DEVELOPMENTS IN FLUIDIZED BED CONVERSION DURING 2011-2016

A summary from the member countries of the IEA-FBC technology collaboration programme

2017. 12

Provided by IEA-FBC TCP

Chairman: JongMin Lee
Operating Country: Korea (KEPCO Research Institute)

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PREFACE

A world-wide interest for fluidized bed as a fuel converter emerged in the 1970s when it was realised that fluidized bed conversion offered several environmental advantages. This started a vivid development in many countries. Among other activities, in 1980 the co-operation on the development of fluidized bed combustion (FBC) was initiated within the International Energy Agency (IEA) with participation from about ten OECD countries. Later, this activity was broadened to include also gasification, and the name was changed to fluidized bed conversion (FBC). Also, several non-OECD countries were invited to participate. This activity goes on, although its character has changed slightly, as the knowledge on FBC is increasing. During the recent years focus has been on selected problem areas, as can be seen from the publications found on the website www.**iea-fbc**.tuwien.ac.at/ where information on the participants and the activities is published. The importance of CO_2 reduction, where FBC plays an important role, has also widened the field of interest, as well as the utilization of new fuels, waste conversion, efficiency enhancement, scale-up in size, and related topics, make the exchange of information of continued value for the participants.

Initially, yearly reports were issued by the IEA-FBC co-operation, but after some years this was found to be of limited value, and the yearly reports were replaced by the website where most relevant information about the members, the organization of the co-operation, and reported results can be easily found. However, it was felt by many members that a five-year report, following the first five-year report issued in 2010, would be of interest, providing an update with the purpose of giving a summary of the status on FBC in the member countries, and the representatives from the 18 member countries agreed to make short surveys on the status of FBC and related development in their countries. The purpose is to show the conditions for FBC, which vary from country to country, and the recent development in each country, during the last five years. These reports follow here.

The reporting countries are:
Austria
Canada
China
Czech Republic
Finland
Greece
Hungary
Italy
Japan
Korea
Russia
Spain
Sweden

2017. 12
Bo Leckner
Department of Energy and Environment
Chalmers University of Technology, Göteborg, Swed

Utilization of fluidized bed boilers ---a worldwide overview

B. Leckner, L. Thorson, J. Kjärstad, F. Johnsson
Chalmers University of Technology, Department of Energy and Environment, Göteborg, Sweden

** Presented at IEA-FBC 73rd Technical Meeting, Tokyo, Japan (December 2016)

Abstract

This is a survey of fluidized bed boilers worldwide, their size, number and type. China and Europe are shown to have their special features: in China the development of coal combustion is fast, in Europe power boilers for solid fuels are built mostly in Poland, while a large number of fluidized bed boilers in Northern Europe are related to the utilization of biomass to supply heat to industry and district heating systems.

Purpose

The purpose of this presentation is to show the present status of fluidized bed conversion (FBC) of solid fuels in the world, particularly combustion.

Background

FBC was first manifested in the form of a patent on a gasifier in 1922 [1]. In the 1970s efforts were made to develop FBC (combustion) owing to the expected advantages of low NOx emissions and sulphur capture by limestone in the bed. Figure 1 shows how bubbling fluidized bed (BFB) was used first and how there was a transition to the development of circulating fluidized bed (CFB) boilers in the mid-1980s because of obvious drawbacks of BFB for combustion of coal [2]. However, BFB showed itself suitable for combustion and gasification of biomass and waste [3]. So, two lines of development are followed: one aiming at coal-fired CFB for industrial use but then gradually, as the size increases, for power production; the other line consists of biomass-fired BFB, but CFB is used for biomass also. The development of pressurized systems (PFBC) was discontinued as seen in Fig. 1.

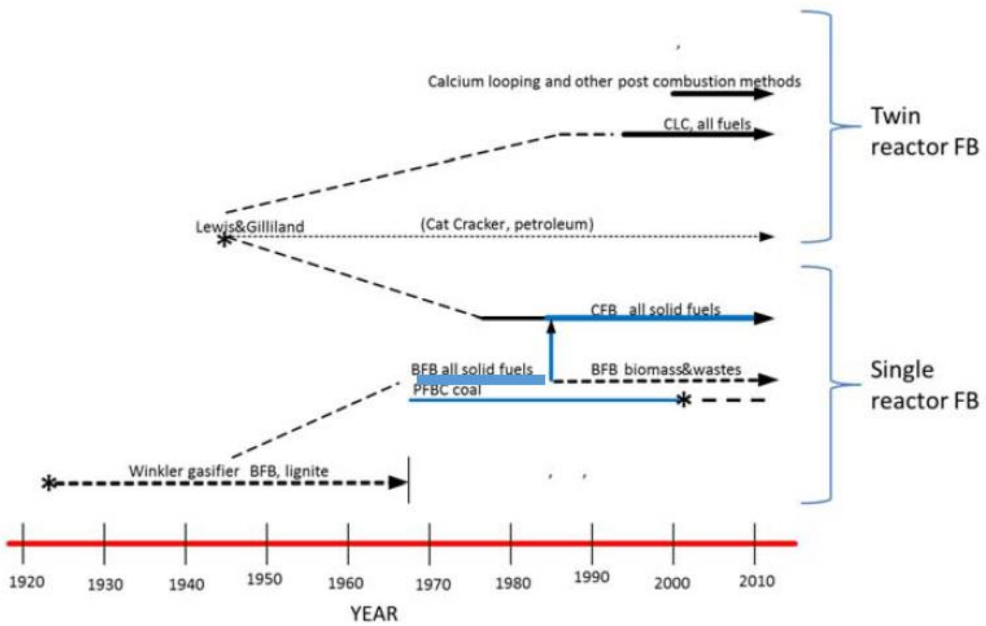


Fig. 1. History of fluidized bed for power production (simplified from [2])

Sources

The present data collection is based on reference lists from mayor boiler manufacturers: Alstom (now GE), Andritz, BW Volund, Foster Wheeler and Valmet, including the former Metso/Kvärner. Chinese and Indian data have been obtained through the kind help from Prof. Yue Guangxi, Tsinghua University, China and Mr. Vinod Kumar and his colleagues, IPMA, Indian Power Management Academy, India.Previous reviews on numbers and power of FBC boilers should be recognized: [4,5,6,7,8]. They are however "old" and an update is necessary. In the present survey 1503 CFB boilers, 457 BFB boilers, and 8 gasifiers (the latter not included in the plots) are considered. This is much less than the 3158 Chinese boilers mentioned by Mao [5] for the year 2007. The reason is that the present study has limited the size of Chinese boilers to above 100 MWe while the data of Mao includes also 25 MWe boilers and smaller (actually 2364 boilers in that size range). In fact, China has a long tradition of using FBC [9], but the first boilers were very small BFB which are below the size threshold of the present study.

The capacities of boilers are often given in tonnes of steam per hour when the boilers are of industrial type. An estimate translation from tonne per hour (t/h) to MWe according to [10] is listed in Table 1.

Table 1. Translation from t/h to MWe according to [10] for Chinese boilers.

Steam capacity t/h	Electric capacity MW_e
75	15
130	25
220	50
400	100
440 (reheat boiler)	135

Then, the electric capacities are recalculated to thermal capacities with an assumed efficiency of 40% (a rough figure, admittedly high, especially for the low capacities).

Worldwide results

The entire data set of boilers is shown on Fig. 2, sorted according to fuel.

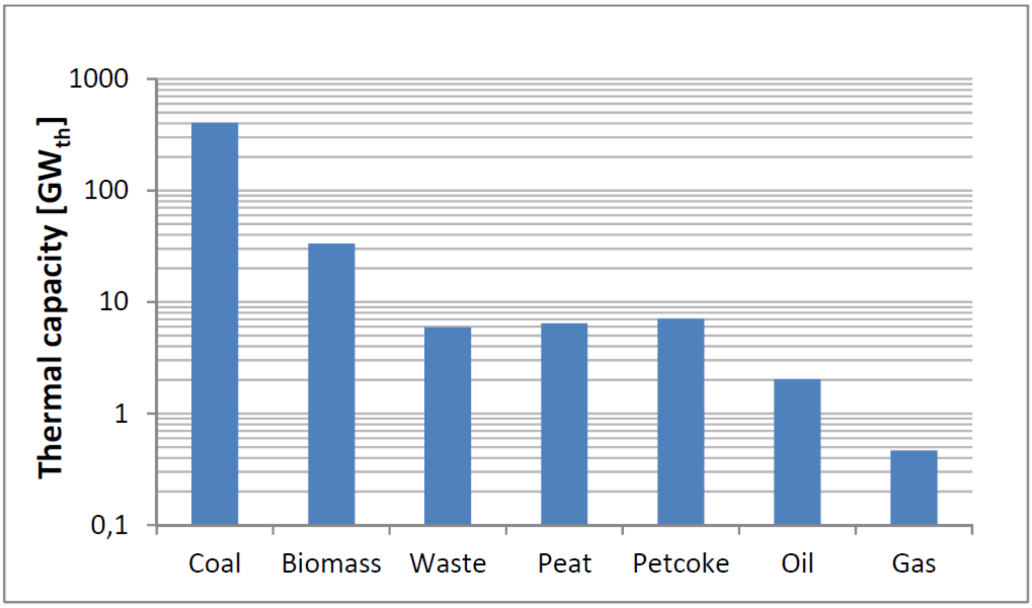


Fig. 2. Total thermal capacity of all included boilers for different fuels.

Coal is the most common fuel (because of its use in China) followed by biomass. When judging the bars in Fig. 2 it has to be noted that the vertical scale is logaritmic. Oil and gas were used in some industrial boilers, but they are not suitable fuels for FBC.

Table 2 shows commercial gasifiers, all related to biomass and waste. These were obtained from Valmet and there may be more from other manufacturers, but many existing gasifiers are small pilot plants or not in commercial operation and therefore not included, some have been dismounted, and that also contributes to the limited amount of FBC gasifiers listed.

Table 2. Gasifiers based on FBC (Valmet).

Manufacturer	Customer	Country	Application	YoC	Fuels	Fuel capacity [MW]
Valmet	Huanggang Chenming Pulp and Paper Co. Ltd	China	Lime kiln	2017	Eucalyptus and pine chips, bark	50
Valmet	Metsä Fibre Oy	Finland	Lime kiln	2017	Birch, pine, spruce bark	87
Valmet	Oki Pulp and Paper Mill	Indonesia	Lime kiln	2016	Acasia fines, acacia bark	110
Valmet	Oki Pulp and Paper Mill	Indonesia	Lime kiln	2016	Acasia fines, acacia bark	110
Valmet	Vaskiluodon Voima Oy	Finland	Power / co-combustion in PC boiler	2013	Peat, forest residue, saw dust, canary grass	140
Valmet	Lahti Energia Oy	Finland	Power / Greenfield gas boiler	2012	SRF, REF, recycled wood	80
Valmet	Lahti Energia Oy	Finland	Power / Greenfield gas boiler	2012	SRF, REF, recycled wood	80
Valmet	Södra Cell	Sweden	Lime kiln	1987	Bark, saw dust	35

A cumulative trend as a function of time of installed thermal boiler capacity from various parts of the world can be read from Fig. 3. Here, the tremendous increase in China is evident. However, The data given for China are only those from foreign manufacturers. The contribution from Chinese boiler makers is even greater (190 GWth) but could not be included in the figure because of lack of data on the year of commisioning.

Figure 3 reveals the sudden increase of the capacity of FBC (CFB) in China and India in the beginning of this millennium, whereas the development in the other regions outside Asia is moderate. Above, it was mentioned that the development of FBC for combustion of solid fuels started already in the beginning of the 1970s. However, the capacities were insignificant, and only after the introduction of CFB in the mid-1980s the capacity starts to increase. This is seen in Fig. 3 and further illustrated in Fig. 4, showing averages over 5-year periods to emphasize the trends. The averaging removes information of the peak values. The single largest boilers are the 600 MWe boiler in Baima (China) and the 5x550 MWe boilers just being taken into operation in Samcheok, South Korea.

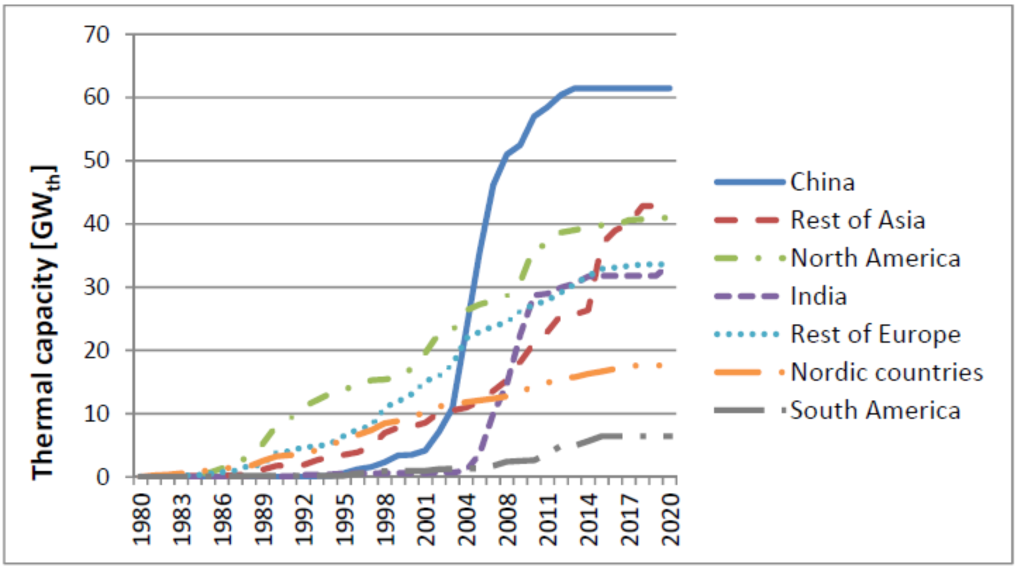


Fig. 3. Cumulative installed capacity per specific area. (Boilers designed by Chinese companies are not included).

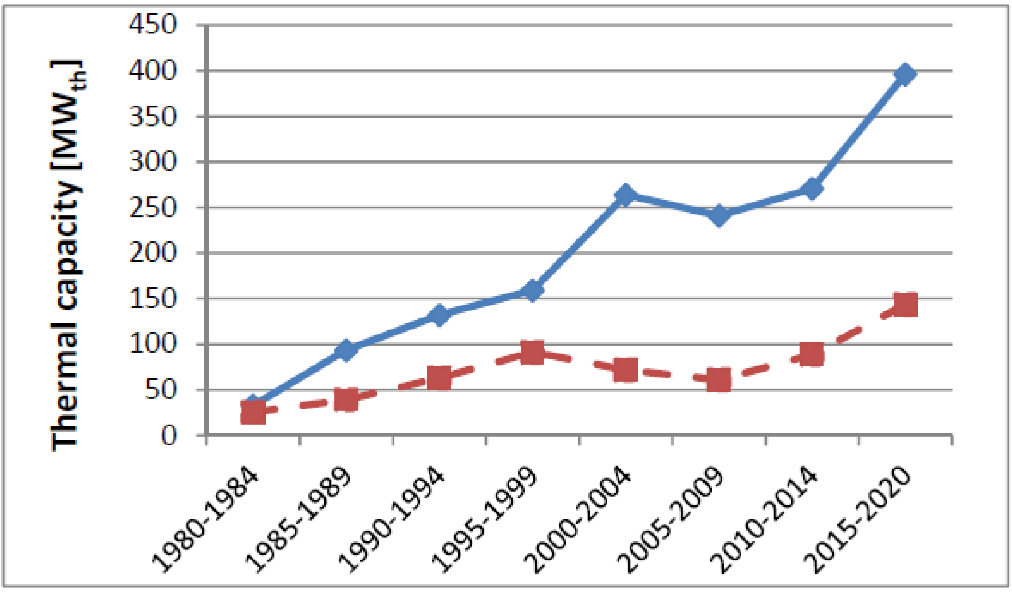


Fig. 4. The growth of individual boiler size, expressed as 5-year averages. Upper curve CFB, lower curve BFB.

The worldwide installed capacity is 427 GWth for CFB and 32 GWth for BFB boilers. Because the BFBs are generally small biomass boilers, the numbers of boilers differ less than the capacities, about 1503 for CFB and 457 for BFB.

European results

The situation in Europe is interesting because of the marked difference between the countries, Fig. 5.

