estimated that it will continue to 2019 and beyond.

The next steps are the continuation of the support of these very innovative developments, the inclusion of the observers like China into the IEA-FBC Implementing Agreement and to further improve and develop the regional and global net-working.

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1 The IEA-FBC Group – Current Status

An overview of the activities of the IEA-FBC group can be found at the following website: http://www.iea.org/techno/iaresults.asp?id_ia=18. Detailed information and many presentations given at different meetings and workshops can be found at: www.iea-fbc.org
A short summary is given below:

The Implementing Agreement for Cooperation in the Field of Fluidized Bed Conversion of Fuels Applied to Clean Energy Production provides a framework for international collaboration on energy technology development and deployment.

Fluidized beds offer several advantages over pulverised fuel combustion, notably low NO_x emission, in-process capture of SO₂ and the ability to burn a wide range of low-grade and potentially difficult fuels (including waste and biomass), as well as mixed fuels. The conversion (combustion or gasification) of solid fuels for production of heat and/or electricity can be made by various fluidized bed techniques working at atmospheric pressure or under pressure, usually: "bubbling" and "circulating" fluidized beds. Supercritical steam conditions can be used for fluidized bed boilers (atmospheric and pressurised) and efficiencies in the range of 45 per cent may be attained in the near future. The world largest fluidized bed boiler is in operation in Lagisza (460 MW_e, supercritical), Poland since 2009.

In addition, the technology can be employed for incineration and existing units have been successfully used for the disposal of high level PCB contaminated wastes, oil remediation and the elimination of low calorific wastes. The technology is also used in the metallurgical industry among others.

The Implementing Agreement on Fluidized Bed Conversion aims to bring together experts wishing to work on common problems. The main activity is technical exchanges during meetings and workshops. Participants are carrying out research on operational issues in support of local commercial fluidized bed conversion activities and sharing the results. Mathematical modelling has been a major activity in the past and a "1D" model for atmospheric fluidized bed combustion of coal has been developed and the exchanges in "3D" modelling of gas/solid flows as been very fruitful in permitting the development of knowledge of local solid concentration and heat transfer. In addition, efforts are undertaken in the field of: - solids attrition and fragmentation. - NO_x and N₂O formation and reduction. - sorbent reactivity and sulphur capture mechanisms. - bed sintering/agglomeration problems. - ash utilisation

The Agreement has published a series of compilations of outstanding papers on R&D activities in fluidized bed conversion and a guide book for the use of the "1D" CFB combustion model.

In addition special focus is given to:

- Gasification and pyrolysis
- Chemical Looping Cycle
- Oxy-fuel fluidized bed combustion
- Ash utilization

The agreement has produced a series of publications and reports of R&D activities in the area of fluidized bed conversion, please refer also to www.iea-fbc.org.

Active members are:

Austria, Canada, Czech Republic, Finland, France, Greece, Italy, Japan, Korea, Poland, Portugal, Sweden, Spain, United Kingdom

Observers are:

South Africa, Serbia, Montenegro, Germany, China, Australia

2 Advantages for Austria of the IEA-FBC membership

- EU – Schengen extension to Eastern Europe, Market & Stability

The European Union has extended its Schengen borders in December 2007 towards the east. The formalities at the borders are drastically reduced which is very helpful for strengthening the co-operation between Austria and its neighbouring countries like Czech Republik, Hungary, Slovakia Poland. E.g. the world's largest CFBC unit is in operation very close to Austria, in Lagisza, Poland (460 MWe). This is an excellent basis to fulfill the aim of this co-operative network. This was also catalysing the formation of the regional IEA-FBC network realized in annual FBC meetings at Puchberg am Schneeberg in Lower Austria (refer to www.iea-fbc.net)

- Chinese Market – as an example

Austria is very interested in a good relationship for economics with China because of the very significant Chinese market. This is also very important for FBC technology. The world largest CFBC units are going to be built in China within the next years burning Chinese coal and biomass. These units are in a range of 600 to 800 MWe. This has to be done with high efficiencies and low emissions to the environment. China is very interested in the co-operation with the IEA and China is attending as observer IEA-FBC meetings. Similarly, Russia and India can be named.

- Advantages for Austrian boiler manufacturers, operators and suppliers

If there are questions or problems to solve the IEA-FBC network is an excellent partner to address. Because of this significant amount of knowledge and experience of hundreds of researchers, plant manufacturers and operators around the globe parallel developments can be reduced to a minimum. This is very helpful for each individual company or research organisation but also for the FBC technology itself. In the past a wide range of problems were already addressed to the IEA-FBC network and short term to long term research projects and developments have been initiated. And this knowledge is not strictly related to combustion alone but can also be extended to a certain degree to the application of FBC technology to refineries, the chemical and metallurgical industries.

- Advantages for research organizations

In this recent time it is very crucial for the performance of successful and excellent research to have collaborations on a global scale. To exchange the status of knowledge and to solve current and future challenges, teams have to be formed and research has to interact on an international frame. Therefore the IEA-FBC network is an excellent basis for starting co-operations, exchange of ideas and knowledge.

3 History of fluidized bed development

The importance of the fluidized bed technology is enormous today, and a permanent increase can be observed not only in the number of installed units worldwide, but also in the number of new application areas where this technology seems to be very advantageous. But how did this success story begin, how did it develop in the different fields of application, and which technology variations were invented throughout its history? These are the questions to be discussed in this chapter.

Early beginnings

The kick-off of the fluidized bed technology is linked to the name of a German scientist, Fritz Winkler. He was the person who introduced gaseous products of combustion into the bottom of a vessel containing coke particles on December 16th, 1921. After increasing the gas speed in the vessel he observed the typical phenomenon of fluidization including an extended volume of the solid heap which looked like a boiling liquid. Although combustion had more important role in some periods in the history of development of the fluidized bed technology, the first application was definitely gasification.

After the above mentioned date of birth of the modern fluidized bed technology, Winkler patented his finding in 1922, he went on taking measurements, and he built commercial fluidized bed plants as large as 12 m² in cross section – very large even by today's standards (Basu, 2006).

As we see, the birth of the fluidized bed technology is definitely linked to a concrete person and a very well defined date in the beginning of the twentieth century. Numerous books and other publications on the technical discussion of this technology have also a historical introduction, and they agree on this point. Despite of this common consensus, the reader may ask, whether it can be really true. What Winkler did is an application of the fluidization technology already. Today we see a broad range of more simple applications of the “pure” fluidization technology as well, where no conversion, no chemical reaction, no material or energy transport happens between the gas and solid phases. Many examples can be taken from traditional industry branches like the food industry or the cement industry. Is it possible, for example, that the widespreadly applied fluidized transport of flour, where only the fluidization effect is utilized, is a result of the Winkler invention as well, and not vice-verse?

An absolutely sure answer to this question can not be given. What we know is that those simple applications in the mill industry, e.g. were still not common that time. Industrial museums and books on technical history say that a boom of these applications happened during the 1930s and 40s only. The reason is simple, this is the period when air blowers became commercially available. May be, even the actors of this exciting story could not have clearly answered the question, which idea affected the other one, in which order and how.

To have a picture about the early beginnings of the fluidized bed technology, one must also mention that some old books describe a few applications before the Winkler Invention. Leva

(1959) says, for example, that the earliest application was around the turn of the century in the water treatment industry, and he mentions another patented solution from 1910 describing a process very similar to the fluidization of solid catalysts by gas.

This is not our role to appoint the exact date of birth of the fluidized bed technology. We only wanted to give an insight into the time and circumstances of the birth of a technology, which reached such a high importance by the current age. However, we believe that the simplified approach followed in most recent publications describes well the reality introduced more detailed above.

Research and commercialization

In general, patented technical inventions are followed by a period of innovation, research and development activities till the new solution reaches its maturity for commercial application (Koornneef et al., 2006). The fluidized bed conversion technique seems to be an exceptional case, since within just a few years some large scale application were in operation already, as mentioned above.

The invention towards the next step of this technology development, the circulating fluidized bed (CFB or: fast fluidized bed) was done by a very curious way. Two researchers (Warren Lewis and Edwin Gilliland, MIT, USA) found this method to be a good solution for gas-solid interaction for catalytic cracking in 1938. It is rather interesting in this event that they were unaware of Winkler's invention done 17 years earlier (Basu et al., 1991)! Since this time CFBs were used extensively in the petrochemical industries, especially for catalytic cracking of mineral oils. As a next milestone in the utilization of the new fast fluidization technique, Lurgi introduced in the 1960s and 70s a new application area, as they put into operation some aluminum calcining units in Lünen. This was followed by large number of CFB calciners soon put into commercial operation worldwide.

As visible, combustion did not belong to the application areas occupied by the fluidization technology in its earliest development period. The beginnings of this new application area go back to two roots. First of them was an invention in the UK, where in the early 1960s it was recognized that the heterogeneous chemical reaction in a fluidized bed can be combustion as well, and steam generation can be carried out by immersing boiler surfaces in the bed (Douglas Elliott, British Coal Utilization Research Association).

Another inspiration for applying fluidized beds as combustors was the calcination process, where the success of the fluidization technique was obvious already. Since the precalcining stage of the cement clinkering process is highly exothermic, some suppliers introduced circulating fluidized beds as precalciners to provide heat by burning coal. Notice that this early solution was a combined use of the fluidized bed technology already – similarly to the most recent applications for chemical looping combustion and dual fluidized bed gasification.

By means of these activities, the application field of the fluidized bed technique was extended also towards combustion, which became later a definitely glorious chapter of this story. The initiation into this new direction was followed by intensive research and

development activities on the application of BFB combustors in the UK, USA and China (Basu et al., 1991).

The first commercial CFB boiler started in 1979 in Pihlava, Finland, and this 15 MW peat-fired unit was manufactured by Ahlstrom. Ahlstrom (since autumn 1995 Foster Wheeler Energia Oy) initially focused on low grade and multifuel FBC applications, while it is the supplier of the world's largest CFBC unit, which is fueled with high grade coal.

The 1980s belong definitely to the great period for the fluidized bed combustion already! At the very beginning of this decade, on February 21st, 1980, the first Implementing Agreement for cooperation in the field of fluidized bed combustion was signed under the auspices of the International Energy Agency, IEA (Olsson et al., 1996). The following nine countries at the same time decided to participate in the agreement: Canada, Denmark, Italy, Japan, The Netherlands, New Zealand, Norway, Sweden and Switzerland. During the history of this international tool for development some countries joined the Implementing Agreement and others withdrew from it, but an increase in the number of associated countries can be observed, by all means. In 2010 there are fourteen active member countries such as Austria, Canada, Czech Republic, Finland, France, Greece, Italy, Japan, Korea, Portugal, Poland, Spain, Sweden, UK (www.iea-fbc.org).

The 1980s (as the beginning of the great period of fluidized bed combustion) were characterized by a number of further milestones reached by this technology. The first CFBC unit designed exclusively for the supply of steam and heat, was built by Lurgi in the Vereinigte Aluminium Werke at Lünen in 1982. This plant generated 84 MW total by burning low grade fuel in the presence of limestone (Basu et al., 1991). In the utility segment the first use of the CFBC technology started in 1985 with the operation of a 90 MWe boiler in Duisburg, Germany, and one year later, with the installation of a 117 MWe combustor (Burnsville, USA) also the BFBC technology entered this segment (Koornneef, 2007).

An interesting episode in the history is the case of the pressurized fluidized bed combustion (PFBC). It was studied by Ahlstrom since 1986 (Chalmers, 1995), and it was an important topic at all FBC conferences that time, since its combination with gas turbines promised very advantageous power generation units of high efficiency. These developments lost their importances later not only because of the higher maintenance costs caused by the pressure vessel, but much rather because of the further development of gas turbines resulting in much higher allowed gas inlet parameters no more compatible with the PFB combustors.

The first half of the 1990s is characterized already by a steadily increasing importance of fluidized bed gasification and other advanced applications of the technology in question. The first unit utilizing biomass and the integrated gasification combined cycle (IGCC) system was operated at full capacity in 1993 in Värnamo in Southern Sweden (Olsson et al., 1996). This shift in the emphasis was expressed also in the title of the IEA Implementing Agreement concerning the topic, where instead of the word "combustion", "conversion" was adopted (Olsson et al., 1996). Besides gasification, a number of further very promising fluidized bed technologies are intensively investigated such as chemical looping combustion (CLC) and Ca-looping for CO₂ sequestration and storage.

At the time of writing, the Łagisza power unit in Poland represents the peak of the fluidized bed combustion technology. It was commissioned on June 27th, 2009 by Foster Wheeler, and it actually holds the first prizes in several categories. With its capacity of 460 MWe (~1000 MWth) it is the world's largest FBC unit, it is the first supercritical and also the first once through fluidized bed combustor in the world.

Thematic sections in the development history

The history of fluidized bed development is rather interesting and varied as shown above. The reason for this lies in its diverse applicability and also in the changes of requirements and circumstances in the worldwide and local trends the technology was faced with throughout its almost one century long history. It also means that the emphasis of application and research was shifted several times from one area to another one. In this section, some of the most important aspects will be discussed, considering the changes in their importance throughout the development history of the fluidized bed conversion technology. The next points can be considered as digested longitudinal sections of the above history along some selected technical aspects.

Application areas

Although combustion dominated both research and application interests throughout some decades (from the early 1970s up to the mid 1990s), it was not always so. Before this period – since the original invention – the main application area was gasification, which was extended by some other fields like catalytic cracking and aluminum calcining that time. After the period of combustion as the central area, a renaissance of gasification could be observed, which was followed soon by a number of brand new promising research areas like Chemical Looping Combustion and Ca-looping.

These changes were motivated obviously by increasing requirements in sustainable and secure energy generation. The dominance period of fluidized bed combustion was because of its applicability for low-grade coals and residues while assuring significantly low emission limits compared to other combustion technologies. After the time frame mentioned, the importance of combustion as an application area did not fall, but also new solutions were developed besides it, driven also mainly by the requirements of sustainable energy production.

Technology variations

Although the circulating fluidized bed technology (CFB, or also: fast fluidization) can be considered as a follower of the Bubbling Fluidized Bed (BFB) technology, its invention was independent from the 17 years earlier one. Both techniques developed rapidly after their introductions, and they still have their balanced separate roles in almost all application areas. In case of combustion, the emphasis was shifted from BFB to CFB in the late 1980s, however, in the last decade, BFB became popular again, especially for the utilization of low grade coals, biomasses and waste-derived fuels in small sized distributed energy generation units.

Pressurized fluidized bed combustion

In the mid 1990s, Pressurized Fluidized Bed Combustion (PFBC) was in the center of interest, because of the perfect correspondence to gas turbines resulting in high efficiency combined cycles. The fast development of gas turbines allowed later much higher gas entry parameters, which were no more compatible with those of the fluidized bed outlet gas. This lost incompatibility, together with the high maintenance cost because of the pressure vessel resulted that this technology belongs to a finished chapter in this exciting story. Nevertheless, pressurized fluidized bed may will have importance in other application areas like Ca-looping, for example.

Fuels for fluidized bed combustion

One of the most important advantages of the fluidized bed combustion (FBC) technology is its flexibility against fuel quality. That's why the development of such combustors could flexibly follow the requirements regarding solids to be combusted throughout its history. Two main directions can be observed since the very early applications, the first one is the utilization of low grade fuels like high ash coal, lignite, peat, different sorts of biomass, waste derived fuel, and their combinations, while the second one is high grade coal. Some shifts of emphasis between these two areas can be observed as functions of time and region, but both directions were always present, and this is true also nowadays. The low grade fuels are rather utilized in bubbling fluidized beds of smaller sizes, while for high quality coals the circulating technique is preferred showing some advantages despite their somewhat more complicated constructions.

4 Advantages and limitations of FBC technology

Fluidized Bed Combustors are used successfully for the thermal utilization of biofuels and waste (wood chips, saw dust, waste from paper industry) as well as for fossil fuels e.g. coals with high ash contents and lignites.

The fuels are burned as single fuel or as fuel mixture in a FBC. The fluidized bed consists mainly of bed material (fuel ash and silica sand) and only to a few percentages of the fuel itself. The fluidization is performed with the combustion air. Due to the fluidization of the bed material and the fuel particles the three-dimensional motion of the solids ensures good mixing conditions in horizontal and vertical directions. This excellent mixing behaviour leads to even temperature and fuel distributions within the combustion chamber which is a significant advantage compared to grate furnaces and pulverized fuel combustors. The fluidized bed material acts efficiently as mobile heat tank and evens changing fuel mixtures and moisture contents.

Due to the fluidization with combustion air a strong coupling between the on-going combustion chemistry and the flow characteristics is given. The fluidized bed has to be operated between the minimum fluidization velocity and the terminal fluidization velocity. If the velocity is high, an increased entrainment of fine particles will arise. This leads to operating conditions which have to be optimized for given particle size distributions. If ashes are generated which melt at low temperatures agglomerates may be formed which may lead to a complete de-fluidization of the fluidized bed combustor.

Generally fluidized bed combustors have high heat transfer rates. Therefore the size of the unit can be kept compact and the heat is used efficiently.

Due to the even temperature distribution and temperature levels (typically 850 °C) no thermal NO_x is produced. The NO_x formed originates from the fuel nitrogen which has to be considered if fuels with high nitrogen contents are burned.

In-situ desulfurization (SO₂ removal) is possible with direct limestone addition into the combustion chamber. Therefore external desulfurization is not necessary.

Besides the bubbling, stationary fluidized bed combustors (FBCs) circulating fluidized bed combustors (CFBCs) are used usually in the thermal power range higher than 100 MW_{th}. These CFBCs operate at higher gas velocities and show excellent heat and mass transport characteristics. Due to fluidization limitations the particle size distribution in CFBCs is smaller (typically below 15 mm) and narrower compared to FBCs (typically up to 40 mm).

5 Fuel mix, operating ranges and preparation

The fuels used vary in a wide range and are usually used as fuel mixture. Typical fuels are bark, wood waste, saw dust, coals with low calorific values and recently plastics, municipal solid waste and sewage sludge (refer to Figure 5.1). The thermal power range is typically between 30 to 900 MW_{th} (combustion) and 8 to 10 MW_{th} (gasification). Circulating fluidized bed combustors are usually used in the higher thermal power range and are able to operate in a very wide range (Figure 5.2).