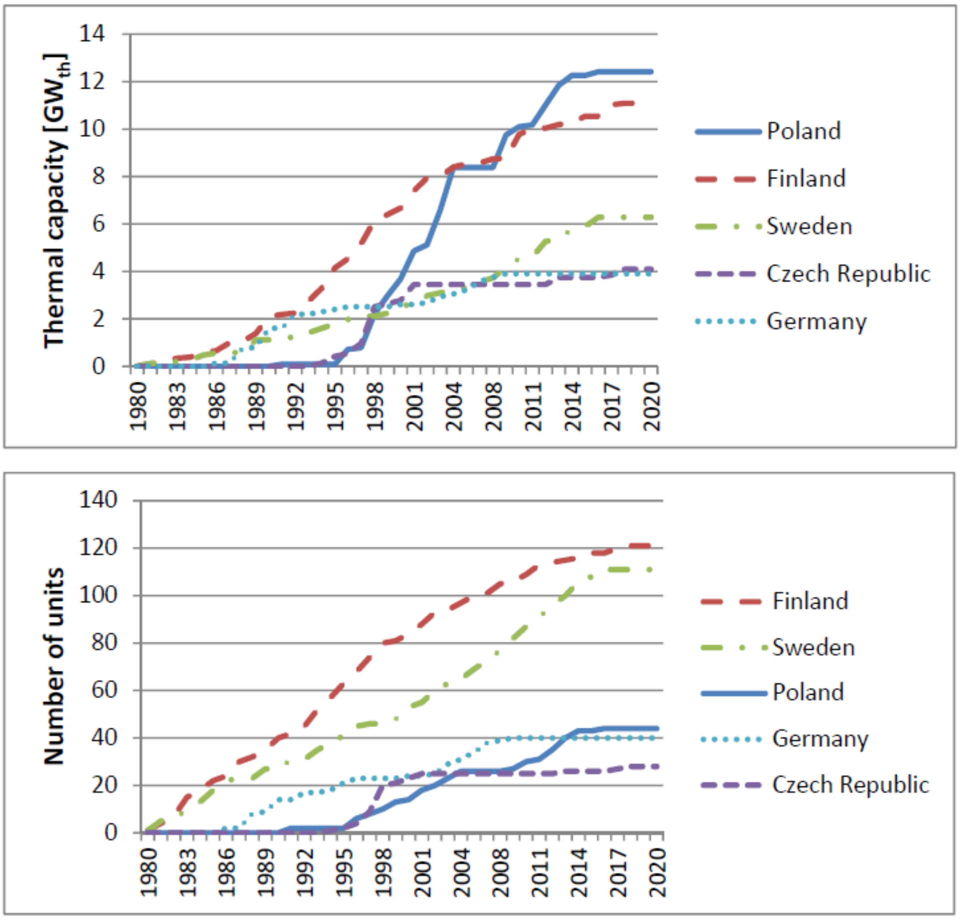


Fig. 5. Trends of capacity and number of units in the European countries having most FBC boilers.

In order to interpret these data, it is useful to know the type of fuels utilized in FBC in Europe, Fig. 6.

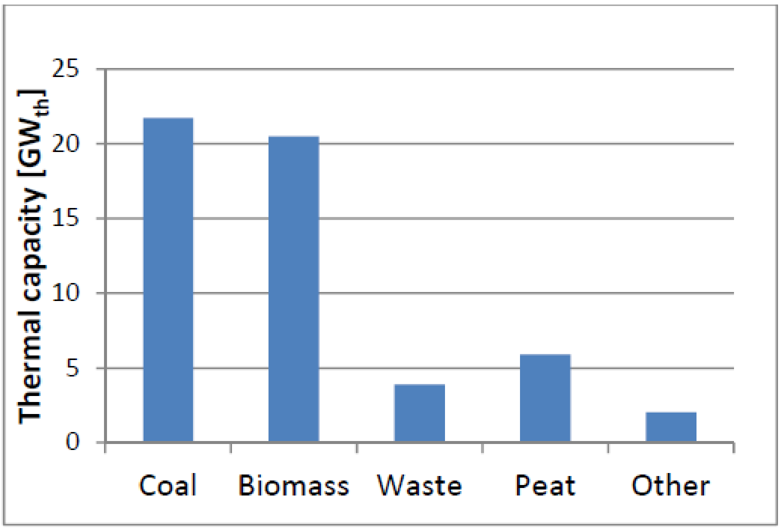
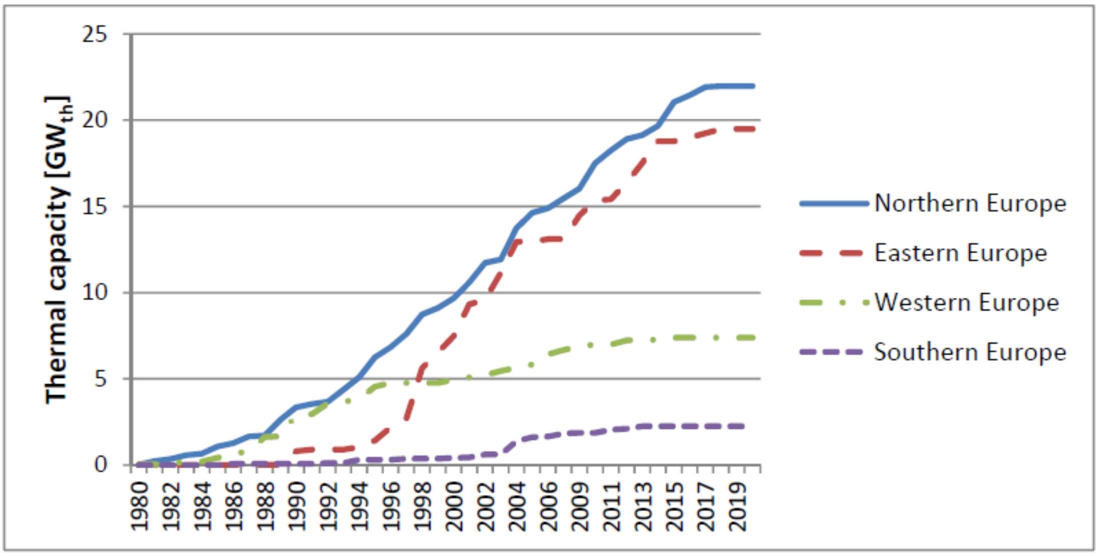


Fig. 6. Fuel utilization in FBC in Europe.

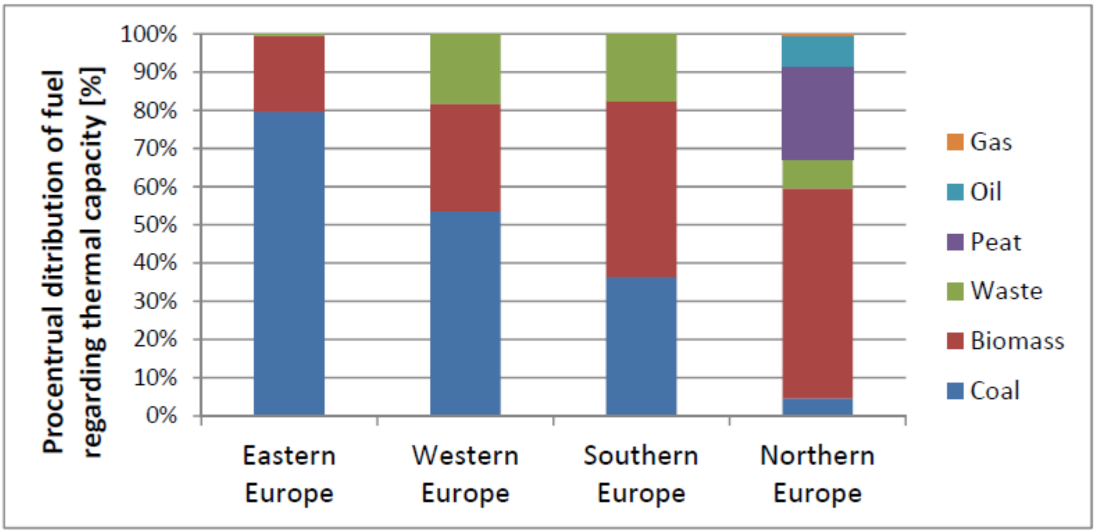
Obviously, in Europe the utilization of biomass and waste is about the same as that of coal. There are 118 boilers burning coal and 332 burning biomass and waste. The corresponding capacities are 22 GWth for coal and 24 GWth for biomass and waste, strikingly different from the worldwide data, dominated by China, where biomass only occupies a minor fraction. Again it is seen that the biomass boilers

(European average size 24000/332 = 74 MWth) in general are smaller than those for coal (European average size 22000/118 = 184 MWth). Now it is understandable that the boilers in Poland predominantly burn coal, while the boilers in Finland and Sweden use biomass and waste. The other countries in Fig. 5 may have both biomass and coal as fuels.

Figure 7 gives a further illustration on the European situation.



a)



b)

Fig. 7. a) The development of FBC in regions. b) The fuel used in European regions.

The use of FBC in Europe was initiated in Northern Europe because of the favourable combination of a political will to use local and renewable fuels and a heat demand from district heating and industry. This situation, translated into Eastern Europe, predominantly Poland, means utilization of the local coal. Here the introduction of FBC was late, possibly retarded by the transitions during and after the collapse of the Soviet Union. In Southern Europe the development is devoid of the stimulating demand from heating systems and suitable industry, and so, the development was slow.

Discussion

China and other Asian countries, where the introduction of FBC for coal combustion in industry and power production has been very strong, differ strikingly from Europe. In Europe, on the other hand, the development differs between regions: Poland—coal, the Nordic countries—biomass, and the other countries show low activity. Likewise, FBC is not much used in Africa and South America. In North-America there is some activity but less convincing than that in Asia.

In general, the curves in Fig. 5 show a gradual stagnation during recent and coming years. This could be due to incomplete statistics, particularly related to boilers under construction or just ordered. In the case of Germany, however, the stagnation is quite clear, most likely a consequence of the political situation in that country, resulting in an effort to transform the energy system towards renewable energy. The statistics of installation of power-producing units in Europe brings some background information, Fig 8.

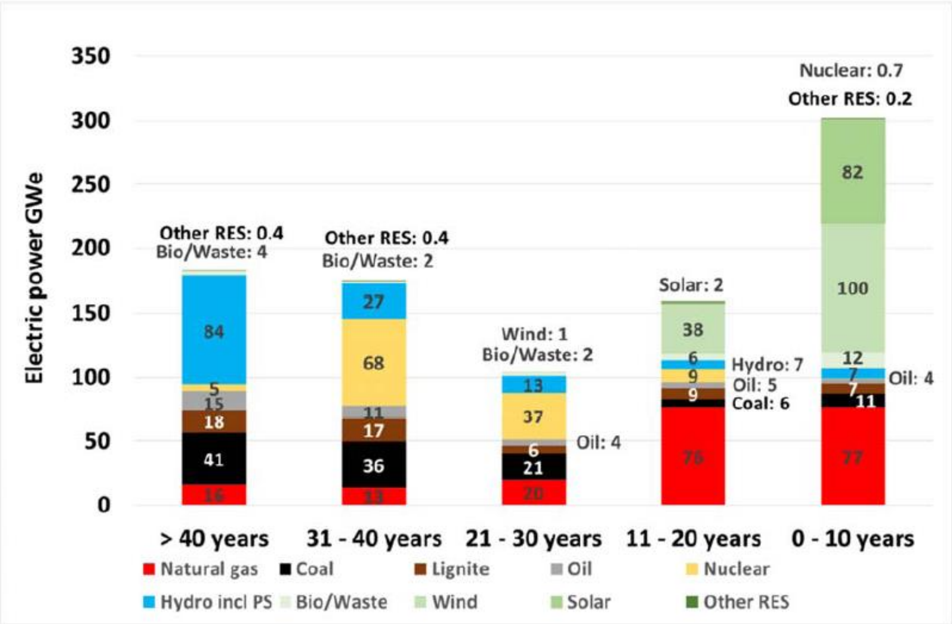


Fig. 8. Age and fuel distribution of European power plants. Derived from [11].

It is clear that very few power plants for coal or lignite combustion have been built during the last 20 years. Instead high efficiency gas-fired combined cycle plants have been preferred. It is also striking to see the strong capacity increase, resulting from wind and solar energy.
The corresponding electric energy production for the years 1990 and 2014 are shown in Fig. 9.

Even during 2014 old nuclear and coal-fired power stations provide the energy required, and not much impact is seen from the great wind and solar power installations made during the last ten years (Fig. 9). It is evident that Europe faces an uncertain energy future where the renewable energy will play a significant role, but it is not obvious that the demand can be satisfied only by renewables, complemented by gas from Russia, North-Africa, and Norway. Either new nuclear energy or coal-fired carbon capture and storage plants appear to be needed. In the latter case FBC will play a role again in the electric utility field.

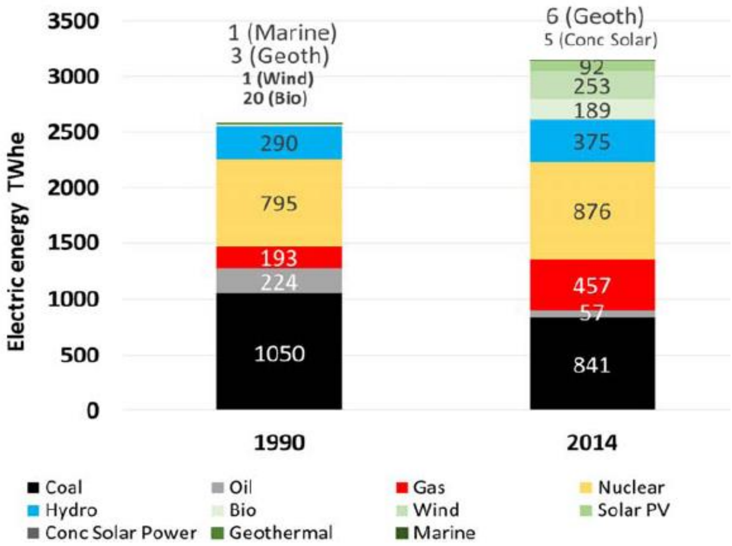


Fig. 9. Electric energy produced in Europe 1990 and 2014. Derived from [12].

Conclusions

FBC has shown to be useful for combustion of various fuels, such as coal, biomass, and waste. Whereas FBC has increased remarkably in Asia, especially in China, its use for power production has stagnated in Europe except in Poland. Its use for biomass combustion is quite established in countries with heat demand in district heating systems and suitable industrial structure, such as in the Nordic countries. FBC is also suitable as a reactor for CO_2 removal: oxy-fuel, chemical looping cycling, calcium cycling etc. Such applications have been proposed for CO_2 removal, but they have not yet been introduced commercially.

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AUSTRIA

Prepared by Franz Winter and Clemens Huber
Institute of Chemical Engineering,Technische Universität Wien, Vienna, Austria

Introduction

Fluidized bed conversion (FBC) technology is mainly used for power and heat generation. In Austria there are 22 fluidized bed units with an overall heat capacity of over 1000 MW. The FBC technology is used in particular because of its excellent conditions for solid - gas reactions and homogeneous temperature- and as well as reaction conditions. On this account it shows a very good ability for emission control. In addition its fuel flexibility is important to note too. Thereby the usage of biogenic materials as well as waste derived fuels plays an important role for minimization of emissions and minimizing the usage of fossil fuels.

Research in FB technology fields is being pursued intensively by different research institutes throughout the country. The main objective is inter alia: the gasification of biomass, chemical looping, CO_2 capture and utilization, fluid catalytic cracking (FCC), utilization of bio-oils, improving heat transfer. Beside that there is an active research interest in using waste heat recovery from different industrial processes.

Fluidized Bed Boilers in Austria

Table 1. Operating facilities

No	year	location	Type	capacity	fuels
1	1981	Gratkorn	BFBC	25 MW	Bark, sludge, biogas, natural gas
2	1986	Gratkorn	CFBC	133 MW	Coal, sludge, heavy fuel oil, biogas, natural gas
3	1984	Bruck an der Mur	BFBC	15 MW	Bark, coal, sludge, biogas, natural gas
4	2004	Niklasdorf	BFBC	40 MW	MSW, industrial waste, wooden residue, sewage sludge
5	1987	Lenzing	CFBC	108 MW	Bark, coal, sludge, wood residue, oil
6	1998	Lenzing	CFBC	110 MW	Plastics, waste, sludge, wood residue
7	2011	Linz	BFBC	66 MW	Municipal solid waste, sewage sludge, screenings
8	1994	Steyrermuehl	CFBC	48 MW	Bark, wood, wood residues, sludge
9	2006	Timelkam	BFBC	49 MW	Wood, wood residues, bark, sawdust
10	2006	Hallein	BFBC	30 MW	Wood chips
11	1984	Frantschach – St. Gertraud im Lavantal	CFBC	61 MW	Bark, coal, sewage sludge, heavy oil
12	2007	St.Veit an der Glan	BFBC	45 MW	Bark, wood, sludge, sawdust,wooden residue, sludge
13	2000	Arnoldstein	BFBC	5 MW	oils, emulsions, wooden residue, sludges, plastics
14	1984	Pitten	BFBC	60 MW	Coal, biogas, sewage sludge
15	2003	Bad Vöslau	BFBC	1 MW	Sewage sludge
16	2009	Fürnitz	BFBC	3 MW	Process waste, sludge

No	year	location	Type	capacity	fuels
17	1992	Vienna	BFBC	3 x 20 MW	Sewage sludge
18	2003	Vienna	RFBC	40 MW	Municipal solid waste, sewage sludge
19	2006	Vienna	CFBC	66 MW	Forest residue
20	2006	Heiligenkreuz	BFBC	43 MW	Forest residue
21	2008	Oberwart	DFBG	10 MW	Wood chips
22	2001	Guessing	DFBG	8 MW	Wood chips, wood residues

Table 2. Declaration of the abbreviations

BFBC	bubbling fluidized bed combustor
CFBC	circulating fluidized bed combustor
DFBG	dual fluidized bed gasifier
RFBC	rotating fluidized bed combustor
	new since last Report

Discussion

The table (Table 1) contains all FBC-facilities in Austria with its most important parameters. Since last IEA FBC Country Report 2005 – 2010 (see www.iea-fbc.org Past Events) one new facility has been commissioned in Linz with a thermal capacity of 65 MW. The facility in Linz produces for public energy supply.