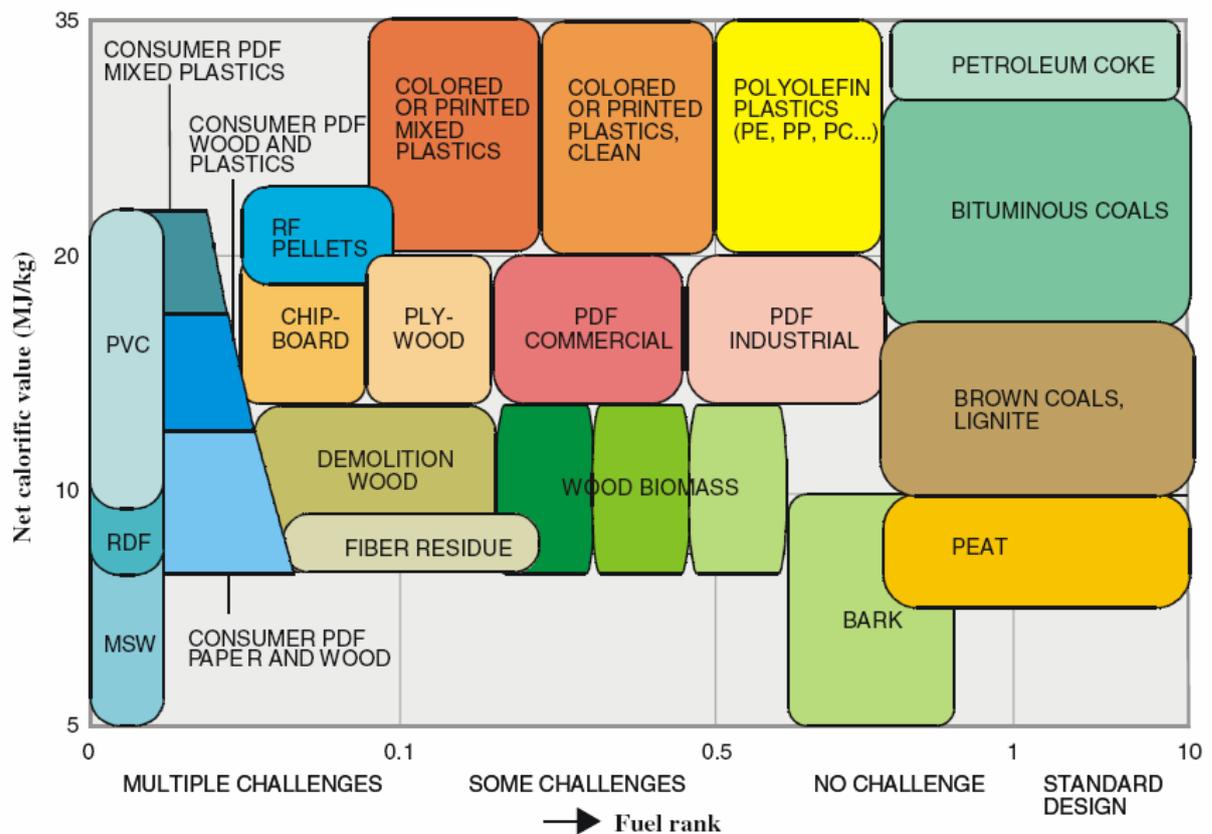


Figure 5.1 Fuels used in FBCs.

Right: standard design of the FBC; left: special design is necessary (Hämäläinen 2005)

MSW: Municipal Solid Waste / RDF: Residue Derived Fuel / PDF: Packaging Derived Fuel

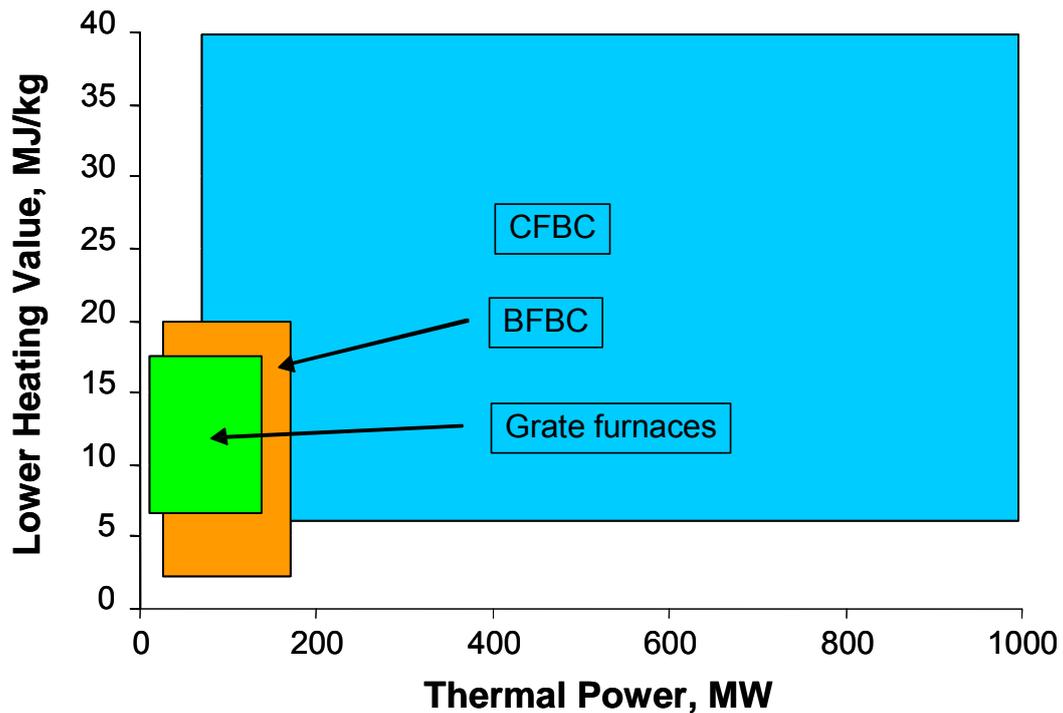


Figure 5.2 Overview of the operating ranges of stationary fluidized bed combustors (BFBCs), circulating fluidized bed combustors (CFBCs) and grate furnaces: modified from [1]. Lower Heating Value of the fuel versus thermal power.

A very important topic for transport and feeding of the fuels is their particle size distribution and density. Problems may arise if the fuel is too large in one of its lengths. Bridging in the feeding lines is possible. Figure 5.3 shows a complex fuel preparation system.

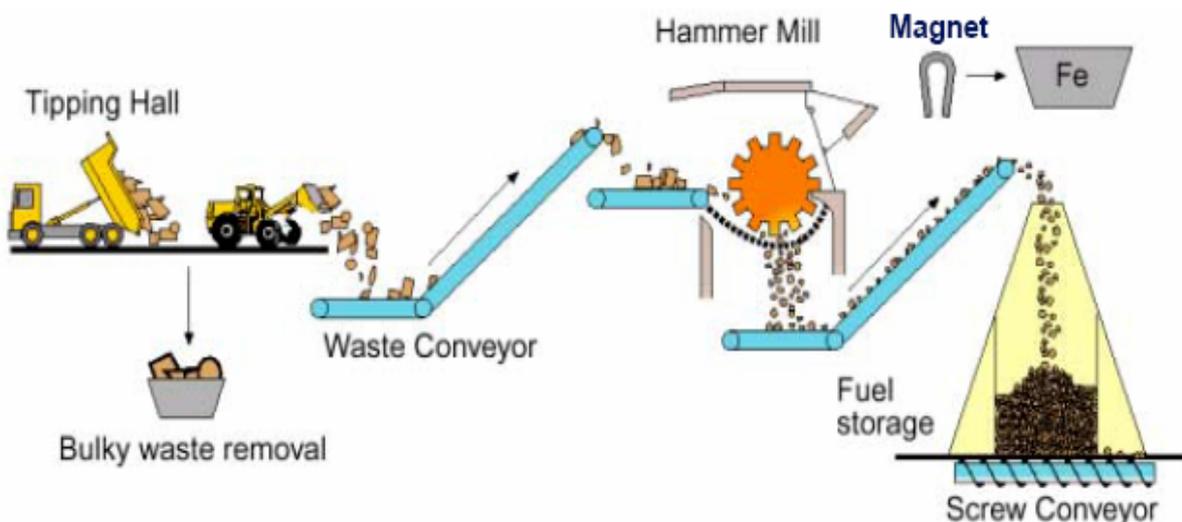


Figure 5.3 Fuel preparation Swedish concept (Andersson 2004).

In case of power plants fired by coal alone, a very good and commonly used way for characterizing the actual fuel is giving its lower heating value, which considers already its moisture content as well. Notice, that this approach is applicable only in case of fuels of

relatively low moisture, typically below 10%. A basic characteristics of most biomass fuels – which constitute an important group of renewable fuels – is however their significant moisture contents, generally above 10–20% or even more (see Table 5.1) The worst cases are regarding this aspect the sludges, especially sewage sludges, where in some cases the extremely high moisture result even negative lower heating values, which do not allow their mono- combustion without effective drying to be carried out generally before transportation.

Table 5.1 Typical calorific values and moisture contents of fuels
(Winter et al. 1996, Biobib 1996).

Fuel	calorific value (MJ/kg) dry	moisture (%) as received
beech wood	17 - 19	10 - 30
spruce wood	19 - 21	10 - 30
grass	17 - 18	10 - 40
waste wood	16 - 17	10 - 30
paper	17 - 18	5 - 30
bark	15 - 16	10 - 30
sewage sludge	15 - 17	55 - 70
lignite	15 - 17	25 - 60
bituminous coal	29 - 33	3 - 5

Drying is a very important part of fuel preparation in case of most renewable fuels. Figure 5.4 indicates this process (thick line) on the example of an energy plant characterized by 43% moisture in its harvesting state. In case of drying biomass fuels on site (in the power plant storage area) besides the positive effect of increasing its heating value, also the loss of total fuel mass should be considered. This is indicated in Figure 5.4 by the thin line, which is the lower heating value relative to the original fuel mass.

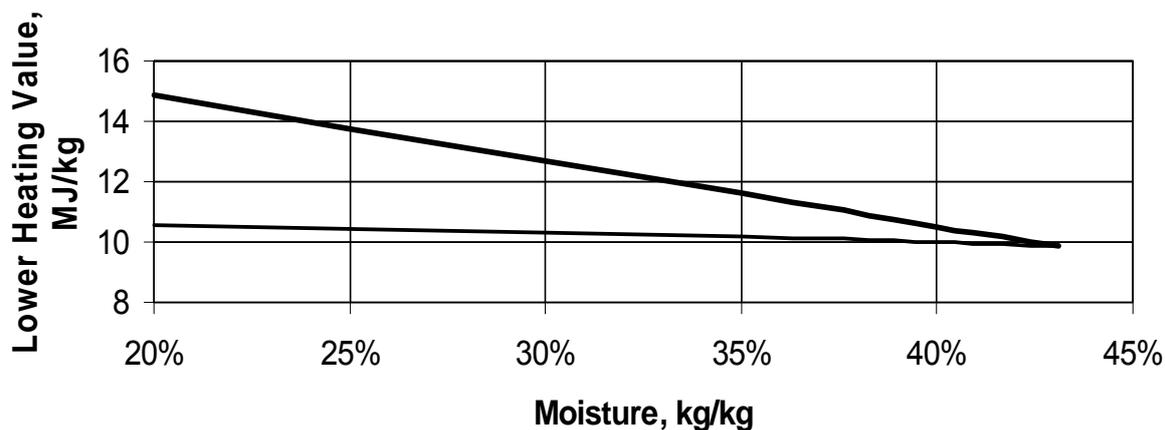


Figure 5.4 Effect of drying of a biomass fuel (energy plant)

Thick line: change of lower heating value (relative to the actual fuel mass)

Thin line: change of lower heating value relative to the original fuel mass

Typical regional differences in the fuel feedstock and technology used can be seen in Figures 5.5 and 5.6. For instance in the USA and Asia mainly coal (coal and coal mix.) is used whereas especially in the Scandinavian countries the utilization of biomass is of high importance even in circulating fluidized bed combustors (CFBCs). In comparison biomass is preferentially used in bubbling fluidized bed combustors (BFBCs).

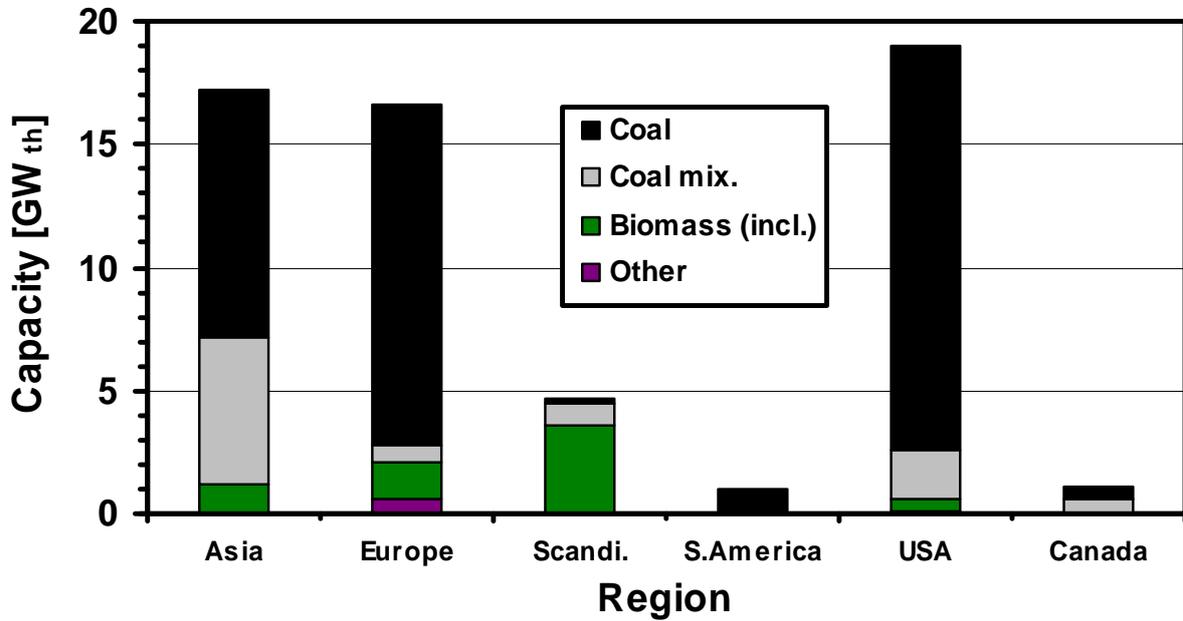


Figure 5.5: Regional differences in fuels for CFBCs (2005-2008) (Hupa 2005)
CFBCs ... circulating fluidized bed combustors

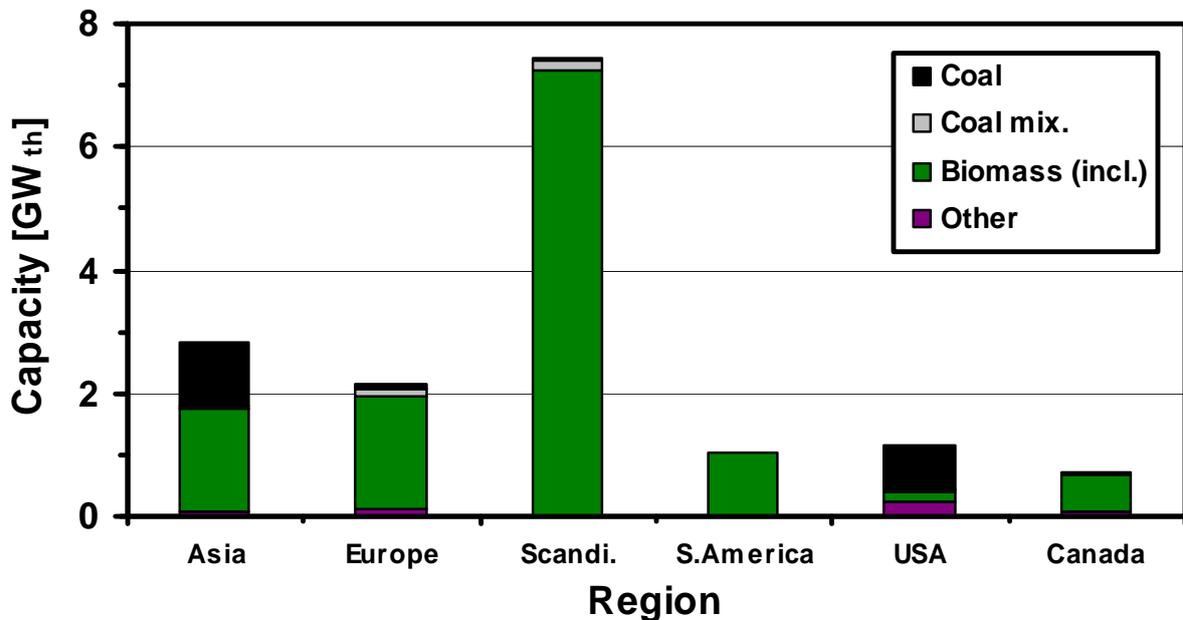


Figure 5.6: Regional differences in fuels for BFBCs (2005-2008) (Hupa 2005)
BFBCs ... bubbling fluidized bed combustors

6 Fluidized bed units in Austria

INSTALLATIONS

Table 6.1 Installations in Austria

owner / location	year	type	capacity	fuels
Sappi Austria / Gratkorn	1981	CFBC	25 MW	Bark, sludge, biogas, natural gas
Sappi Austria / Gratkorn	1986	CFBC	133 MW	Coal, sludge, biogas, natural gas
Norske-Skog / Bruck a.d. Mur	1984	BFBC	15 MW	Bark, coal, sludge, biogas, natural gas
Verbund / Zeltweg*)	1998	CFBG	10 MW	Wood
ENAGES / Niklasdorf	2004	BFBC	40 MW	MSW, industrial waste, wooden residue, sewage sludge
Lenzing AG / Lenzing	1987	CFBC	108 MW	Bark, coal, sludge, wood residue, oil
RVL / Lenzing	1998	CFBC	110 MW	Plastics, waste, sludge, wood residue
Solvay / Ebensee	1987	CFBC	43 MW	Coal, wood waste
UPM Kymmene Austria / Steyrermuehl	1994	CFBC	48 MW	Bark, wood, wood residues, sludge
Energie AG Oberösterreich / Timelkam	2006	FBC	49 MW	Wood, wood residues, bark, sawdust
M-real Hallein AG / Hallein	2006	BFBC	30 MW	Wood chips
Mondi Packaging AG / Frantschach – St. Gertraud im Lavanttal	1984	CFBC	61 MW	Bark, coal, sewage sludge, heavy oil
FunderMax / St.Veit a.d. Glan	2007	BFBC	45 MW	Wood, wood residue, saw dust, process waste, sewage sludge
ABRG / Arnoldstein	2000	FBC	8 MW	Oils, emulsions, wooden residue, sludges, plastics
Hamburger / Pitten	1984	BFBC	65 MW	Coal, biogas, sewage sludge
AWA Bad Vöslau / Bad Vöslau	2003	BFBC	1 MW	Sewage sludge
Fernwärme Wien / Vienna	1992	FBC	3 x 25 MW	Sewage sludge
Fernwärme Wien / Vienna	2003	RFBC	40 MW	municipal solid waste, sewage sludge
Wien Energie Bundesforste Biomasse Kraftwerk (WEBBK) / Wien-Simmering	2006	CFBC	66 MW	Forest residue

Biomassekraftwerk-Heiligenkreuz Errichtungs-GmbH / Heiligenkreuz	2006	BFBC	43 MW	Forest residue
BKG GmbH / Guessing	2001	FICFB	8 MW	Wood chips, wood residues
Energie Oberwart GmbH/Oberwart	2008	FICFB	10 MW	Wood chips

BFBC bubbling fluidized bed combustor
 FICFB fast internal circulating fluidized bed combustor
 DFBG dual fluidized bed gasifier
 CFBC circulating fluidized bed combustor
 CFBG circulating fluidized bed gasifier
 RFBC rotating fluidized bed combustor
 *) not in operation, **) operation starts

Table 6.1 contains the most important features of fluidized bed combustors and gasifiers in Austria.