The share between bubbling and circulating fluidized bed combustors is close to 1:1 (Fig. 1) based on thermal capacity. More than the half of the boilers have a thermal capacity between 10 and 50 MW (Fig. 2). The majority of FBC- operators arises from paper industry followed by waste incineration. Together they account for 75 percent of the overall operation (Fig. 3). Apart from this the biomass facilities are claiming the highest share from the rest. The usage of FBC boilers for industrial purpose is dominated by the paper industry followed by waste incineration industry, the energy sector consists in equal shares of waste incineration and biomass utilization as well as a fraction of sludge utilization (Fig. 4).

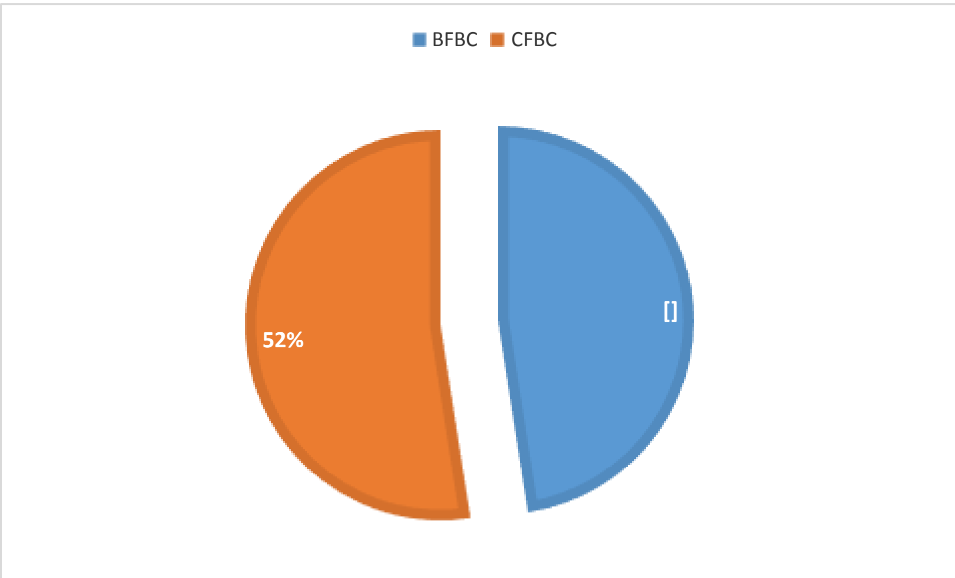

Fig. 1. BFBC and CFBC facilities in Austria (based on thermal capacity)

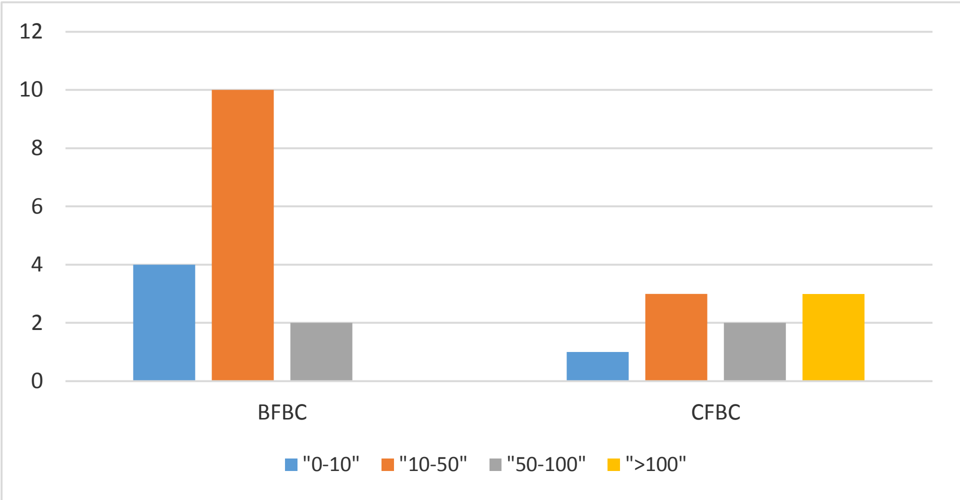

Fig. 2. Number of boilers arranged by thermal capacity [MW]

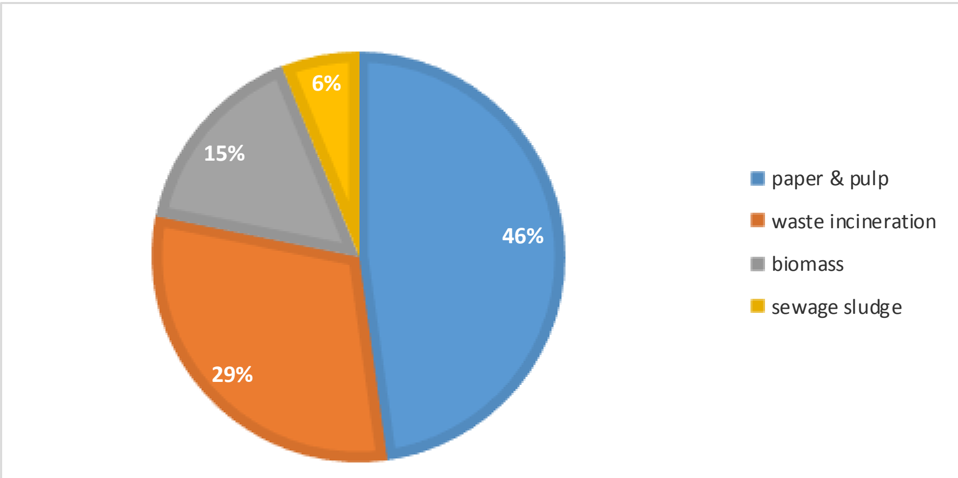

Fig. 3. Different main application sectors using FBCs (based on thermal capacity)

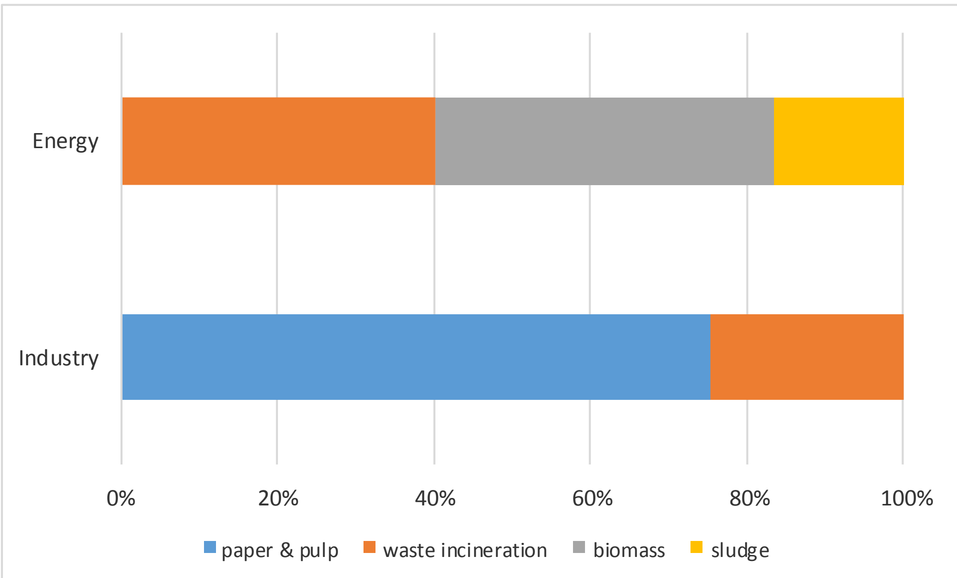

Fig. 4. Distribution of operation (breakdown by sector)

Current research and development projects related to FBC

1. Energy efficient CO_2 capture and carbon neutral CO_2 supply chain for greenhouse fertilization at Wien Simmering

Gerhard Schöny
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

The capture of CO_2 from power plants or industrial processes for subsequent permanent storage or for industrial use of the CO2 is characterized by a significant energy demand of the CO_2 separation step. This leads, consequently, to a reduced energy efficiency of the original process. The main technical challenge in CO_2 capture and storage (CCS) is to find technologies with minimum energy requirement. Gas-liquid absorption into aqueous solutions of monoethanolamine is the technology most favoured at the moment for CO_2 capture from exhaust gas streams. The energy demand for 90% CO_2 capture with conventional scrubbing systems is about 3.7 GJ/ton of CO_2 captured. The principal goal of the proposed project is to show that this performance number can be improved by expectedly 40% using a continuously operated temperature-swing-adsorption (TSA) process based on solid sorbents (Fig. 5).
Partners of this consortium have previously developed the proposed continuous TSA capture technology from a paper concept to laboratory size. The innovative core of the process is the reactor system that features stacked fluidized bed contacting devices. This allows for exploitation of improved thermodynamic driving forces for gas separation in counter-current operation as well as for application of advanced heat integration measures. High capture efficiency of well above 90% were reached in laboratory using only five practical stages in each gas-solid contacting device. Since also chemical and mechanical degradation effects of the sorbent were found to be low during laboratory testing, the process is considered as highly promising for CCS.

ViennaGreenCO_2 will lead the way to demonstration of the TSA CO_2 capture technology by investigation of the technology at pilot scale. A pilot plant is designed with focus on scalability and built at the site of the biomass combined heat and power (CHP) plant Vienna/Simmering (Fig. 5). Tests with real combustion exhaust gas over several hundreds of hours will be conducted. The design, construction and operation of the pilot plant is accompanied by focused research activities regarding the basic process performance (existing laboratory unit) fluid dynamics (cold flow model of the pilot plant), low temperature fluidized bed heat transfer and heat exchanger design (heat transfer test facility), mathematical modelling of the TSA system, overall process simulation and optimized heat integration. The outcome of the pilot scale experimental campaigns constitutes the basis for solid techno-economic evaluation of the proposed technology.

An additional aspect of ViennaGreenCO_2 is the investigation of the possibility to locally supply captured CO_2 to vegetable farms in Vienna/Simmering for greenhouse fertilization. This would save transport effort and costs compared to the current situation, where the farmers buy technical CO_2 from distant fossil sources. If the CO_2 utilization route is technically feasible, this may create a niche situation for sustainable operation of a next scale CO_2 capture demonstration unit at the Vienna/Simmering site beyond the proposed project.

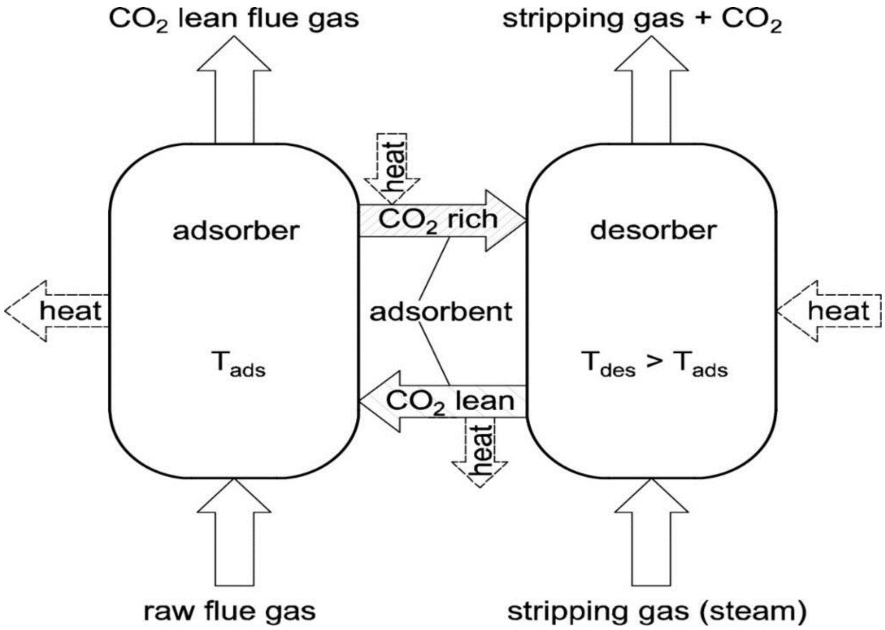

Fig. 5. Principle TSA

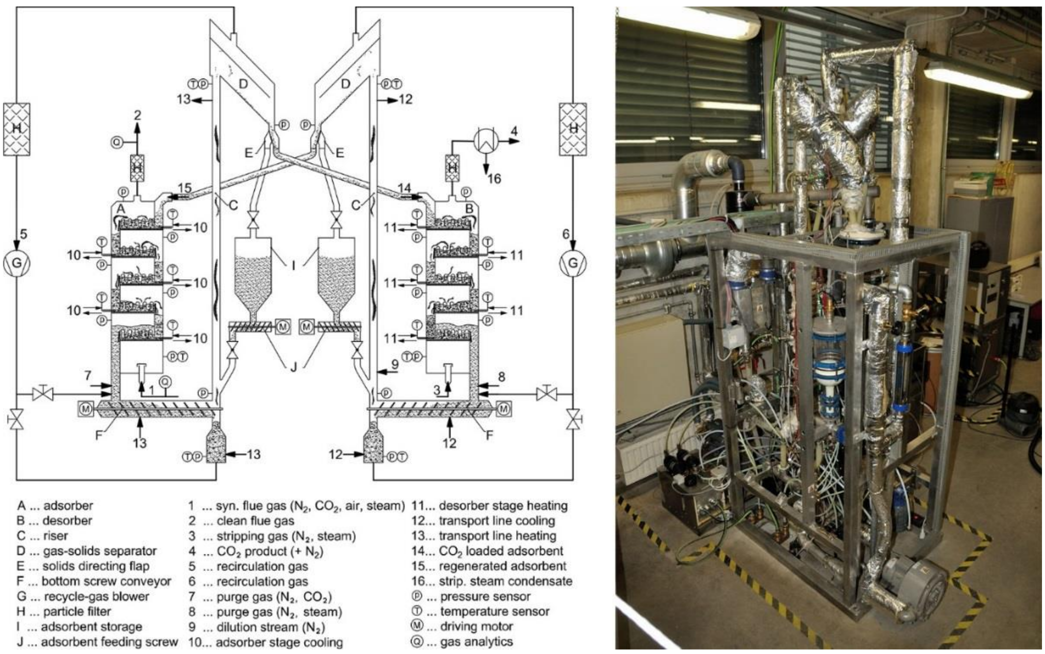

Fig. 5. Experimental set-up

Partner:
University of Natural Resources and Life Sciences, Vienna
Department of Material Sciences and Process Engineering
M-TEC Energie.Innovativ GmbH
WIEN ENERGIE GmbH
Josef Bertsch Gesellschaft m.b.H. & Co.KG
lk-projekt niederösterreich | wien GmbH
Shell Global Solutions International B.V.
LGV-Frischgemüse Wien reg.Gen.m.b.H.

Contact: Gerhard Schöny, gerhard.schoeny@tuwien.ac.at

2. BioCH4.0 – Efficient upgrading of biogas to biomethane by means of continuous temperature swing adsorption

Gerhard Schöny
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

Today, biogas is primarily used for heat and power production. Because of the economic pressure in the power sector caused by large capacities of renewable energy, it is necessary to find different applications for biogas to ensure economic feasibility of biogas plants in the future. One of these alternatives is to produce biomethane from biogas (i.e. biogas upgrading). Here, separation of CO_2 is the process step with the biggest effect on the overall efficiency of the total biogas upgrading step. The state-of-the-art technologies used for CO_2 separation in this field are: pressure swing adsorption, amine scrubbing and membrane separation. However, none of these technologies is currently economically feasible which sets the demand for the development of a more efficient and cost effective alternative.

Amine scrubbing seems to be the most attractive technology from a technical point of view and will thus be used as benchmark technology. The aim of the development of a new technology is thus to keep the advantages of amine scrubbing process while its disadvantages are reduced or even eliminated. Temperature swing adsorption (TSA) processes for CO_2 capture have been identified to have a great potential to achieve this goal. Thus, the bioCH4.0 project will generally study and experimentally test the application of a temperature swing adsorption (TSA) process for biogas upgrading to biomethane. The applied TSA process uses a multistage fluidized bed reactor design and solid amine sorbents for selective capture of CO_2 (Fig. 6). Furthermore, this new process also features full heat integration using innovative heat exchanger designs and a heat pump in order to realize significant efficiency increase. The main project objective is to develop a process to provide bio methane with higher efficiency and lower costs compared to the state-of-the-art technologies. This will also be shown in a concluding techno-economic evaluation and comparison with other technologies.