Figure 6.1 Overview of fluidized bed combustors and gasifiers in Austria.

7 Fluidized bed units in Hungary

In this chapter, an overview will be given about the current status of fluidized bed conversion in Hungary. So that it could be understood, an introduction to the overall energy situation of the country will be given first. Most of the FBC units operated in Hungary were developed, designed and delivered by native research institutes and companies. That is why, the most important institutions involved in this subject, together with their technological characteristics will be also introduced.

Overall energy situation

The annual total primary energy supply in Hungary is roundly 1 exajoule (1092 PJ in 2003; 1125 PJ in 2007), which is mainly covered by natural gas, oil and nuclear energy. The percentage of nuclear energy in the total electricity production is significant with its share of about 34%. An interesting characteristic in the Hungarian structure of energy consumption is the dominance of households (34%) and commercial activities (24%). After 1990, the collapse of the socialist regime, the industrial demand decreased significantly, a slight growth can be observed since 2000 only.

A very important indicator of the Hungarian energy situation is the fact that about three-fourth of total primary energy supply is covered by natural gas, which is the second highest share within the EU-27. The only country having higher relative natural gas consumption is Holland, but it has an own gas production above its domestic consumption. Gas and oil production decreased definitely throughout the past three decades in Hungary. All these facts together show a strong dependency on energy imports mainly from Russia.

Energy consumption (and also CO₂ emissions) per capita in Hungary is very low (ca. 2600 kgoe/cap), which value lies definitely below the EU-27 average (ca. 3700 kgoe/cap), however, energy intensity is higher than the European average.

About 5% of electrical energy supply is based on renewable sources. Although this value overrides definitely the obligation accepted by the EU, it is still below the EU-27 average.

The composition of renewable energy supply within total electricity production is rather monotonous: besides 12% hydro and 6% domestic waste, it is definitely dominated by firewood with its more than 75% share.

Institutions involved in Fluidized bed conversion

To understand the situation of fluidized bed combustion in Hungary it is essential to know some local institutions involved in this technology. The reason is that most of the industrial FBC units were not purchased from international suppliers, they were developed and commissioned by local institutions instead.

The most important, determining company in this process was VEIKI (Institute for Electric Power Research). This research institute has developed, patented and took into operation a special construction called 'hybrid fluid' combustor. This solution was developed especially for retrofitting and upgrading existing pulverized-coal fired boilers into fluidized bed combustors. The bottoms of such boilers were completely changed, while the special 'internal circulation' method was applied. This later term refers to an FBC in which the air distributor is divided into three bands. The air speed applied in the centrally located biggest one corresponds to that of circulating fluidized beds, while in the two peripheral bands much lower gas velocities are applied in order to allow an internal recirculation – without the need of external cyclones. (See, e.g. www.veiki.hu; Reményi et al., 1989)

Important research activities started somewhat later at the Budapest University of Technology and Economics (BME), Department of Energy Engineering. This institution set up and operates a 5 m high, 80 kWth experimental FBC utility, where important research activities were carried out considering also the local characteristics of biofuel sources and energy consumption behaviors (Szentannai et al. 2005, 2007). Besides gasification, a new and successful area of this university department is the application of advanced control techniques in order to assure more reliable and flexible operation of industrial FBC (and also other) power generation units resulting direct financial benefits. (See, e.g. Szentannai et al. 2009, 2010)

The strengths of FLAMMA Physics Ltd. lie in the optimization and problem solving of Hungarian FBC units by means of high level expert know-how also in the field of Computational Fluid Dynamics (CFD) modeling. Practical results of this scientific company led to significant improvements in the operational characteristics also of some hybrid fluid FBCs.

Important results were achieved by the University of Miskolc, Department of Combustion Technology and Thermal Energy, where besides combustion also gasification was investigated on a high international level. (See, e.g.: Winkler et al., 2007; Szemmelweisz et al., 2009)

Industrial-scale fluidized bed combustors

At the time of writing, fluidized bed conversion technology in the industry size is represented by ten fluidized bed combustors located in five Hungarian power plants. These locations – in timely order of their first FBC installations – are Ajka, Kazincbarcika, Pécs, Oroszlány and Komló (see map in Fig. 7.1). An earlier, rather historical case was the power plant Győr (western Hungary), where a small-sized FBC unit was installed by a Japanese company in the late 1980s; this 16 t/h unit is no more in operation for a long time.



Figure 7.1: Power plants with fluidized bed combustors in Hungary.

The first fluidized bed combustor in the power plant Ajka was built on the basis of an existing boiler according to the VEIKI patent in the early 1990s. This one was followed by the reconstructions of three further boilers based on the same technology through the next years. All these boilers are fuelled mainly by forest wood together with other sorts of biomass and some coal. The thermal capacity is 88 MW each. (See further readings on the homepage of the power plant: www.bakonyi.hu .)

Power plant Kazincbarcika operates two FBC units reconstructed according to the VEIKI patent in the first years of the 21st century. Thermal capacities of the boilers are 72 MW, and the main fuel is also forest wood, together with sawdust, wood residues and some brown coal. (Homepage of the owner: www.aes.com .)

Power plant Pécs (www.pannonpower.hu) differs from the others, since here not the 'hybrid fluid' technology was applied. As part of retrofitting of an existing unit, a Finnish company delivered a BFB combustor of much higher capacity, 140 MW in the mid 2000s. The main fuel of this boiler is forest wood too.

Two hybrid fluid boilers are in operation in Oroszlány, the first of them was commissioned in 2005. Both of them are fuelled mainly also by biomass. The latest news at the time of writing reported about the decision of liquidation of this power plant (www.vert.hu).

In February 2010, a new fluidized bed combustor was put into operation by the town Komló. The capacity of his small unit is 18 MWth, and it was designed and built by the Hungarian companies TE Ganz Röck and ETV Erőterv. This combustor supplies hot water for the district heating system of the city, and it is fuelled mainly with forest wood substituting 10 million m³ natural gas annually.

Future plans

Regarding further plans in the development of the Hungarian energy generation system it is evident that new power plants must be built during the upcoming decades. Since the local resources on hydro power, solar- and wind energy are limited or exploited already, the main alternatives are nuclear, gas, biomass and coal. All these resources will be most probably utilized throughout the power plant investments of the next period, and the fluidized bed conversion technology will most likely play an important role in the case of the two last mentioned energy sources.

Concrete plans and some preparations were already done regarding new FBC units on two locations Dunaújváros and Kazincbarcika.

In Dunaújváros (on the river Danube) a paper manufacturer intends to build two fluidized bed combustors, 91 MWth each. The fuel of these units will be coal and residues from the paper industry.

In Kazincbarcika, where two biomass-fuelled retrofitted FBCs are currently in operation, two big sized, modern CFB units should be handed over in the second half of the 2010s. They are planned to produce 2x165 MWe on the basis of brown coal.

8 Statistical characteristics of FBC units in and around Austria

Statistical investigations on the basic data of FBCs located in a given area may deliver important insights into actual trends of the technology in question. In this chapter, some statistical results will be presented, which refer to 32 FBC units located in and around Austria.

The first diagram (Fig. 8.1) shows an almost permanent activity in building both circulating- and bubbling fluidized bed units. Interesting is the period between 1985 and 2000, when a certain plateau can be observed in case of the BFBC units – with a jump in the middle of this period. A similar plateau in building new CFBC equipment happened, but after a very similar jump in 1992-93, a new period of permanent increase started. A similar behavior is evident also from the next diagram (Fig. 8.2), which indicates the evolution of the number of units installed along time.

According to this diagram, the total number of BFB units was in most periods higher than the number of the CFB units (the line of BFB equipments runs somewhat above the half of the total numbers). According to the recent data, 20 BFB and only 12 CFB units are currently in operation in and around Austria. This seems to be a specific regional characteristics in no strict correspondence with the overall global statistics. (See as reference: Hupa at al., 2005.) The reason may lie in the more frequent application of small sized, distributed biomass fuelled bubbling fluidized bed combustors in Austria.

Both diagrams show a permanent importance of this technology in spite of its more decades long history. This observation is in a strong correspondence with the international trends (Hupa at al. 2005).