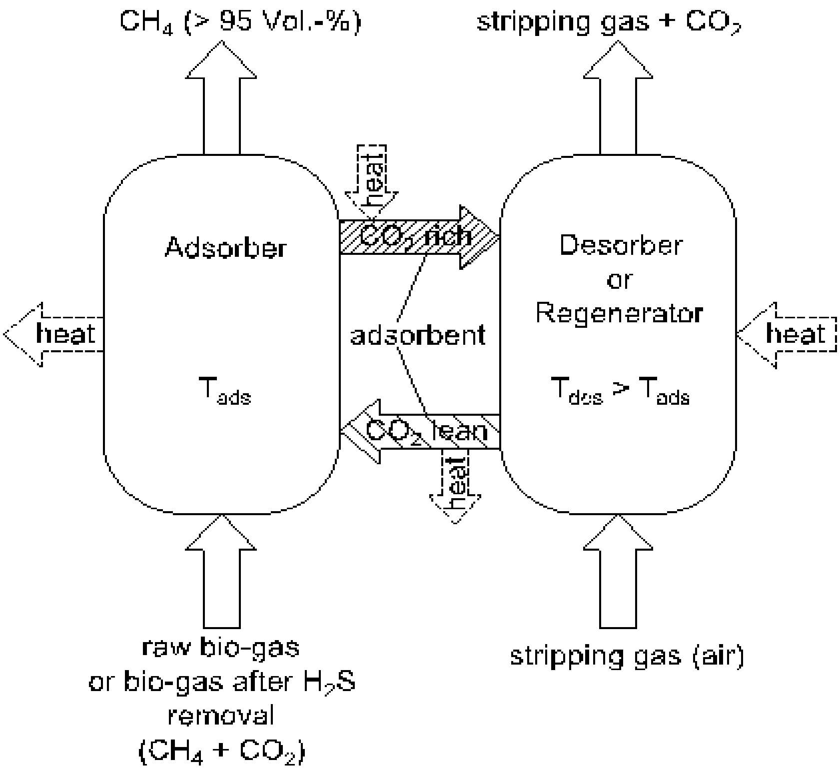

Fig. 6. Biogas Upgrade Principle

Partner:
TU Wien Institute of Energy Systems and Thermodynamics (TU-IET)
Austrian Institute of Technology (AIT)
Josef Bertsch GesmbH & Co KG (Bertsch)
AAT Abwasser- und Abfalltechnik GmbH (AAT)
FRIGOPOL Kälteanlagen GmbH (FRIGOPOL)
Biogas Strem Errichtungs- und Betriebs GmbH & Co KG (BG-Strem
Contact: Gerhard Schöny, gerhard.schoeny@tuwien.ac.at

3. Fluid dynamic evaluation of fluidized bed systems for innovative energy conversion processes

Stefan Penthor, Michael Stollhof, Karl Mayer and Hermann Hofbauer
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

Fluidized bed systems, consisting of two, or more, interconnected fluidized beds are widely used in innovative energy conversion processes, like e.g. chemical looping combustion (CLC), biomass steam gasification or carbonate looping. The bed material is used to transport heat and/or chemical species from one reactor to the other while it is ensured that there is no gas leakage between them. Further, scaled physical flow models, so-called cold flow models, are a powerful tool to investigate the fluid dynamic characteristics of a fluidized bed design. They are smaller than the original design and operated at ambient conditions.

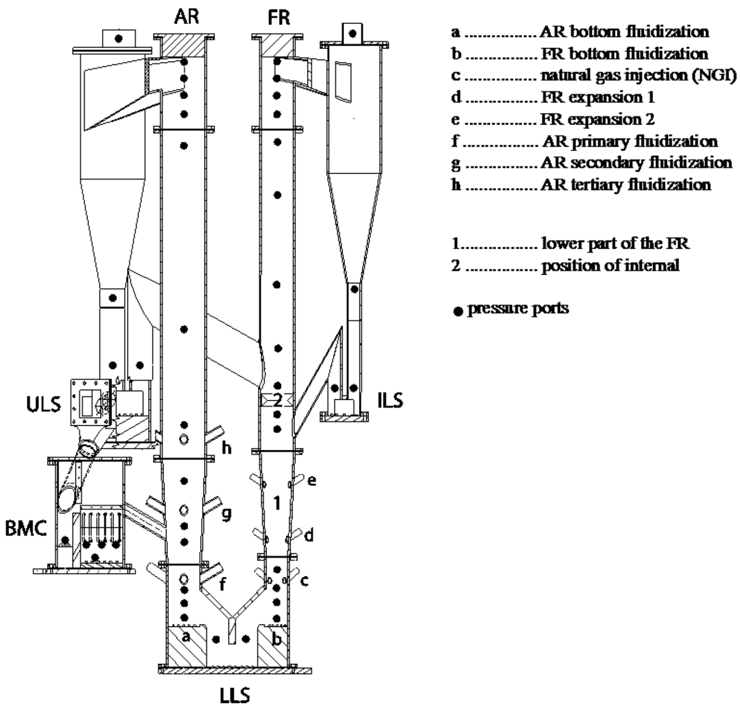

Fig. 7. Scaled cold flow model of a CLC reactor design

A cold flow model (scale 1:11), made of acrylic glass, has been used to investigate the fluid dynamic feasibility of different reactor geometries of a next scale (10 MWth fuel input) CLC reactor design. The cold flow model is scaled according to the scaling criteria of Glicksman and consists of two circulating fluidized beds connected at the top and bottom (Fig. 7).
Several parameters like e.g. the amount of fluidization gas for both reactors, the influence of total inventory, and the influence of fuel conversion, were investigated. Pressure profiles were used to get a comprehensive overview of the fluid dynamic behavior of the proposed reactor design.

Acknowledgements: This work has received funding from the European Union Seventh Framework Program (2007-2013) under grant agreement no 608571 (http://www.clc-success.eu).
Contact: Stefan Penthor, stefan.penthor@tuwien.ac.at

4. Thermal gasification of low-grade residues for the production of reusable materials and energy (VergRestWert)

Johannes Schmid, Matthias Kuba and Hermann Hofbauer
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

Thermal gasification in dual fluidized bed systems is an efficient method to generate electricity and heat from biomass and to reduce greenhouse gas emissions. Various other ways are possible for the utilization of the product gas e.g. the synthesis of BioSNG, Fischer-Tropsch Diesel and other synthetic hydrocarbons to replace fossil fuels. Nowadays commercially operated plants mostly produce electricity and heat and suffer from high fuel costs and low electricity prices. High operating costs due to the utilization of the catalytically active bed material olivine and high disposal costs for the ash due to the fact that olivine contains heavy metals have negative impact on the economic operation of these plants.

Fig. 8. 100 kW Pilot plant at TU Wien, ready for the gasification of chicken litter

This project aims to replace the bed material by an alternative, heavy metal free mineral which has catalytic activities at least in interaction with the biomass ash or additives.

Changing the bed material to a heavy metal free one enables the possibility to remove nutrient rich biomass ash early in the process as BioChar and to close the natural nutrient circle by using this BioChar as a fertilizer. Based on that process change low melting ash species are not in intensive contact with temperatures up to 900℃ in the combustion reactor like nowadays which reduces the risk for fouling and agglomeration. As a consequence fuels with worse ash melting properties can be used. Anyway, the ash after the combustion reactor can be aimed to be used as a fertilizer.

Within this project an alternative bed material should be found and tested in different pilot plant scales. A better understanding of ash related behaviour in dual fluid gasification systems should be gathered. The utilization of low quality fuel with bad ash melting properties should be demonstrated by using chicken litter.

Char-rich and nutrient rich biomass ash should be evaluated on the utilization as BioChar as a fertilizer. The economic efficiency for industrial scale plants considering the changes in operation, raw materials and products should be evaluated. An economic evaluation will underline the importance of this technology.

Partner:
Bioenergy 2020+ GmbH (Consortium Leader)
TU Wien, Institute of Chemical Engineering
Repotec GmbH & Co KG
Contact: Johannes Schmid, johannes.schmid@tuwien.ac.at

5. Optimization of „Sorption Enhanced Reforming“ for an improved CO_2-balance of a raw iron production by the use of biomass (ERBA II)

Johannes Schmid, Stefan Müller and Hermann Hofbauer
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

The present research project "ERBA II" investigates a process for the reduction of fossil CO_2-emission of an iron production. "Sorption Enhanced Reforming" enables an improvement of the overall CO_2-balance of an iron production by the use of biomass. Therefore, „ERBA II" is used to investigate so far hidden potential of "Sorption Enhanced Reforming" at laboratory scale with respect to process efficiency, hydrogen production rate as well as selective CO_2 transport. Achieve results should lead to a relevant improvement of the overall process to enable technical measures for a significant reduction of fossil CO_2 emission of iron production. A novel dual fluidized bed reactor system should enable these improvements. A combination of the fluidized bed system with an integrated O_2 combustion will show the potential of an innovative "below zero emission technology". The development of new chemical processes is necessary to enable an increased utilization of renewable energy sources in iron industry. voestalpine is known as one of the leading steel producers in Europe. Used blast furnace technology is seen as leading bench mark for other steel makers.

The previous research project ERBA already proved that "sorption enhanced reforming" is a promising process route, which allows the utilization of woody biomass in iron production, ensuring the quality of final products at the same time. The research group "gasification and gas cleaning" at Vienna University of Technology is one of the two leading research groups in the field of "sorption enhanced reforming" worldwide. The research project ERBA II aims at a target-oriented optimization of the basic principles of "sorption enhanced reforming" for an application in iron industry. As a part of the present project, voestalpine and Vienna University of Technology put their knowledge together to enable an optimization of the process with respect to its efficiency. The carried out work includes:

experimental investigation at laboratory-scale,
an evaluation of achieve measurement-data with respect to large-scale operation,
as well as an improvement of the used process route to enable an application as "below zero emission"-process.

The research project ERBA II will enable an optimization of basic principles of "sorption enhanced reforming" at laboratory-scale. The gained knowledge prepares the operation of "sorption enhanced reforming" as "below zero emission"-process. The achieved results are applied to prepare a process route for an iron production with reduced fossil carbon dioxide emissions.

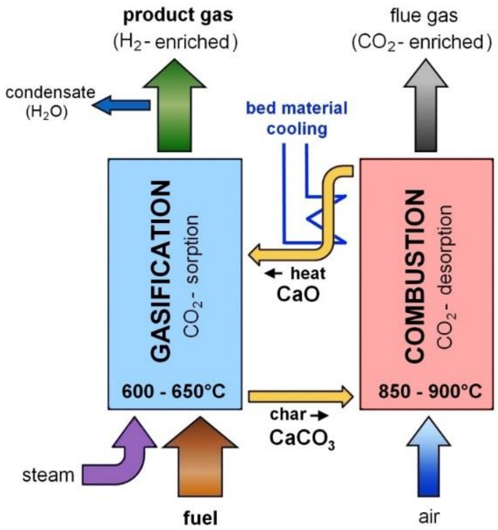

Fig 9. Basic principle of the "Sorption Enhanced Reforming" process

Partner:
voestalpine Stahl GmbH, Linz (Consortium Leader)
TU Wien, Institute of Chemical Engineering
Voestalpine Stahl Donawitz GmbH

Contact: Johannes Schmid, johannes.schmid@tuwien.ac.at

6. Bio Fuels from Fluid Catalytic Cracking by co processing and processing pure bio oils in circulating fluidized bed

Alexander Reichhold
TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria

Oils from renewable biological sources are gaining in importance in response to decreasing crude oil reserves and subsequently increasing oil prices. Therefore an investigation was carried out into the possibility of adding oils from biological sources to the feedstock of FCC (Fluid Catalytic Cracking) processes. The purpose was to produce fuels in the gasoline and diesel boiling range and light olefinic hydrocarbons for the petrochemical industry (Fig. 110).

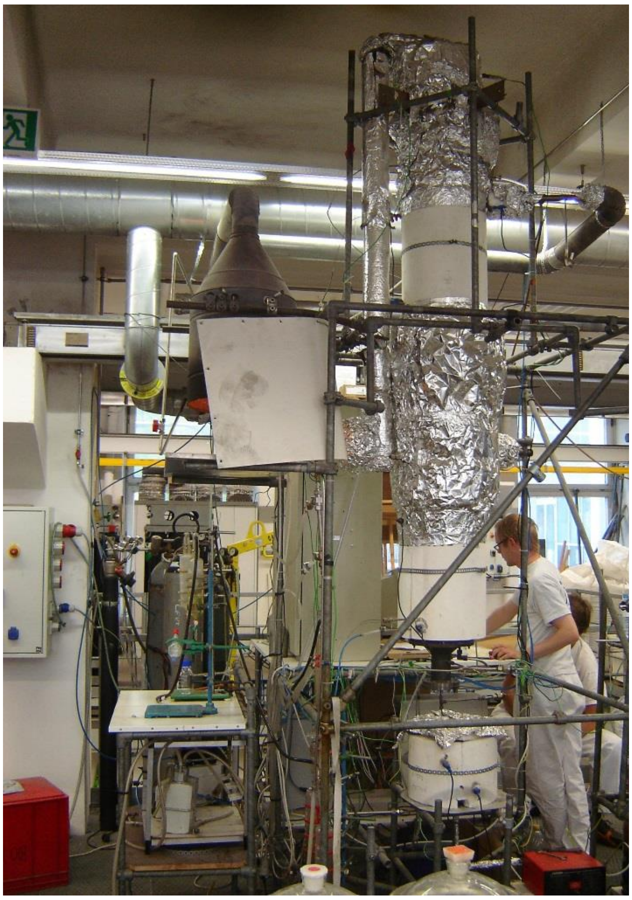

Fig. 110. From base to final product

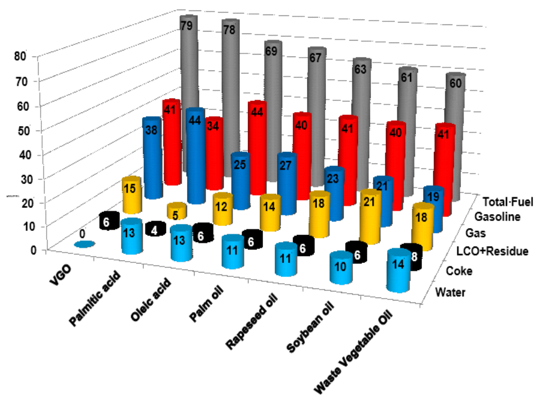

Fig. 11. Pilot plant

Fig. 12. Experimental results

The experiments were conducted in a continuously operated pilot-scale FCC-unit with internal CFB-design and focused on a thorough analysis of the basic applicability of these oils in a FCC-unit in terms of cracking reactions and subsequent effects on catalyst circulation and obtained product distribution. (Fig. 12) Special consideration was given to the effect of the bio oils on the octane numbers of the obtained products in the gasoline boiling range. The applied bio oils, rapeseed oil, soy oil, palm oil and sunflower oil, were added to hydrated vacuum gas oil (standard FCC-feed) in different concentrations ranging up to 100 mass percent. The different experiments were conducted as continuous test runs and results were compared with the base case operation, using 100% vacuum gas oil.
Based on a lot of experimental Data a model for simulating the FCC and OCP (Olefin Cracking Process) was developed. The methods used for the modelling comprise the Multiple Linear Regression (MLR), the Principle Component Analysis (PCA), and the Principle Component Regression (PCR).

A new and fully continuously operated FCC – pilot plant with high flexibility was designed and constructed (Fig. 13). The motivation for this project is given by the different challenges when not feeding the system with standard FCC feed (VGO) but using several vegetable oils, animal fats, pyrolysis oils, fatty acids, used frying oils, tall oil and others.

In particular the different coking behaviour leads to different capacity ratios between riser reactor and regenerator. With a special focus on the performance of thermal cracking reactions in the system at lower temperature levels it is necessary to provide thermal decoupling between riser and regenerator which is achieved by the installation of a special heat exchanger system.

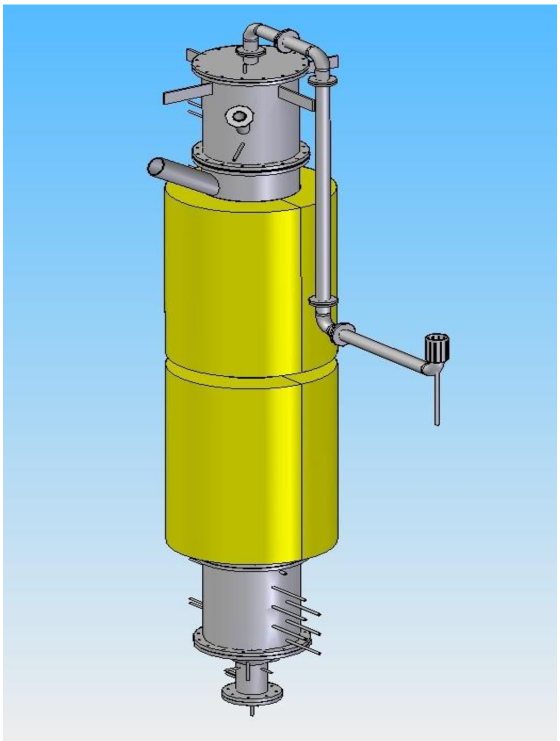

Fig. 13. Scheme of pilot plant

Contact: Alexander Reichhold, alexander.reichhold@tuwien.ac.at

7. Measurement device for heat transfer rates between fluidized bed and immersed tube bundles

Gerhard Hofer and Tobias Pröll
University of Natural Resources and Life Sciences, Vienna
Dept. of Material Sciences and Process Engineering, Peter-Jordan-Str. 82, 1190 Vienna, Austria

Particle-convective heat transfer is essential to a number of fluidized bed processes and proper estimation of expectable heat exchange rates can help to optimize the design of such systems. A specific field of application is low-temperature continuous gas separation, e.g. continuous adsorption units, where phase change enthalpies have to be provided or removed from the beds.

A bubbling fluidized bed heat exchange testing device for optimization of the heat exchanger geometry with respect to heat transfer rates has been built and used for determination of effective heat transfer rates and for validation of fluidized bed heat transfer models.

Fig. 14 shows the test device built from acrylic glass for operating conditions up to 50°C. An electrically heated probe with internal temperature sensors is used in combination with distributed temperature sensors to determine the heat transfer rate, which can be easily calculated from the electric heating power and the temperature difference. Both horizontal and vertical tube alignment is possible.

Dummy tubes of varying dimension and packing density can be placed in the bed to assess the bundle effect compared to the heat transfer rate of a single tube configuration.

First results show reproducible trends and compare reasonably with certain models from the literature.

Fig. 14. Bubbling fluidized bed heat exchange testing device in horizontal tube modification.

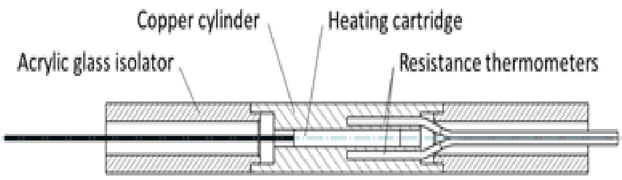

Fig. 15. Probe for the measurement of heat transfer rates including a 200W heating cartridge and two platinum resistance thermometers

Contact: Gerhard Hofer, gerhard.hofer@boku.ac.at; Tobias Pröll, tobias.proell@boku.ac.at

8. Dry Blast Furnace Slag Granulation with Waste Heat Recovery

K. Doschek, H. Raupenstrauch
Montanuniversitaet Leoben, Chair of Thermal Processing Technology,
Franz-Josef-Str. 18, A-8700 Leoben, Austria

Molten blast furnace slag represents one of the largest untapped energy sources in the iron and steel industry. The state-of-the-art practice is to solidify molten blast furnace slag by rapidly cooling it in granulation plants, using large volumes of water. The product is used as a substitute for cement clinker or as an aggregate material in road construction. With this commonly used production method it is not possible to utilise the remnant heat energy of the molten slag. Furthermore, the granulate needs to be dried in an additional energy intensive process step.
Aim of the R&D project “FORWÄRTS 2.0” is to develop a reliable dry quenching technology for molten blast furnace slag to recover the high-temperature waste heat while reaching the process conditions required for the production of a glassy slag suitable for the cement industry.
The dry slag granulation concept is based on the centrifugal atomisation of liquids. The rotation of a cup forces the slag outward to the lip where it is atomised. The resulting slag droplets cool in their flight and in the slag bed by cooling air. The slag bed is kept in motion by the design of the cooling air distributor (fluidized bed). The cooling air can pass the discharging modules in order to create a direct bottom up flow in the granulate bed (counter flow principal). The air distribution ensures a high heat exchange rate between the granules and the cooling air. The hot off gas can be used to drive different heat recovery applications, see Fig. 16. (Werner et al. 2016)

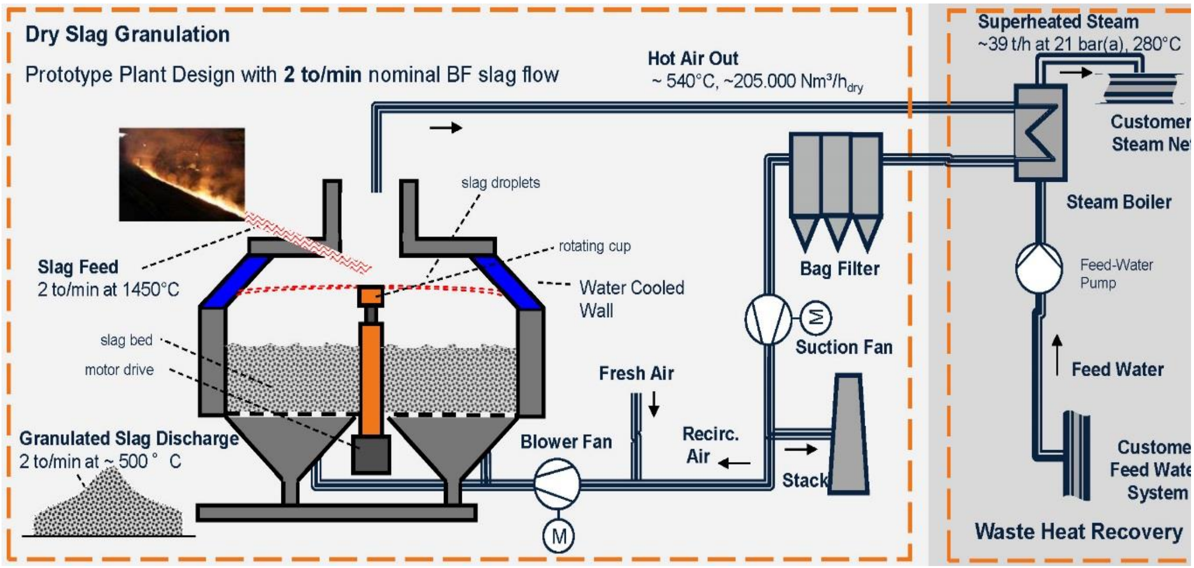

Fig. 16. Industrial Plant Concept – Schematic Process (Fenzl 2016)

“FORWÄRTS 2.0“ is currently underway by Primetals Technologies Austria GmbH and comprising voestalpine Stahl GmbH, FEhS - Building Materials Institute and the Chair of Thermal Processing Technology. This project is funded by the Climate and Energy Fund within the research programme ”Energieforschung”.

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Contact:
K. Doschek, klaus.doschek@unileoben.ac.at; H. Raupenstrauch, harald.raupenstrauch@unileoben.ac.at

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CANADA

Prepared by Robin Hughes, Dennis Lu, Thangam Parameswaran, Jaber Shabanian, Marc Duchesne, Robert Symonds, Emma Moreside, Arturo Macchi and Poupak Mehrani

Canadian Needs Driving Fluidized Bed Conversion Development

Stationary fuel combustion for producing energy to generate power, steam, or heat is the largest source of industrial CO_2 emissions in Canada and represents ~75% of the total reported emissions. Development of fluidized bed conversion technologies are intended to increase Canada's global competitiveness by spurring the commercialization of greenfield and retrofit syngas, power, steam, and heat production technologies adhering to Canada's targets to reduce greenhouse gas (GHG) emissions. Cost and environmental performance are the overriding issues in the development of fossil fuel production in Canada, in the form of market competitiveness and social license, respectively. Significant advances are required to reduce the environmental impact of fossil fuel extraction, in particular from unconventional oil and gas operations, and to reduce the environmental impact of fossil fuel conversion to power, steam, and heat.

FBC development in Canada has been focussed on improvements in near-zero emission power, steam, and heat generation systems that will contribute to major breakthroughs in cost and efficiency improvements in energy conversion and maximize resource productivity. The objectives of technology development include:

Reducing GHG Emissions: Development of transformative technologies with technology developers, researchers, end-users, and provincial organizations.

Increasing Energy Production From Renewables: Utilization of biomass as the feedstock to fluidized bed conversion technologies to permit the production of hydrogen and syngas.

Addressing Other Environmental Challenges: Reduction of criteria air contaminant emissions and water consumption compared to conventional technologies.

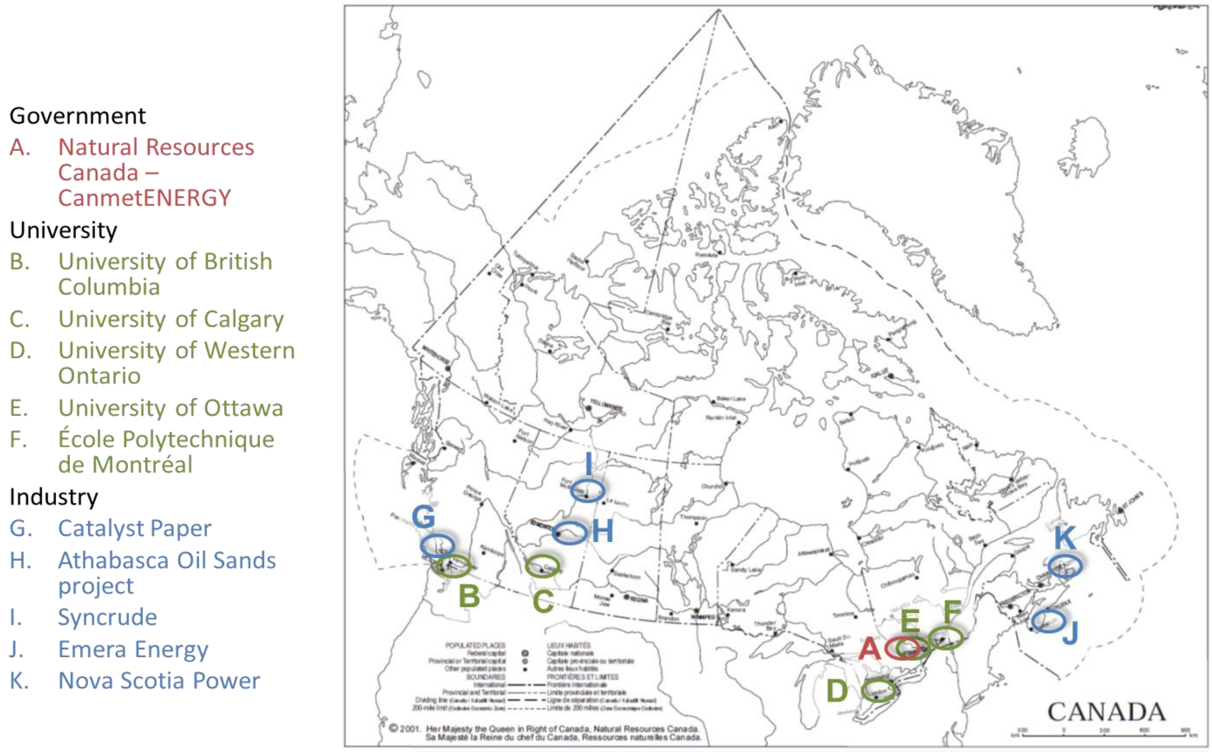

Fig. 17. Organizations discussed in Developments in Fluidized Bed Conversion in Canada 2010 – 2015.

Research Centers

Natural Resources Canada - CanmetENERGY

Oxy-PFBC

Oxy-PFBC under development at CanmetENERGY utilizes a high aspect ratio bubbling fluidized bed, with pulverized fuel and sulphur sorbent elutriated through the bed resulting in a compact and efficient power generation technology. O_2, mixed with recycled CO_2, is used as the oxidant and as the fluidizing transport medium. Bed temperature is controlled by injecting the fuel in stages at different axial locations in the bed. Heat generated from the combustion process is removed by in-bed and convective heat exchangers. The heat is used to drive supercritical steam or supercritical CO_2 power generation cycles.

Oxy-PFBC systems are predicted to make fossil fuel power plants with near zero emissions economically attractive by reducing the cost of CO_2 capture to between $US 16/tonne and $US 28/tonne based on third party economic analysis. This is superior to current commercial technologies and exceeds the US DOE's targets for emerging second generation technologies and nearly achieves the DOE's transformational targets. Specifically, oxy-PFBC, using a traditional steam Rankine power cycle, is expected to decrease the cost of electricity by 22% compared to current state-of-the-art air-fired pulverized coal power plants with post-combustion capture at 98.3% CO_2 capture.

CanmetENERGY is collaborating with the Gas Technology Institute, Linde, Canadian Power Utilities (TransAlta, Capital Power Corporation, Nova Scotia Power and SaskPower), the government of Alberta, the Electric Power Research Institute, and various universities to develop the technology. A 1.2 MWth oxy-PFBC is being built at CanmetENERGY in Ottawa to support technology development.

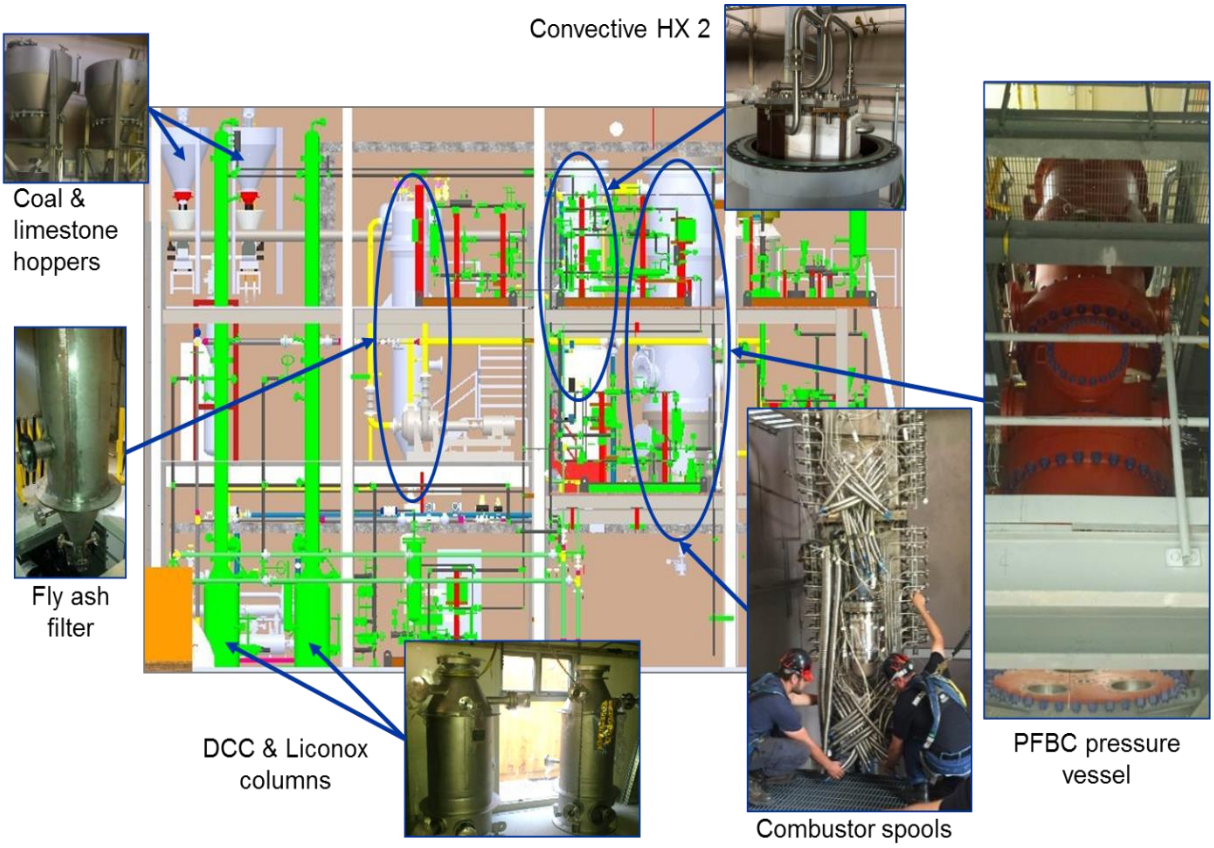

Fig. 18. 1.2 MWth oxy-PFBC pilot plant under construction at CanmetENERGY in Ottawa, Canada.

Calcium Looping

Significant progress has been achieved on the R&D of Chemical looping (CaL) processes. CanmetENERGY's pilot-scale dual fluidized bed facility, shown in Figure 1, was renovated and successfully commissioned in the summer of 2013. The facility was designed with a unique feature which enables operation in full oxy-fuel mode with flue gas recycle (either wet or dry), allowing for production of a flue gas CO_2 concentration greater than 90%. The calciner can operate in either bubbling or fast fluidization mode, which allows for flexibility in sorbent particle size, and is equipped with both an overflow discharge and loop-seal (in the return-leg) utilized for sorbent transfer to the carbonator. By allowing for different solids transfer methods, a variety of sorbents with varying physical characteristics (i.e., particle size, density) were tested without the risk of enhanced particle attrition and fragmentation. Other key features of the system include an electric boiler used for steam addition to the carbonator and/or calciner and a transfer auger/eductor to transfer the sorbent from the carbonator to the calciner, and vice versa. The facility has the capacity for continuous operation over a wide range of operating conditions and can be loaded with different fuels (e.g., gas, biomass, coal, and coke) and a variety of sorbents (natural or synthetic).

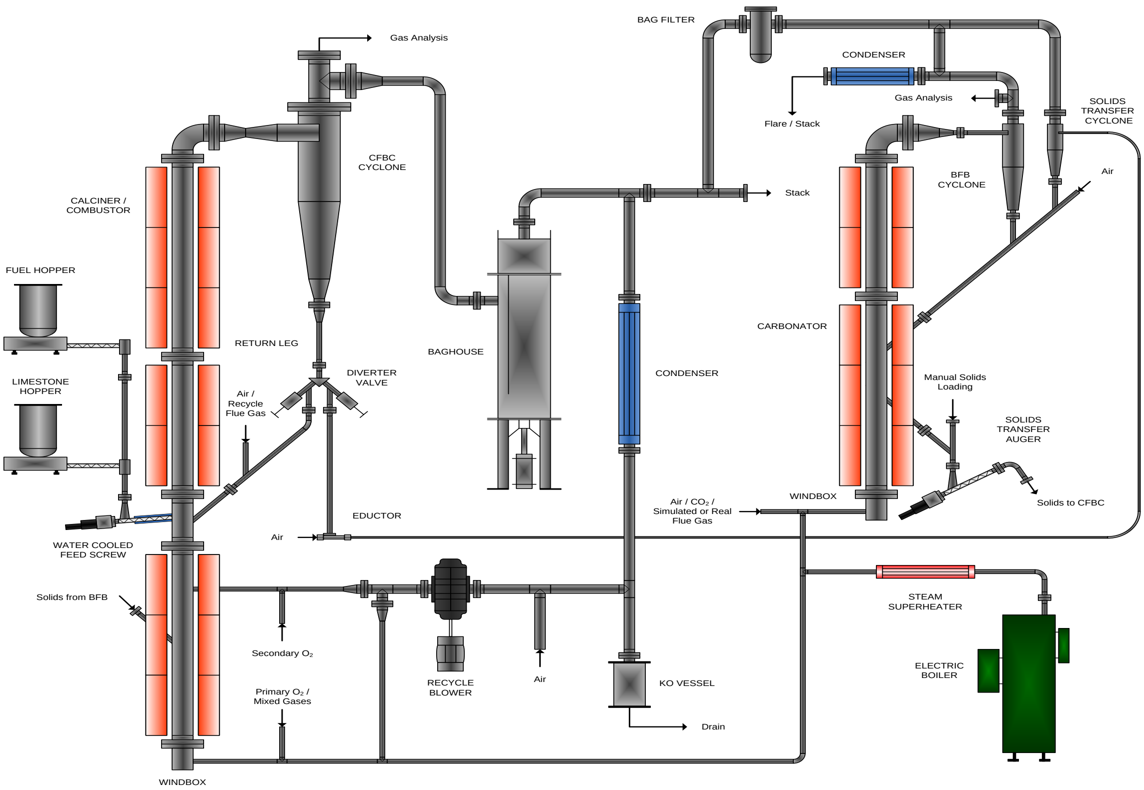

Fig. 19. CanmetENERGY dual fluidized bed pilot-scale facility.