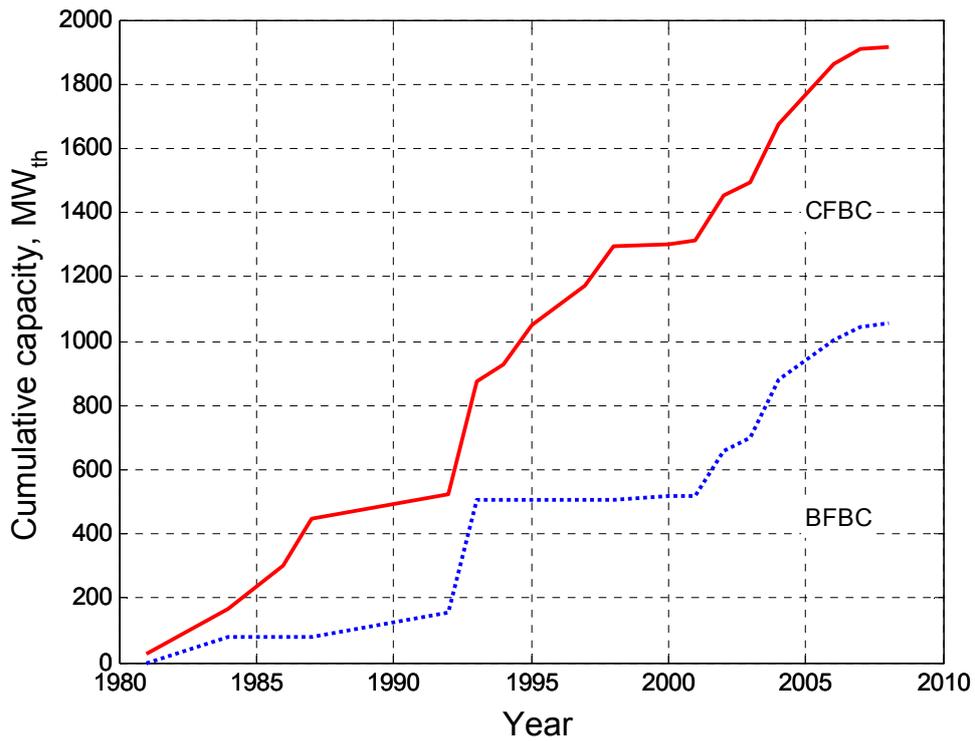


Figure 8.1: Evolution of total installed capacity of FB devices in the investigated region.

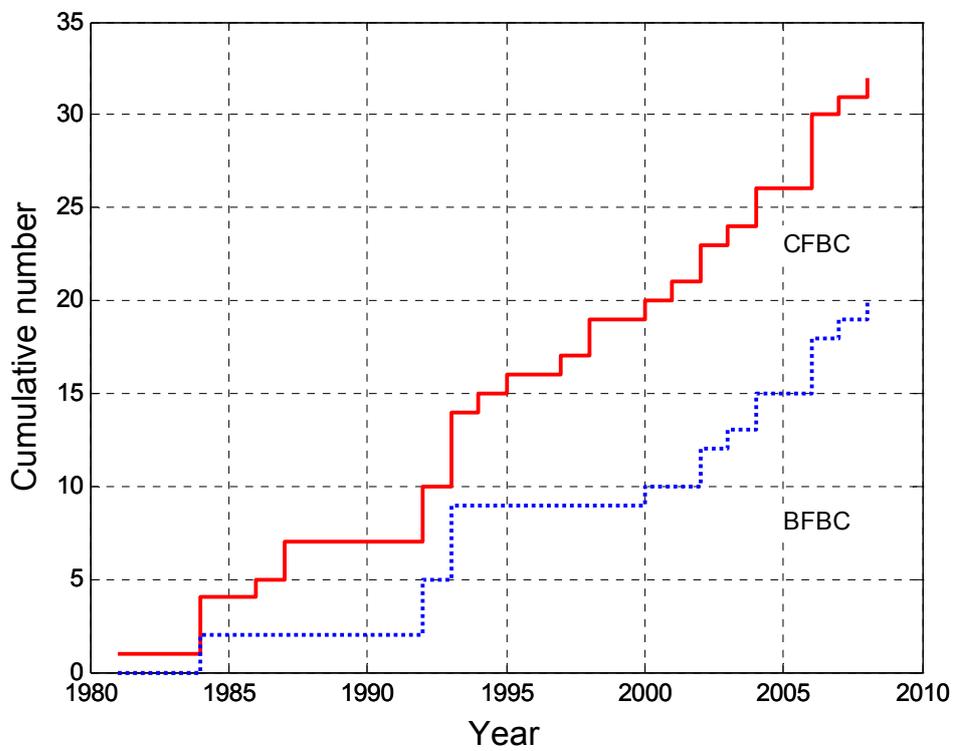


Figure 8.2: Evolution of total number of FB devices in the investigated region.

According to an overall opinion, CFBCs dominate in the range of higher unit capacities, while BFBCs are rather built as relative smaller ones. The next diagram (Fig. 8.3) shows that this is partially true only. Although the cumulative distribution function of BFB capacities runs at lower unit capacities compared to that of the CFB units, the difference is not definitely so significant!

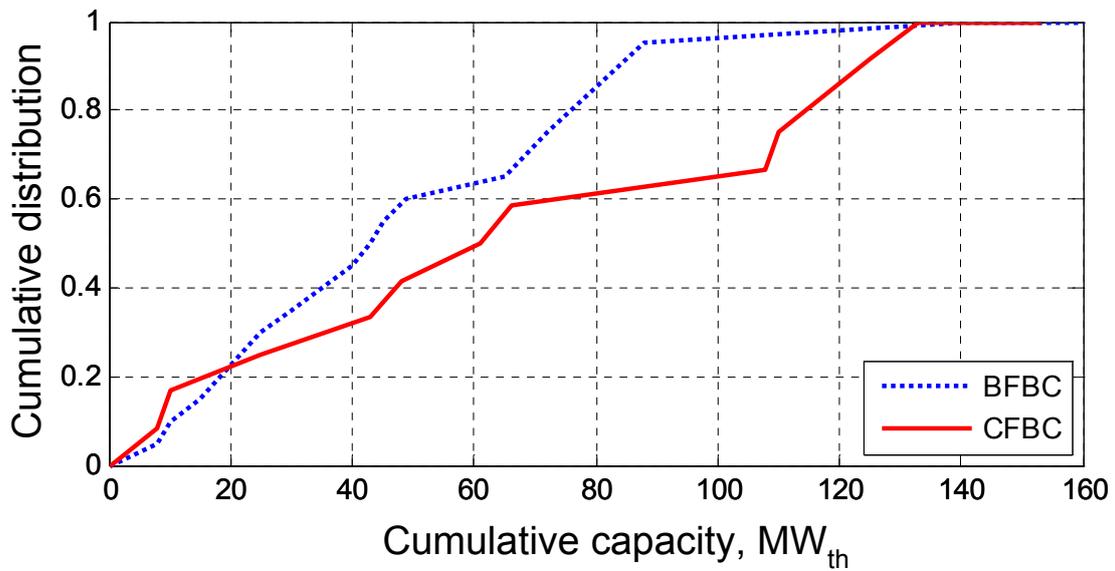


Figure 8.3: Cumulative distributions of the applications of the two FBC technologies in the investigated region.

9 Developments using fluidized bed technology

9.1 Developments in biomass utilization

According to the most general definition co-combustion is the simultaneous combustion of two or more fuels in the same plant for energy production. Besides this level of definition some more restricted ones are commonly used. These restrictions refer to either the scale of the fuels applied or the physical distance between the places where the different combustions happen. According to a more restricted, however more widely used definition co-combustion is the simultaneous combustion of coal and some other fuels in the same combustion chamber. These other fuels are generally problematic ones such as waste derived fuels or biomass. The followings reflect especially to the co-combustion of coal with biomass fuels.

Since fluidized bed combustors have excellent characteristics regarding fuel composition and quality changes, it is no wonder that they are also advantageous for the purposes of co-combustion.

Problematic fuels and also different sorts of biomass bring with their problems also in case of co-combustion, of course, that's why the investigations on this topic is very important nowadays. It is of high importance to know, how co-combustion effects these problematic behaviours of the additional sorts of fuel. The recent results will be summarized below, introducing the effects of co-combustion ranging from the (expected) disadvantages up to the (welcomed) synergies.

Disadvantages

Effects that are brought along by the biomass fuel – according to its ratio:

- Na, K → tendency for agglomeration
- Cl → corrosion (HCl)
- High water content → lower energy

Neutral characteristics

Effects that must be considered while setting the operational parameters, however, after that they do not cause any further significant problems.

- High volatile content. This must be considered while setting the combustion control parameters such as temperature control and air staging.

Advantages

Effects that are brought along by the biomass fuel – according to its ratio:

- Better burnout. Abelha et al. 2008 and Szentannai et al. 2006 report carbon burnout rates at different sorts of biomass above 99% or even above 99.5%.

Synergie effects

A number of positive effects have been observed and published, in which the resulting effect is more intensive than the superposition of the two separate effects (of two mono-

combustions of coal and biomass) would be. The most important and best documented synergy effects will be listed below.

- Lower NO_x-Emission due to NH₃ release from biomass.
- Lower SO₂-Emission due to high calcium contents of some biomass sludges.
- Lower agglomeration tendency due to the removal of alkali vapours by aluminum-silicates.

A future development is the increasing utilization of sewage sludge in fluidized bed combustors. Sewage sludge is co-combusted in large-scale pulverized coal boilers (Werther 2004) or in CFBCs with coal as the main fuel (Peltola 2004, Figure 9.1) or in small-scale units as single fuel or co-combusted with e.g. municipal solid waste (MSW) (Vienna district heating).