A test campaign with continuous CO_2 capture and various levels of steam in the oxy-fired calciner was completed in the pilot plant. The calciner was operated with steam concentrations of 0%, 15% and 65% at the inlet of the windbox. A significant increase in surface area was seen with a steam concentration of 15% and the pore volume consistently increased with increasing steam concentration. The increase in steam in the calciner decreased the fresh sorbent make-up rate; for instance, a 78% reduction in make-up was observed with 65% steam in the calciner. The increased carrying capacity of the sorbent was due to the increase in pore volume and surface area which were a result of the increase in steam concentration and corresponding decrease in CO_2 concentration and of the possible decrease in calcination temperature, which would reduce thermal and CO_2-induced sintering. In commercial operation, the increase in steam concentration could be achieved by taking a slip stream of low quality steam from the steam cycle or by operating a wet flue gas recycle system, depending on the desired extent of dilution.

In addition to realistic calcination conditions, a natural gas burner was used as the flue gas source for the carbonator. Natural gas was chosen as a fuel for ease of operation and to eliminate SO_2 and ash being sent to the carbonator. The flue gas was not treated before being sent to the carbonator thus resulting in a realistic concentration of H_2O and CO_2. A minimum carbonation efficiency of 90% was maintained during all continuous operations with two different pelletized sorbents (Cadomin and Spanish pellets) and continuous sorbent make-up flows, with some conditions reaching 95% carbonation efficiency. It is clear that both pellet types reached great overall carbonation conversion (20-25%) with excellent consistency over the test period (8-10 hours). The attrition of CaO-based pellets was also studied in the pilot-scale system. Two groups of pellets prepared from Cadomin and Spanish limestones with 10% calcium aluminate cement as a binder were examined. The results revealed that ~50% of the sorbent collected after the tests fell below the lower limit of the feed size interval, i.e. 250 μm.

A project funded by the CMC Research Institutes (Carbon Management Canada) developed methods to improve the efficiency of the gasification process, while simultaneously reducing and sequestering CO_2 emissions. The work focused on beneficiating coal and on improving the performance of limestone-based sorbents for in situ CO_2 capture in a Dual Fluidized Bed (DFB) CaL process. The project was a joint venture between CanmetENERGY, École Polytechnique, and the Universities of British Columbia, Calgary, Alberta, Saskatchewan, Laval, Western Ontario, Ottawa and Toronto.

CLC-CaL

CanmetENERGY began studies in chemical looping combustion – calcium looping (CLC-CaL) in 2012. CLC was intended to replace oxy-fuel combustion for sorbent regeneration via the use of a metal oxide oxygen carrier (such as CuO) which provides the oxygen to burn the fuels in the sorbent regeneration stage. The integration of the two technologies was expected to result in a higher net efficiency and lower capital cost for carbon capture and storage (CCS) than CaL alone for both post-combustion CO_2 capture for power generation and pre-combustion CO_2 capture for hydrogen production.

The diagram below provides an overview of how the integrated process could be developed for three energy conversion cycles associated with post-combustion carbon capture, enhanced hydrogen production via methane reforming, and solid fuel gasification, each with CO_2 capture:

1) **Post Combustion CO_2 Capture**: (i) removal of CO_2 from flue gas by CaO/Cu composite sorbent in the carbonator, (ii) regeneration of Cu in the air reactor, and (iii) regeneration of $CaCO_3$ using methane (or H_2/biomass) which reacts with CuO (concentrated CO_2 stream is produced in regenerator).

2) **Sorption Enhanced CH_4 Reforming**: (i) reforming of CH_4 with in situ CO_2 capture (stream of H_2 is produced), (ii) regeneration of Cu in the air reactor, and (iii) regeneration of $CaCO_3$ using fuel gas (CH_4, refinery off-gas or H_2/biomass) which reacts with CuO (concentrated CO_2 stream is produced in regenerator).

3) **Biomass / Solid Fuel Gasification**: (i) gasification with CO_2 with in situ CO_2 capture, (ii) regeneration of Cu in the air reactor, and (iii) regeneration of $CaCO_3$ using methane and hydrogen produced in step (i) which reacts with CuO (concentrated CO_2 stream is produced in regenerator).

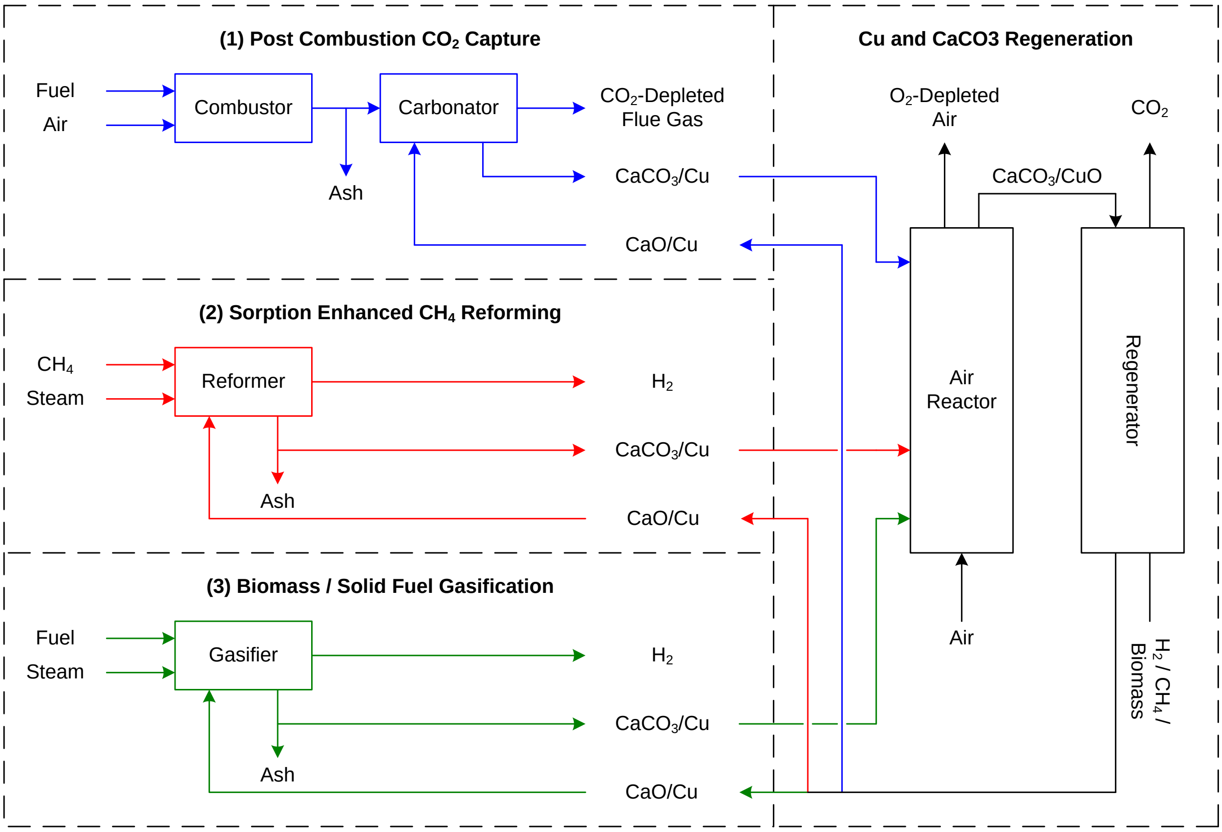

Fig 20. Chemical looping combustion calcium looping (CLC-CaL).

The work was carried out with a partnership with the Universities of Ottawa, Calgary and École Polytechnique with additional involvement from Dr. Edward Anthony at Canfield University (UK) via the project funded by CMC Research Institutes (CMC).

Pressurized Chemical Looping Combustion

In 2014 CanmetENERGY began studying pressurized chemical looping combustion and reforming for zero emissions heavy oil extraction, syngas production and heavy oil upgrading. Process simulation (UniSim Design Suite R430) has confirmed high overall efficiency for the proposed processes. Total pressure and methane partial pressure are the most important parameters for ilmenite conversion rate and oxygen transport capacity. The modeling and experimental results have provided insight into the phase and morphology transformations accompanying the use of ilmenite in PCLC/R. Agglomeration appears to be a possible risk at high temperatures that will need to be managed.

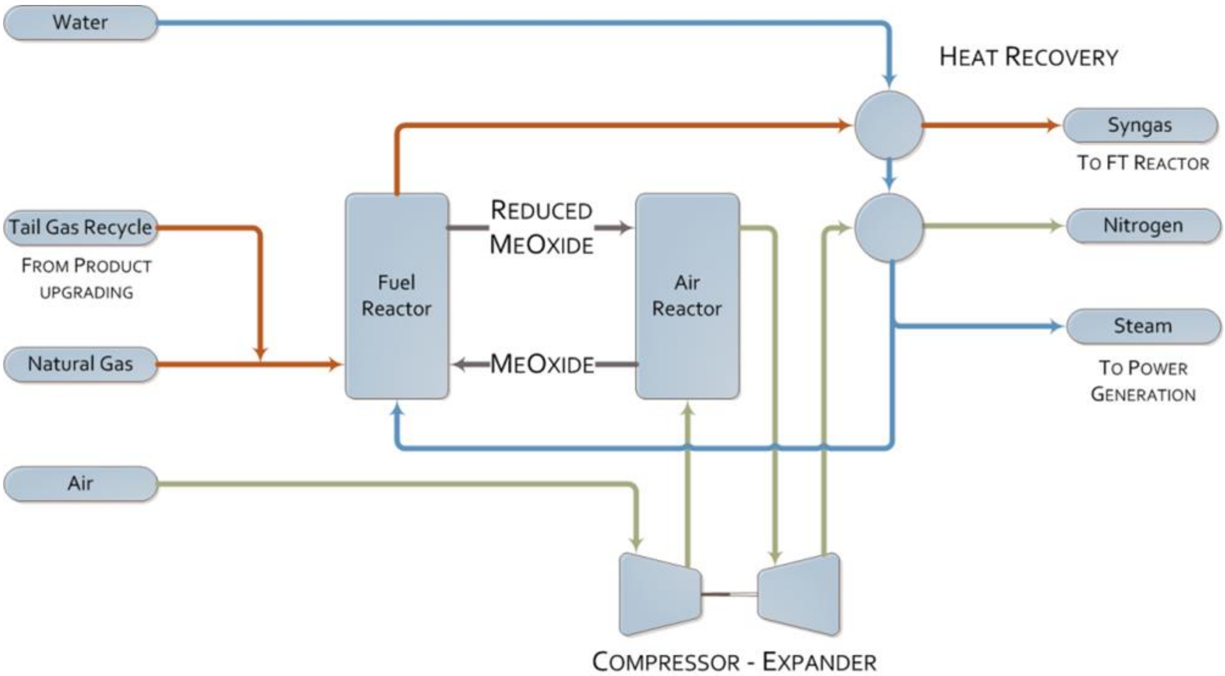

Fig. 21. Pressurized chemical looping configured for syngas production for FT-synthesis.

A PCLC unit could replace conventional steam generators in conventional SAGD applications so that the plant's total steam demand is produced by PCLC units with a CO_2 stream produced for sequestration. Process configurations for the integration of PCLC and SAGD have been created to help researchers at CanmetENERGY further conduct process simulations and process pinch analyses.

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École Polytechnique de Montréal

Combustion

Recent studies have focused on reduction of fuel-bound contaminants, i.e., SOX, NOX, and Hg, from coal-fired combustors in collaboration with Accordant Energy. This was achieved through the co-combustion of coal and ReEngineered FeedstockTM (ReEF) in a bubbling fluidized bed combustor and a pulverized coal boiler. ReEF is a solid fuel made from the non-recyclable fraction of municipal solid waste (MSW) to which air emission sorbents are physically bound. This strategy offers several advantages:

1. Increased residence time of sorbent in the combustor compared to the most direct injection options,
2. Decreased coal consumption,
3. Decreased volumes of MSW in landfills and hence decreased emissions of the greenhouse gas (GHG) methane, decreased odour pollution, and decreased wastewater generation,
4. Increased coal combustion (carbon burnout) efficiency during the coal-ReEF co-combustion as ReEF has high volatile matter, making it more reactive than coal, and
5. Easily adjusted ReEF formulation and physical properties which can be employed with different solid fuels without requiring modifications to the feeding system while ensuring optimal sorbent residence time in the combustion zone.

Experimental results show good performance of ReEF in reduction of SO2 and Hg emissions in the following cases: (i) when co-combusting 20% ReEF (LHV basis) with a granular bituminous coal in a 20 cm I.D. and 2 m height atmospheric bubbling fluidized bed combustor of coarse silica sand particles (mean particle size = 820 µm) in the 800-1000℃ range, and (ii) when co-combusting pulverized coal and ReEF with the same co-feeding ratio in a 5 cm I.D. and 4.25 m height atmospheric pulverized coal boiler in the 1200-1500℃ range.

Despite its promising performance in air emission reduction, some formulations of ReEF led to defluidization of the bubbling fluidized bed combustor or agglomeration of ashes and, hence, fouling and slagging in the pulverized coal boiler during operation. The defluidization fate of the atmospheric bubbling fluidized bed combustor during the co-combustion of over 70 ReEF formulations over short duration tests (1 hour per temperature level) under otherwise similar conditions was explored. Collating the defluidization outcomes by the specific formulations of ReEF with respect to sorbent stoics, a defluidization prediction map was developed. The map defines the sodium and calcium stoic limits in the ReEF formulation, where bed defluidization will occur within a short duration at the different temperature levels. The applicability of the map over extended periods was verified through combusting the solid fuel mixture with critical ReEF formulations having calcium and sodium compositions close to the defluidization boundary of 900℃ for over eight hours at 850℃.

In addition, a novel approach was introduced for the early detection of defluidization conditions in a bubbling gas-solid fluidized bed combustor. The new approach benefits from its simplicity, effectiveness, and robustness with respect to the variation of influential operating parameters, i.e., bed temperature (±100℃), superficial gas velocity (±10%), and bed mass (±20%). The approach was established through the simultaneous measurements of local temperature and in-bed differential pressure signals. It showed promising performance in the timely detection of the onset of agglomeration minutes to hours before complete defluidization. According to the experimental observations, two detection thresholds for the advanced recognition of agglomeration in bubbling fluidized beds of coarse silica sand particles were proposed.

Gasification

A detailed investigation was carried out on chemical looping gasification of biomass. Comparing the physical and chemical performance of different oxygen carriers revealed that despite its high cost and toxicity, cobalt oxide is a good candidate to be adopted as an oxygen carrier, particularly for solid fuel gasification. The transient gas composition at the outlet of a biomass fluidized bed gasifier was modeled with the help of a hydrodynamic model, i.e., two phase flow model for the dense bed and a plug flow model for the freeboard region, and kinetic expressions from open literature. A techno-economic comparison of a biomass chemical looping gasification unit with a conventional gasification unit with pure oxygen was conducted.

Hydrodynamics

The influence of interparticle forces on the hydrodynamics of a gas-solid fluidized bed was thoroughly investigated at different superficial gas velocities, covering fixed bed state, bubbling, and turbulent fluidization regimes. Also, hydrodynamics of a bubbling gas-solid fluidized bed was characterized at high temperature in the presence of interparticle forces. A separate set of studies focused on the characterization of hydrodynamics and mixing phenomena in gas-solid fluidized beds containing mixtures of sand and irregular shaped biomass particles. With the help of experimental data, a one-dimensional model was proposed that predicts the volume fraction of biomass particles along the axis. In a separate study, a new experimental approach with the application of an optical fiber probe was developed and implemented to determine the characteristic jet penetration lengths. The experimental results of this study were employed to develop five new correlations for the prediction of various jet penetration lengths with upward and downward injections. Under an industrial chair program with TOTAL, the group has constructed a pilot-scale high pressure and temperature gas-solid fluidized bed reactor, i.e., 15 cm ID and 4.9 m in height, to characterize the fluidization behavior of a wide spectrum of particles at elevated pressures and temperatures. The unit is capable of operating at 20 bar and 1000℃. This research is currently in progress.