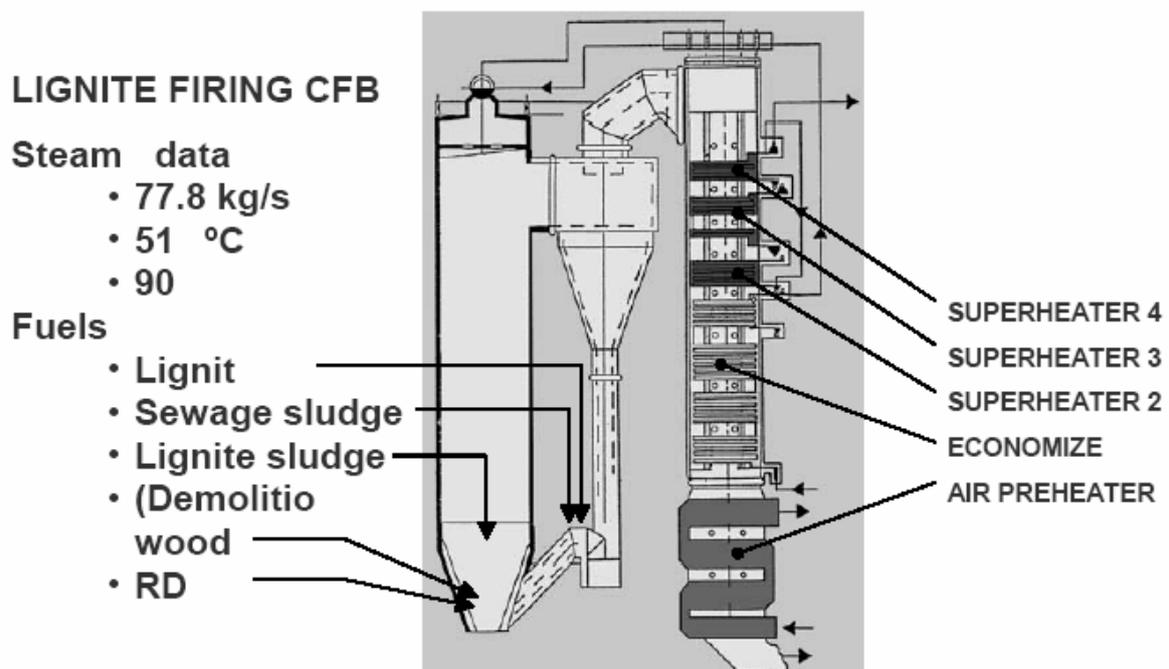


Figure 9.1 Co-combustion of sewage sludge with lignite and waste in a circulating fluidized bed combustor (CFBC) (Peltola 2004).

Smaller FBCs with wood as fuel are in Austria, e.g. in Hallein with a thermal power of ca. 30 MW, Heiligenkreuz (45 MW), Timelkam (49 MW) (Winter 2004) and Vienna.

In Finland the strategy is to use large fluidized bed combustors with peat, wood and biomass as the main fuels. In Alholma the worldwide largest fluidized bed combustor operating on biomass basis can be found (550 MW) (Jaud et al. 2004). As fuels waste wood, saw dust, bark, peat, coal and oil are used.

A current trend is the increased utilization of municipal solid waste (MSW) and biomass waste in fluidized bed combustors. Examples can be found in Austria and Germany: Fernwärme Wien (40 MW), Niklasdorf (40 MW), Neumünster (75 MW).

Another trend is the application of fluidized bed reactors for gasification. The Güssing gasifier (8 MW) uses a dual fluidized bed system and operates on biomass. Other gasifiers based on fluidized bed technology are scheduled.

Main reasons for the application of the fluidized bed technology are the efficient utilization of a very wide range of different material flows from process industry (e.g. pulp and paper) and households for heat and power production, the utilization of renewable energy sources, the reduction of landfill waste and the reduction of CO₂. The fluidized bed technology is significantly contributing to CO₂ reduction.

9.2 Scale-up as a tool for industrial development

Scale-up is the common name of the engineering tasks in which a bigger equipment should be designed based on measurements and experiences gathered on a smaller one. The problems to be solved throughout these tasks are rather similar, independently upon the character of the initial equipment, whether it is a laboratory-scale to industrial-scale or an industrial-scale to industrial-scale task. Both the previous and the later cases (see Figure 9.2) are of great importance, and the most commonly used methods are (Leckner et al. 2009)

- the method of dimensionless numbers, and
- the concept of chemical similarity.

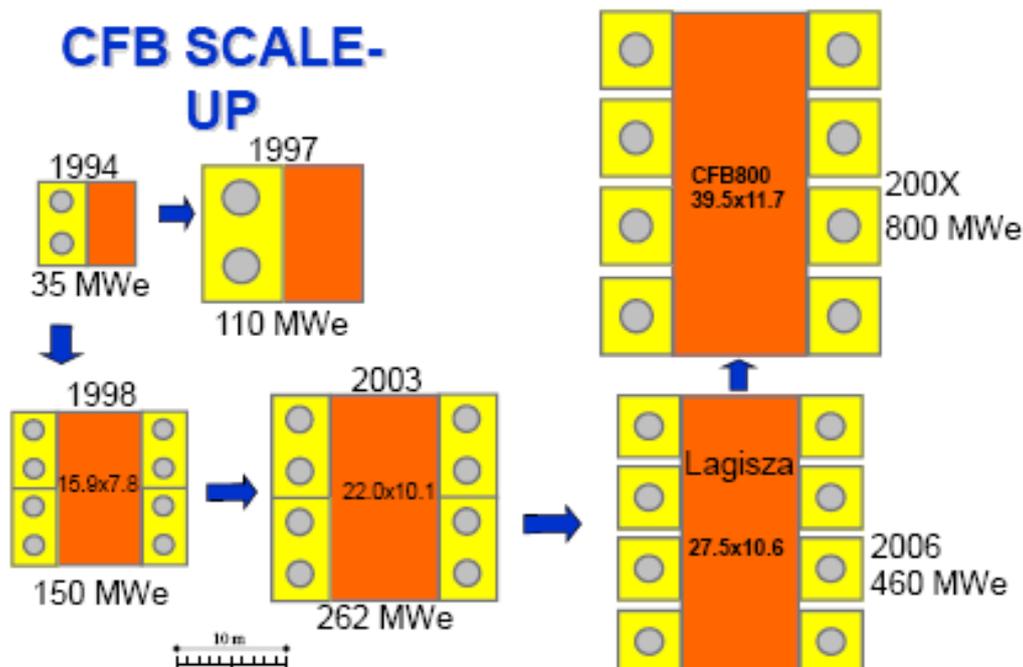


Figure 9.2. Scale-up of CFB – modular approach (Barisic et al. 2008).

9.3 Developments for new application areas

The most perspective new application areas of the fluidized bed technology are Fluidized Bed Gasification, Oxyfuel Combustion and Chemical Looping Combustion.

Figure 9.3 shows a possible construction for biomass gasification consisting of two fluidized beds.

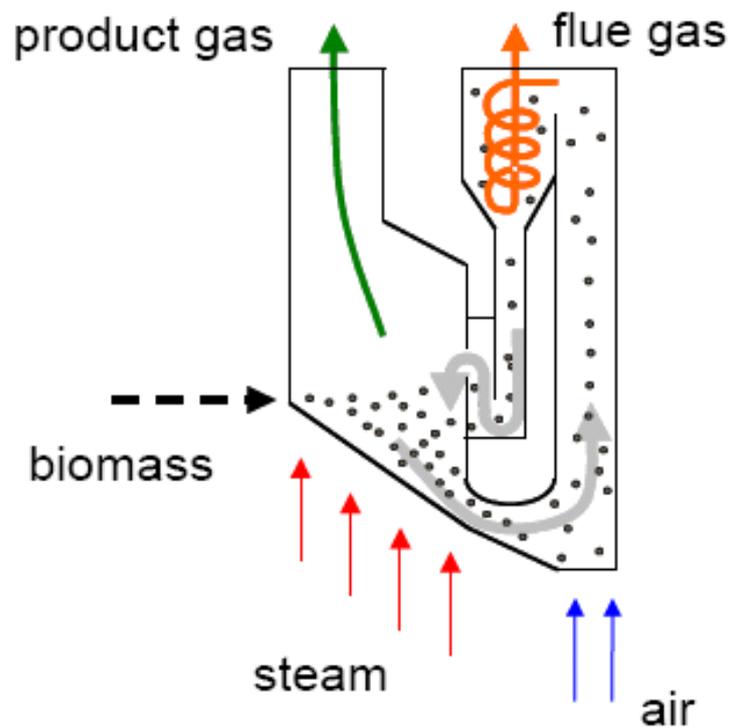


Figure 9.3 Scheme of Dual Fluidized Bed Biomass Gasifier (Pröll et al. 2006)

Another advanced application area of the fluidized bed technology is Oxyfuel combustion (for further details refer to Zhao et al. 2009) and Chemical Looping Combustion (Figure 9.4). The FBC technology itself plays an important role in the CO₂ reduction already, but the specific goal of the new Chemical Looping concept is a definitely CO₂-neutral combustion of fossil or renewable fuels.