Three phase fluidized beds/bubble columns

Hydrodynamics of a bubble column reactor operating with non-Newtonian liquids having different rheological properties was investigated in detail. By applying the dimensional analysis and with the help of experimental data collected in this study, two new correlations were developed to predict the gas hold-up and bubble size in bubble columns operating with non-Newtonian liquids. Under an industrial chair program with TOTAL, the group has constructed a pilot-scale high pressure and temperature bubble column reactor, i.e., 15 cm ID and 5.3 m in height, to characterize the fluidization behavior of different liquids and slurry phases at elevated pressures and temperatures. The unit is capable of operating at 20 bar and 200 ℃. The influence of operating pressure on hydrodynamics of bubble column reactors in the presence of non-Newtonian liquids was investigated. A new correlation was accordingly developed to predict the gas hold-up in bubble column reactors operating at elevated pressures. This research is presently in progress at high temperature and high pressure conditions. Moreover, investigations on the effects of slurry phase characteristics and concentration on the bed hydrodynamics of a slurry bubble column reactor operating at elevated pressures and temperatures are currently in progress.

Fig. 22. High pressure, high temperatures gas-liquid-solid bubble column at École Polytechnique de Montréal.

Fig. 23. High pressure, high temperature gas-solid fluidized bed at École Polytechnique de Montréal.

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University of British Columbia

The University of British Columbia (UBC) is actively involved in fluidization research. It hosts a Fluidization Research Centre (FRC) that was established in 1997 with funding provided by the Mitsubishi Chemical Corporation (MCC), the Natural Sciences and Engineering Research Council of Canada (NSERC) and a number of other government and industrial sponsors. The FRC conducts fundamental and applied research on fluidized bed reactors, their modeling and/or applications. FRC's objective is to achieve better understanding of fluidization phenomena, develop generic fluidized bed reactor models, investigate new diagnostic methods and analysis techniques, and to improve understanding of fluidization behaviour to enable more reliable design and operation of industrial-scale fluidized bed reactors. Faculty members involved with the FRC are John R. Grace, Xiaoto Bi, C. Jim

Lim, Paul Watkinson, Norman Epstein, Martha Salcudean, Fariborz Taghipour, Naoko Ellis and Shahab Sokhansanj. Current research topics include:

1. Sensor Development
2. Pure Hydrogen Production via the FBMR Process
3. Spouted Bed Studies
4. Catalytic Cracking of Biomass Gasification Tar
5. Zinc Sulphide Roasting
6. Advanced Fluidized Bed Reactor Model Software
7. Chemical Looping Systems
8. Environmental Catalysis in Air Pollution Control
9. Feeding of Biomass Particles
10. Reactivation of Partially Sulfated Limestone
11. Hydrodynamics of Fluid Coker
12. Heat Transfer in Turbulent Fluidized Beds
13. Circulating Fluidized Bed Gasification
14. Hydrodynamics of Hydrotreater Reactors
15. Behaviour of Turbulent Fluidized Beds
16. Biomass Torrefaction in Fluidized Bed
17. Modeling and Simulation of Fluidized Bed Reactors
18. Sorbent Attrition in Fluidized CO_2 Capture Systems
19. Dioxin/Furan Emissions from Fluidized Bed Combustion
20. Propane Dehydrogenation in a Fluidized Bed Membrane Reactor

Facilities at the University of British Columbia include a dual fluidized bed gasification pilot plant, consisting of a bubbling fluidized bed gasifier and a CFB riser char combustor, which has been designed, fabricated, and commissioned for biomass steam gasification to produce high quality syngas. This state-of-the-art dual-bed unit has attracted several other projects, including catalytic combustion, chemical looping gasification for in-situ carbon capture, catalytic tar cracking etc.

In the allothermal steam gasification of biomass, the biomass is fed into the bubbling bed gasifier with sand/catalyst as the bed material and is gasified at 750-850℃ by steam. The gasification residue bio-char mixed with sand is circulated into the riser and combusted by air, and the heat generated from the combustion heats up the sand/catalyst which is returned to the gasifier to support the endothermic steam gasification process. Stable production of high quality syngas of rich H_2 and CO, low N_2 content and high heating value, has been successfully achieved. Experimental tests are now focused on improving the system performance and durability, characterizing the hydrodynamics, heat and mass balances for different feedstocks, and developing catalysts under different operating conditions. A novel in-situ solid circulation measurement technique has been devised and demonstrated to support the development of a reactor model for simulation and reactor scaling. In parallel, new catalyst for catalytic tar removal has been under development in a bench scale fixed reactor system and will be incorporated into the pilot gasifier for evaluation and demonstration.

Fig. 24. Dual fluidized bed gasification pilot plant at the Pulp and Paper Centre, University of British Columbia.

University of Ottawa

The University of Ottawa is active in several research areas related to fluidized beds including gasification, fast pyrolysis, oxy-fuel combustion, SOX and CO_2 capture using CaO-based sorbents, chemical looping combustion, and bitumen upgrading.

In regards to oxy-fuel combustion, tests were conducted to evaluate fuel particle residence times and bed-to-surface heat transfer rates at elevated pressures and in the presence of boiler tube bundles. Experiments have been carried out to investigate SOX capture via CaO-based sorbents as well as steam production for the mining of bitumen. Concerning gasification and fast pyrolysis, experiments have been performed with biomass and refuse derived fuel where the impact of various pre-treatment methods (comminution, drying, pelletization, torrefaction, or carbonization) on product yield were evaluated. Modeling biomass fast pyrolysis with validation using a pilot-scale reactor at CanmetENERGY-Ottawa is underway. Work has been carried out in a pressurized entrained flow gasifier to characterize the fuel feed pneumatic conveying as well as the resulting slag physical properties in the reactor. Research on CaO-based sorbents has been primarily to improve their cyclic CO_2 sorption capacity and to investigate their performance under real conditions in a pilot-scale reactor at CanmetENERGY-Ottawa, with information then used in process simulations. The characterization and modeling of the cyclic redox of ilmenite in the context of various pressurized chemical looping processes is underway. Finally, research is being conducted on modeling visbreaking and hydrotreating for the partial upgrading of bitumen.

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University of Western Ontario

Between 15 and 20% of Canada's heavy oil production is processed in fluidized bed cokers, a subject of interest at the University Western Ontario. In the fluid coking process heavy oil is sprayed into a fluidized bed of hot coke particles, where its long hydrocarbon chains are thermally cracked into more valuable components. When the liquid concentration is high, particles may stick together (referred to as bogging) and result in poor fluidization. At UWO, jet penetration and bogging are studied extensively. Supersonic nozzles are used to inject high pressure steam into the fluidized beds to keep the coke particles at an optimal distance. Measurement and modeling studies to reduce steam consumption and improve the efficiency of fluidized bed cokers using supersonic nozzles and investigations of bed agglomeration in a bubbling bed have also been reported. The research includes the development of hydrodynamic and chemical simulators of chemical processes of industrial interest, such as the coupling of predictive hydrodynamic models for fast gas-solid reactors to the kinetics of partial oxidation reactions. These studies are relevant to heavy oil upgrading, thermal cracking of biomass and other solid wastes for the production of bio-oil and bio-oil upgrading.

The projects have involved the monitoring of industrial operations such as high- and low-pressure fluidized beds, pneumatic transport lines and solids dryers, as well as the study of solids attrition in fluidized beds, the remediation of electrostatic effects, and the optimization of solids mixers, cyclone separators and filters. Collaboration with industry (e.g. Syncrude Canada), technology transfer and commercialization activities are facilitated through the Institute for Chemicals and Fuels from Alternative Resources (ICFAR).

The Particle Technology Research Centre (PTRC) at UWO is engaged in research programs in fluidization, ultra-fine powder processing, particle production, clean fuel technology and related topics. PTRC has established partnerships with other institutions including the National Research Council of Canada, Radex Powder coatings, General Motors and Ely Lilly.

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Commercial Operations & Studies

Power Generation

Nova Scotia Power

The Point Aconi circulating fluidized bed Generating Station, operated by Nova Scotia Power, remains the largest fluidized bed power generation facility in Canada. It is located on Cape Breton Island, Nova Scotia and has a power production capacity of 171 MWe. It has been in operation since August 13, 1994 using a wide range of fuels such as coal, petroleum coke, and more recently, biomass.

Emera Energy Inc.

Emera Energy Inc. (previously South Shore Power) is currently operating a 30 MWe bubbling fluidized bed boiler. The facility is located in Brooklyn, Nova Scotia and utilizes biomass residues from sawmills and other wood operations. An agreement with Nova Scotia Power is in place to continue to produce power until 2028. The boiler has been on-line since 1995 and was originally constructed to provide power to the now defunct Bowater Mersey Paper Mill.
Catalyst Paper Corporation

Catalyst Paper Corporation operates two paper mills, Port Alberni and Powell River, which utilize bubbling fluidized bed boilers for steam and power production via the combustion of wood waste products from paper production. Both units have been on-line since 2001 since the acquisition of the mills from Pacifica Papers.

Oil Upgrading

Syncrude Canada Ltd.

Syncrude Canada Ltd. currently operates two types of fluidized beds within its bitumen upgrading facilities: fluidized bed cokers and an LC-Finer. The fluidized bed cokers are dual fluid bed thermal conversion units that crack long chain bitumen molecules into more valuable short chain molecules – heavy gas oil, light gas oil and naphtha. The fluid coking process is a continuous operation where fluidized coke particles are transferred back and forth between the reactor and burner vessels. A portion of the coke produced in this process is transferred to the burner to provide heat for the thermal cracking process. The LC-Finer is an ebulated bed process that uses catalysis and hydrogen to convert bitumen into gas, oils, and naphtha.

The two original fluidized bed cokers (Mildred Lake upgrader, Alberta) have been expanded in capacity over the years and in 2005, each had a nominal capacity rating of approximately 105,000 barrels per day of a 50/50 mix of bitumen and heavier vacuum topped bitumen feed. This capacity was unchanged from the prior year. The third fluid coker, added in 2006 as part of the Stage 3 expansion, has the same purpose as the original two cokers but is designed to process 100,000 barrels per day of 100% vacuum topped bitumen. The longest run between fluid coker maintenance turnarounds is currently 786 days. Fluidized bed cokers are also used by Imperial Oil in their Sarnia, Ontario refinery. The LC Finer (Mildred Lake upgrader, Alberta) cracks bitumen molecules into lighter components via the addition of hydrogen and in the presence of a catalyst. This unit does not convert all of the bitumen to light products. An unconverted residual stream is produced and this stream is sent to the fluidized bed cokers to supplement the feed to those units. In 2006, the LC Finer unit had a nominal capacity rating of approximately 50,000 barrels per day of a 60/40 mix of bitumen and vacuum topped bitumen feed. This capacity was unchanged from the prior year. The longest run between LC-Finer maintenance turnarounds is 944 days.

Syncrude Canada Ltd. and ExxonMobil, in collaboration with the Institute for Chemicals and Fuels from Alternative Resources (ICFAR), are developing fluidized bed technologies to increase operability and liquid yields of fluidized bed cokers and to reduce the environmental footprint of heavy oil upgrading.

Athabasca Oil Sands Project (AOS)

The Athabasca Oil Sands Project (AOSP), located in Alberta, Canada, is a joint venture operated by Shell and co-owned by Shell (60%), Chevron Canada Limited (20%) and Marathon Oil Canada Corporation (20%). The AOSP consists of the Muskeg River and Jackpine mines and the Scotford Upgrader, and has a production capacity of 255,000 barrels of oil a day of synthetic crude. Located in Strathcona County, 45 km northeast of Edmonton, Alberta, Shell opened the refinery and chemical plant on the Scotford site in 1984. Scotford was the first refinery to exclusively process synthetic crude oil from Alberta's oil sands. LC-Finer trains 1 and 2 opened in 2003 and currently have a nominal capacity rating of approximately 79,000 barrels per day of 100% bitumen. In 2010, a third LC-Finer train was opened with a nominal capacity rating of approximately 47,000 barrels per day of 100% bitumen.

CHINA

Prepared by Hairui Yang, Hai Zhang and Man Zhang

Overview

As one of the most commercial clean coal technology, fluidized bed coal combustion technology develops fast and continually in the last five year, which is suitable for utilization of low quality coal in China. Most of the fluidized bed boilers are circulating fluidized bed (CFB) boilers, so far, the total capacity of large scale CFB boilers (larger than 100MW) is over 61675MW and the total number is over 338 units, which is over 12% of total capacity of coal fire power in China.

There are three main directions in the development of Chinese CFB boiler technology, first is the scaling up, i.e. to developing the supercritical/ultra supercritical CFB boilers. With financial support of this work by Key Project of the National Eleven-Five Year Research Program of China, the world largest 600MW supercritical CFB boiler was erecting in Baima Power plant in Sichuan Province and passed the 168h test in Arial 14th, 2013. At end of 2015, 10 units of 350 MW supercritical CFB boilers were put into operation, and other 60 units are under construction or ordered. With financial support of this work by Key Project of the National Thirteen-Five Year Research Program of China, the ultra-supercritial 660MW CFB will be develped and demonstration in 2019.

Table 1. 350MW supercritical CFB in operation

The Name of Owners	Provience	Unit	Boiler Manufacturer	Generator's output	Operatin
Shanxi Guojin	Shanxi	2	Dongfang Boiler Co., Ltd.	350MW	2015, July
Huadian Shuozhou	Shanxi	2	Shanghai Boiler Co., Ltd.	350MW	2015, October
Shendong Hequ	Shanxi	2	Dongfang Boiler Co., Ltd.	350MW	2015, December
Shanxi Hepo	Shanxi	2	Dongfang Boiler Co., Ltd.	350MW	2015, December
Xuzhou Huamei	Jiangsu	2	Dongfang Boiler Co., Ltd.	350MW	2016, Janury

The second is to develop energy-saving CFB boilers, which depends on the optimization on gas-solid flow in the furnace and simply the boiler structures, so-called Specific State Design (SSD) theory of CFB boilers, the first two units of 300 MW CFB boilers with energy saving process could be stably operated with pressure head of 10 kPa in wind box. Together with other measures, the auxiliary power consumption rate is as lower as 4.5%.

The third direction is to develop the low emmision technology. The new National Emission Regulation (NER) was proposed and published in early 2012, as list in Table 1 and 2, which enforces more stringent limitations on dust, NO_x, SO_2 and mercury. Some limitations (especially NO_x), which are much lower than those used in other countries, will bring much more stringent challenges on the CFB technology and industries in China, though low NO_x emission is the unique advantage of CFB technology. New solutions are carring out to meet the requirement of the new NER with the Key Project of the National Twelve-Five Year Research Program of China.

For the coal-fired power plants, China government enforced the new national regulation on emission in early 2012, which is listed in Table. 2.

Table 2. Emission standards of air pollutants of coal-fired power plants (mg·Nm^{-3})

Pollutant	Boiler	Limit
Dust	Total	30
SO_2	Newly built	100 (200*)
	Existing	200 (400*)
NO_x（Based on NO_2）	Total	100 (200**)
Mercury and other	Total	0.03

* Standards of Guangxi, Chongqing, Sichuan and Guizhou

** W flame PC boiler and existing CFB boiler, the units under construction before Jan 1st, 2012

More stringent emission regulation will be implemented in the well developed, low environmental capacity and ecological vulnerable regions, as listed in Table. 3.

Table 3. Emission standards of air pollutants for coal-fired power plants in special regions (mg·Nm^{-3})

Pollutant	Boiler	Limit
Dust	Total	20
SO_2	Total	50
NO_x（Based on NO_2）	Total	100
Mercury and other	Total	0.03

In the regulation above, the oxygen concentration of flue gas should be referenced to 6%.

Also every year one workshop on CFB fundamental or operation is arranged quarterly for all the academic and industrial colleagues by Tsinghua University and China Electricity Council. And a website, www.cfbpower.com is established and a Chinese Journal named CFB Power Generation was published.

Furthermore, the 68th IEA-FBC meeting was arranged in May, 2014, Beijing.

Research centers

Tsinghua University
South East University
Zhejiang University
Huaneng Clean Energy Research Institute
Institute of Engineering Thermophysics, CAS

Largest companies in Finland building FB boilers

Dongfang Boiler Co., Ltd.
Harbin Boiler Co., Ltd.
Shanghai Boiler Co., Ltd.