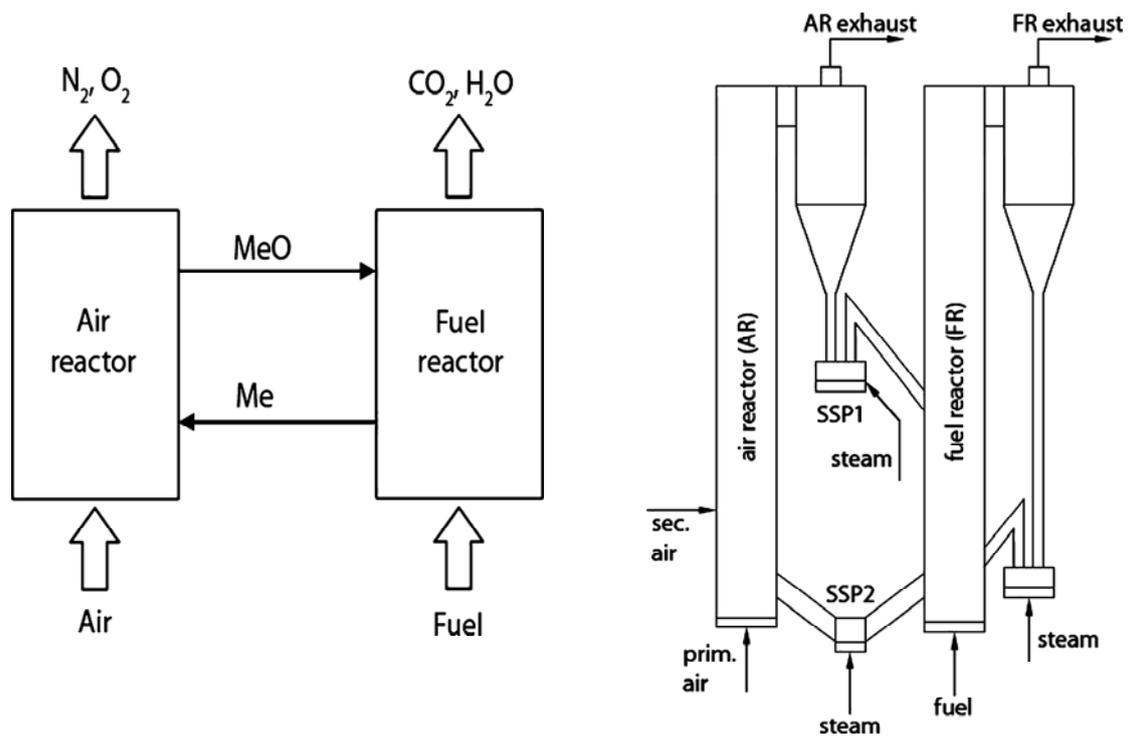


Figure 9.4 Principle and possible design of Chemical Looping Combustion (Kolbitsch et al. 2008)

10 Conclusions and Outlook

Fluidized bed combustors show excellent mixing and heat transfer conditions. They burn efficiently and with low emissions. Due to the high heat capacity of the fluidized bed a wide range of different usually low-quality (with very low calorific values and high moisture contents) or difficult fuels can be used.

Limitations exist due to the particle size distribution of the fuel, fuel chemistry and emissions and fluidization characteristics including ash behavior.

State of the art is the utilization of a wide fuel mix (mainly wood wastes, bark, sludges, coal) in relatively small (< 50 MW) mainly bubbling fluidized bed combustors (BFBC). Current industrial development trends are an increased utilization of sewage sludge, small fluidized bed combustors (< 50 MW) with wood as the main fuel and large units (> 100 MW), as well as the utilization of municipal solid waste (MSW) and gasification.

However, with coal as the main or only fuel (also coal with lower quality) the fluidized bed technology is targeting the size range of pulverized coal (PC) boilers with circulating fluidized bed combustors (CFBCs) in the utility size of 600 – 800 MWe with net efficiencies of 45 -50% (Hotta 2009). A significant step into this size range is the first supercritical and nowadays world's largest CFB boiler (460 MWe) which has been put into operation in 2009 in Lagisza, Poland.

Worldwide there is a significant increase of fluidized bed combustors, refer to Figure 10.1.

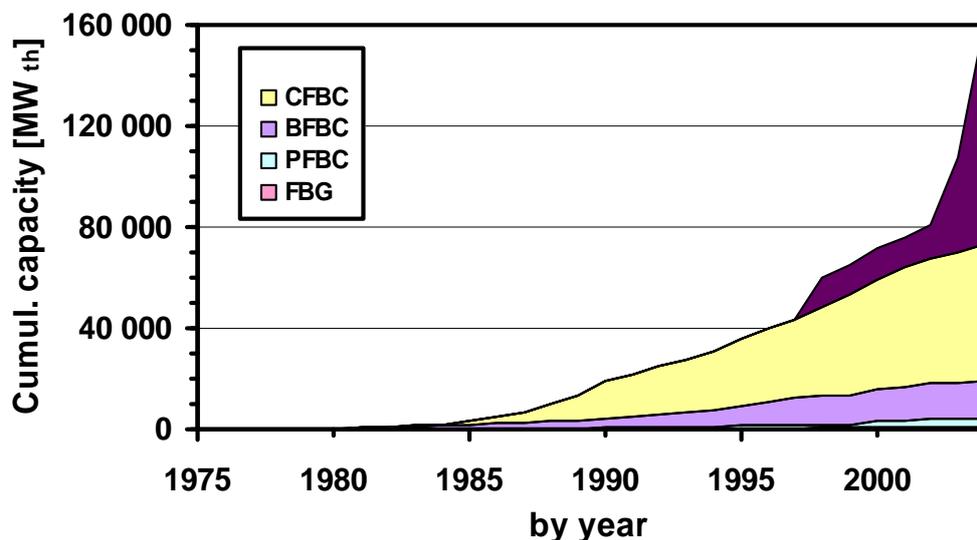


Figure 10.1 Capacity of fluidized bed devices worldwide (Hupa 2005).

Especially in China there is a very strong trend to install large-scale CFBCs in the 600 MWe size range with high efficiencies. Refer to Figures 10.2 and 10.3. During the Five Year Plan (2007 – 2011) 50 units of 300MWe CFB boilers are to be built and more CFB boilers burning coal waste with total capacity of 2000 MWe are under approval (Yue et al. 2009).

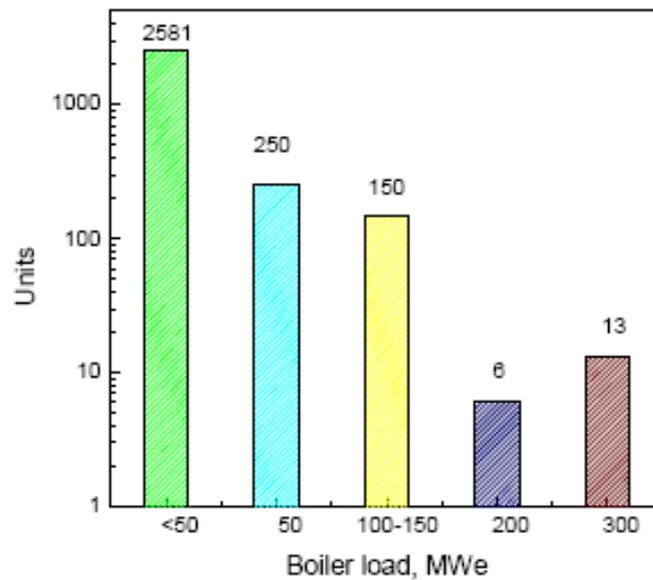


Figure 10.2 The market of CFB boilers in China by end of 2008 (Yue et al. 2009).

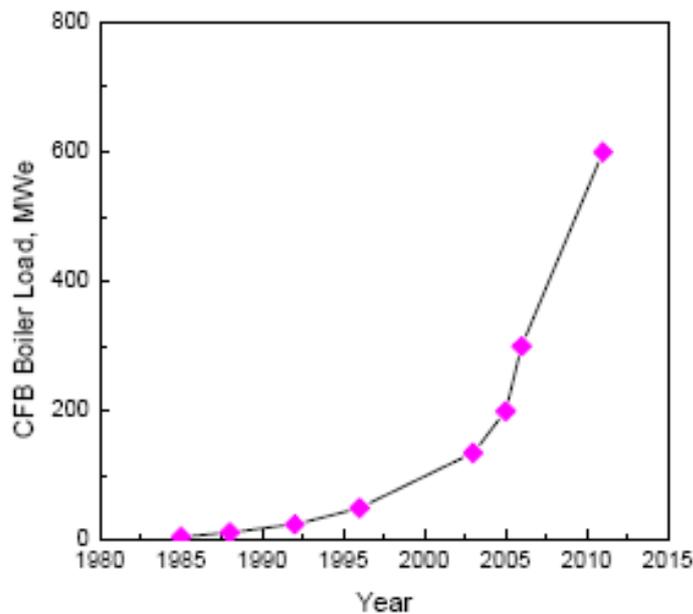


Figure 10.3 CFB boiler scaling history in unit capacity in China (Yue et al. 2009).

Further developments are focused on novel technologies such as fluidized bed gasification and pyrolysis as well as oxyfuel combustion and chemical looping combustion (CLC) with special respect to CO₂-neutral energy generation both from biomass and fossil fuels.

The International Energy Agency – Fluidized Bed Conversion (IEA-FBC) Implementing Agreement supports and stimulates by information exchange (refer also to www.iea-fbc.org and more regional: www.iea-fbc.net) these very important and significant developments and demonstrations. The IEA has prolonged this very successful Implementing Agreement for the next five year term (2009 to 2014) and it can be well estimated that it will continue to 2019 and beyond.

The next steps are the continuation of the support of these very innovative developments, the inclusion of the observers like China into the IEA-FBC Implementing Agreement and to further improve and stimulate the regional and global net-working.

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