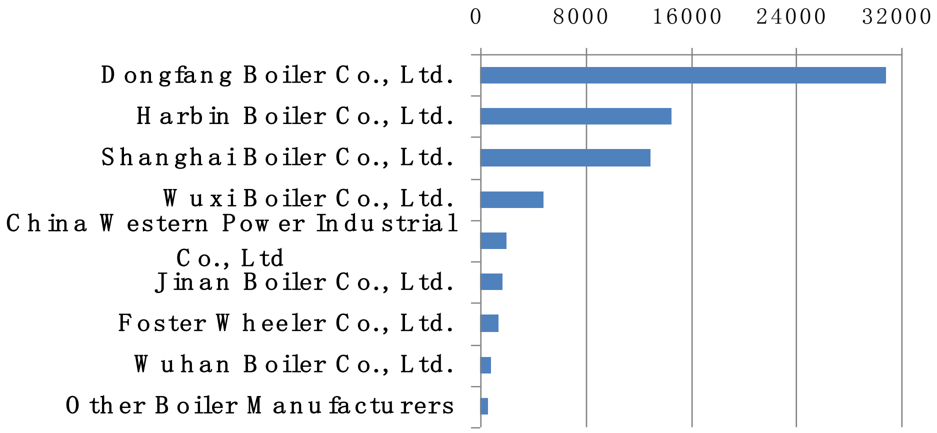

Fig. 1 the total capacity of the boiler companies in China

Large Scale CFB boilers in China

Table 4. The total number of the large scale CFB boiler and the capacity

Scale	Number	Capacity/MWe
100MW Scale Unit	42	4200
135MW Scale Unit	204	28405
200MW Scale Unit	33	6670
300MW Scale Unit	92	28150
Supercritical Unit	6	2350
total	377	69775
Quantity:135+300	296	56555
Percentage: 135+300	78.5	81.1

CFB boilers distribution among China by province

Tab. 5 The CFB distribution by province

Region	Province	Installed Capacity（MWe）
North China	Beijing	100
North China	Tianjin	635
North China	Hebei	2750
North China	Shanxi	10265
North China	Inner Mongolia	11640
East China	Shanghai	200
East China	Jiangsu	2180
East China	Zhejiang	1270
East China	Shandong	4505
East China	Fujian	3340
East China	Anhui	2770
East China	Jiangxi	1090
South China	Guangdong	5415

South China	Guangxi	800
South China	Hainan	400
Central China	Henan	3665
Central China	Hubei	600
Northeast	Liaoning	3240
Northeast	Jilin	660
Northeast	Heilongjiang	600
Southwest	Sichuan	2360
Southwest	Chongqing	900
Southwest	Yunnan	2235
Southwest	Guizhou	900
Northwest	Shaanxi	2410
Northwest	Gansu	290
Northwest	Qinghai	975
Northwest	Ningxia	1470
Northwest	Xinjiang	2410

So far, except of Hunan province, Hainan Province and Tibet, other 29 provinces all has large scale CFB boilers. According the capacity and unit number, Inner Mongolia, Shanxi, Guangdong and Shandong are the top four. At same time, over 92 cities have the CFB boilers larger than 100MW, shown in Figure 2.

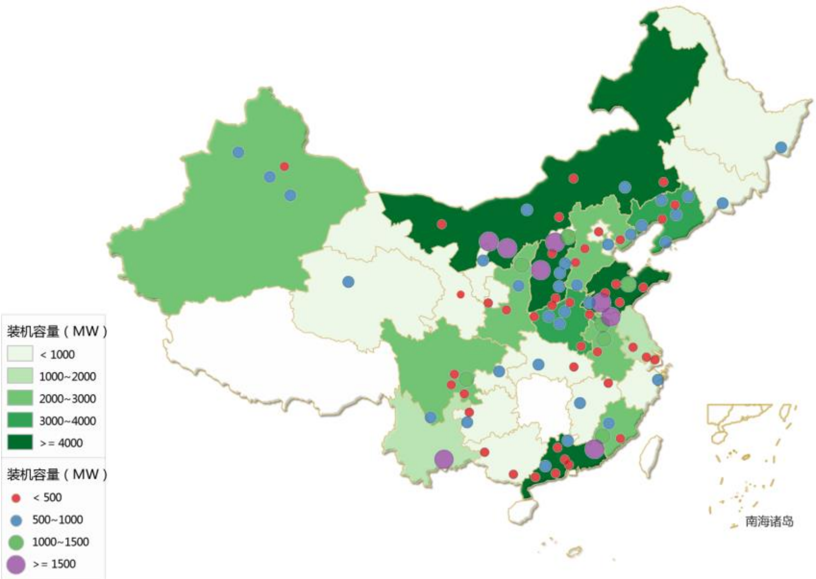

Fig. 2. Status of the CFB boilers in China

CFB boilers oversea

More and more Chinese CFB boilers, especially the large scale were exported oversea. Most owners are from southeast, Middle East and Africa.

Table 6. The CFB distribution by province

The Name of Owners	Capacity/MW	Unit	Boiler Manufacturer	Generator's output
Vietnam Son Dong Power Plant	110	1	Harbin Boiler Co., Ltd.	100MW and below

Vietnam Son Dong Power Plant	110	1	Harbin Boiler Co., Ltd.	100MW and below
Vietnam Cam Pha Power Plant	150	1	Harbin Boiler Co., Ltd.	135MW
Vietnam Cam Pha Power Plant	150	1	Harbin Boiler Co., Ltd.	135MW
Vietnam Cam Pha Power Plant	150	1	Harbin Boiler Co., Ltd.	135MW
Vietnam Cam Pha Power Plant	150	1	Harbin Boiler Co., Ltd.	135MW
Indonesia PT PLN	100	1	Jinan Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Jinan Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Indonesia PT PLN	200	1	Shanghai Boiler Co., Ltd.	200MW
Indonesia PERAWANG IKPP MBTG24 Power Plant	200	1	China Western Power Industrial Co.	200MW
Concepcion Coal Fired Power Station in Philippines	100	1	Wuxi Boiler Co., Ltd.	100MW and below
Concepcion Coal Fired Power Station in Philippines	100	1	Wuxi Boiler Co., Ltd.	100MW and below
India MADHCOM Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
India MADHCOM Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
India MADHCOM Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
India MADHCOM Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
India NAVA Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
India JINDAL Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India JINDAL Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India JINDAL Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India JINDAL Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW

India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India JSW Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
India Ausa Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India Ausa Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India Ausa Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India Ausa Power Plant	150	1	Shanghai Boiler Co., Ltd.	135MW
India GREENESOL Co.	150	1	Hangzhou Boiler Co., Ltd.	135MW
Turkey ICDASBIGA Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
Turkey Silopi Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
Turkey ICDASBIGA Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
Turkey ICDASBIGA Power Plant	135	1	Dongfang Boiler Co., Ltd.	135MW
Botswana MORUPULEB Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
Botswana MORUPULEB Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
Botswana MORUPULEB Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
Botswana MORUPULEB Power Plant	150	1	Wuxi Boiler Co., Ltd.	135MW
Bosnia and Herzegovina	300	1	Dongfang Boiler Co., Ltd.	300MW/subcritical
Mongolia	350	2	Harbin Boiler Co., Ltd.	350MW supercritical

Publication and patent in CFB technology

The publication activities have been extensive in the last 5 years. From 2011, over 500 papers and 200 parents were published every year.

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Czech Republic

Prepared by Dagmar Juchelkova-VŠB-TU Ostrava,
František Hrdlička-ČVUT Praha

Introduction

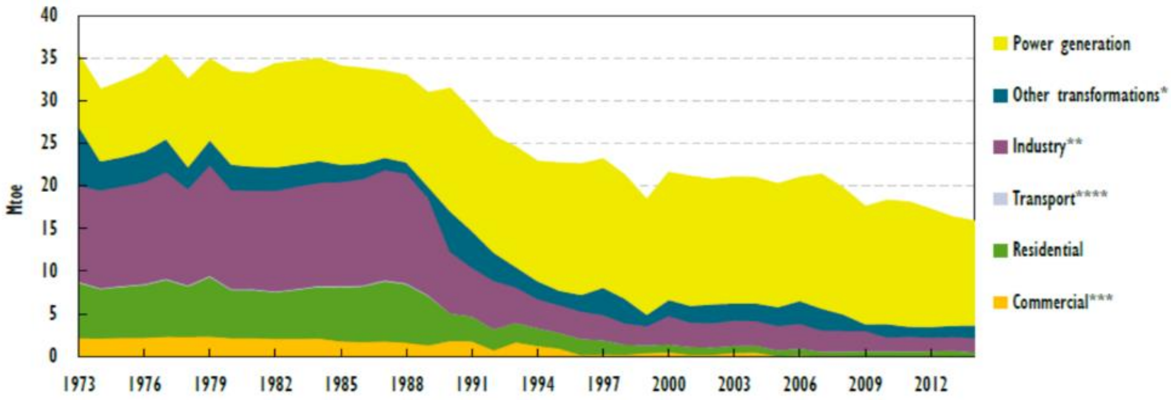
According to the Country Report of the Czech Republic (2016 Review) - The Czech Republic has made good progress in the development and implementation of energy policy.
The State Energy Policy (SEP), which replaced the previous 2004 policy, was approved by the Czech government in 2015. The principal strategic objectives of the SEP are security of energy supply and a competitive and sustainable energy sector. The SEP also established key targets for energy security, emissions, energy savings, electricity generation and affordability and set out the strategic goals for the proportions of primary energy sources and electricity production, which are set out in relatively broad ranges.

The updated draft State Energy Concept shares a common vision with the previous energy concept and sets out the following six strategic priorities:

- Achieve a balanced energy mix, with preferential use of all domestic energy resources and maintain excess production of electricity;
- improve energy efficiency, particularly in the buildings sector, and reduce energy intensity;
- promote regional development of electricity networks, strengthen international co-operation and enhance integration of electricity and gas networks with neighbouring countries;
- enhance the competitiveness of the Czech economy by supporting more research and development and higher education;
- increase energy security and the ability of the Czech Republic to respond to energy supply disruptions;
- minimize the impacts of energy use on the environment.

There are indicators and targets associated with each of the strategic priorities. The draft State Energy Concept also provides a scenario of the Czech energy market to 2050 with shorter term objectives and policy recommendations. Future development of the energy sector is predicated on the desire to enhance security of energy supply and maintain the Czech Republic as a net electricity exporter. Objectives for the future energy mix would be achieved through further diversification of energy supply and preferential use of indigenous resources, comprising coal, uranium and renewable energy, mainly biomass and waste.

Future expansion of nuclear capacity has been presented as one of the major pillars of the updated draft SEC. According to the most recent version of the updated draft Concept, nuclear power is projected to account for over 47 % of the power generation mix in 2050. Coal is projected to account for less than 12 %, less than the projected share of renewable energy sources (some 30 %). Gas will continue to play a complementary role (about 11 %). The draft Concept outlines indicative targets for domestic resources, including nuclear fuel, with 90 % and 80 % shares in overall electricity and district heating, respectively. The draft Concept also envisages reductions in energy intensity and in CO_2 emissions. It promotes more research and development and the training of future energy technicians to counter the shortage of such expertise in the Czech Republic.



* *Other transformations* includes other transformations such as coke ovens and refining, and energy own use.

** *Industry* includes non-energy use.

*** *Commercial* includes commercial and public services, agriculture/forestry and fishing (negligible).

**** Negligible.

Note: TPES by consuming sector.

Source: IEA (2016b), *Energy Balances of OECD Countries 2016*, www.iea.org/statistics/.

Fig. 1. Coal supply by sectors1973-2014

Fluidized Bed Combustion

There are used over 30 fluidized bed combustors, and a huge interest for co-combustion of various types of fuel (presently by alternative fuels based on waste).

Table 1. Circulating fluidized bed boilers in the Czech Republic

Location	Year	Type	Number	Capacity (tph)	Producer	Fuels	Operating system
Třinec	1995	CFBC	1	160	Lurgi (SES Tlmače)	HC	ABB
	1997	CFBC	1	160			Siemens
Poříčí	1996	CFBC	1	250	Foster Wheeler (CNIM)	HC/BC	Siemens
	1998	CFBC	1	250		BC	
Tisová	1996	CFBC	1	350	EVT (Vítkovice)	BC	Valmet
	1998	CFBC	1	350	LURGI (SES Tlmače)	BC	Valmet
Zlín	1996	CFBC	1	160	Babcok Wilcokx ABB Alstom	HC	Honeywell
	2000	CFBC	1	125	Lurgi (SES Tlmače)	HC	Honeywell
Komořany	1995 to 1999	BFBC Retrofil	10	125	Power Internat	HC	ABB-1x, Honeywell Foxboro-5x
Hodonín	1996	CFBC	2	170	AEE Austria	Lignit, HC	Valmet
Ledvice	1998	CFBC	1	350	ABB Alstom	BC	ABB
Olomouc	1998	Compact	1	190	Foster Wheeler (FORTUM)	HC, BC	Valmet
Štětí	1998	CFBC Retrofil	1	220	Foster Wheeler	BC, BIO	Valmet
Ml.Boleslav	1998	CFBC	2	140	EVT (Vítkovice)	HC	ABB
Kladno	1999	CFBC	2	375	ABB Alstom	HC	ABB
Plzeň	1999	CFBC	1	180	ABB Alstom	BC	

HC – hard coal, BC – brown coal, BIO – biomass , tph – tons steam per hour (tph)

BFBC – bubbling fluidized bed combustor, CFBC – circulating fluidized bed combustor

The table contains the most important features of fluidized bed combustors currently in operation.

Table 2. Coal-fired power plants (not only FB) in the Czech Republic, operational in 2010, with status under EC Large Combustion Plants Directive (LCPD), incl. planned plats

Plant name	Location	Owner	CHP	Capacity, MW	Units, MW (commissioned)	Fuel	LCPD	Notes
Chvaletice	Přelouč, Východní Čechy	ČEZ, a.s.	Yes	800	4 x 200 (1977-78)	sub-bituminous	NERP	FGD (1997)
Dětmarovice	Ostrava, Severni Morava	ČEZ, a.s.	Y	800	4 x 200 (1975-76)	bituminous	NERP	FGD (1998)
Hodonin	Jižni Morava	ČEZ, a.s.	Y	105	1 x 50 (1997) 1 x 55 (1997)	lignite	NERP	CFBC CFBC
Kladno	Central Bohemia	Matra Powerplant Holding B.V. (89%) Středočeská energetika, a.s. (11%)	Y	305	2 x 135 (2000) 1 x 34 (1978)	bituminous, sub-bituminous	NERP	CFBC
Komořany	Most, Ústecký kraj	United Energy, a.s.	Y	239	4 x 32 (1959/58/58/78) 1 x 35 (2006) 1 x 22 (1995) 1 x 34 (1997)	lignite	NERP	
Komořany II	Most, Ústecký kraj		Y			lignite		CFBC
Ledvice II	Teplice, Severni Čechy	ČEZ, a.s.	Y	220	2 x 110 (1966/68)	sub-bituminous	NERP	FGD (1996)
Ledvice III	Teplice, Severni Čechy	ČEZ, a.s.	Y	110	1 x 110 (1998)	sub-bituminous	NERP	CFBC
Ledvice IV	Teplice, Severni Čechy	ČEZ, a.s.			1 x 660	sub-bituminous		planned
Mělnik I	Stredni Čechy	Energotrans, a.s.	Y	352	4 x 60 (1960-61) 2 x 56 (1961)	sub-bituminous	NERP	FGD (1998) FGD (1998)
Mělnik II	Stredni Čechy	ČEZ, a.s.	Y	220	2 x 110 (1971)	sub-bituminous	NERP	FGD (1997)
Mělnik III	Stredni Čechy	ČEZ, a.s.	Y	500	1 x 500 (1980)	sub-bituminous	NERP	FGD (1998)
Mladá Boleslav	Northern Bohemia	RWE Power (21%) OBAG Aktiengesellschaft (21%) Středočeská energetika, a.s. (12%) VW Kraftwerk GmbH (12%) Skoda Auto, a.s. (34%)	Y	88	2 x 44 (1998)	bituminous	NERP	CFBC
Most	Most, Northern Bohemia	Appian Group			1 x 600-800	lignite		planned
Opatovice	Hradec Králové, Eastern Bohemia	Energetický a Průmyslový Holding (J&T Finance Group a.s.)	Y	360	6 x 60 (1959) 1 x 100	sub-bituminous	NERP	FGD (1996-97) planned
Počerady	Louny, Severni Čechy	ČEZ, a.s.	Y	1 000	5 x 200 (1970-77) 1 x 660	sub-bituminous	NERP	FGD (1994-96) planned
Poříčí	Trutnov, Východní Čechy	ČEZ, a.s.	Y	165	1 x 55 (1958) 2 x 55 (1997/98)	bituminous, sub-bituminous (some imported)	NERP	CFBC
Přerov	Olomouc	Dalkia Česká republika a.s.	Y			n.a.	n.a.	n.a.
Pruněřov I	Chomutov, Severni Čechy	ČEZ, a.s.	Y	440	4 x 110 (1967-68)	sub-bituminous	NERP	FGD (1995)
Pruněřov II	Chomutov, Severni Čechy	ČEZ, a.s.	Y	1 050	5 x 210 (1981-82)	sub-bituminous	NERP	FGD (1996)
T700 Chemopetrol	Litvínov, Ústí nad Labem	Chemopetrol, a.s.	Y	109	3 x 25 1 x 28 1 x 6	sub-bituminous	NERP	
Tisová I	Sokolov, Západni Čechy	ČEZ, a.s.	Y	184	3 x 57 1 x 13	sub-bituminous	NERP	CFBC (1996/97)
Tisová II	Sokolov, Západni Čechy	ČEZ, a.s.		112	1 x 112 (1959)	lignite	NERP	FGD (1997)
Třebovice	Ostrava, Northern Moravia	Dalkia Morava, a.s.	Y	152	1 x 50 (1951) 1 x 30 (1961) 1 x 72 (1968)	bituminous	NERP	
Tušimice II	Kadaň, Severni Čechy	ČEZ, a.s.	Y	800	4 x 200 (1974-75)	sub-bituminous	NERP	FGD (1997)
Vřesová I	Sokolov, Western Bohemia	Sokolovská uhelná, a.s.	Y	220	4 x 55 (1966)	lignite	NERP	FGD (2002)
Vřesová II	Sokolov, Western Bohemia	Sokolovská uhelná, a.s.	Y	400	2 x 200 (1995/96)	sub-bituminous	NERP	IGCC (1995/96)

Notes: CFBC – circulating fluidised bed combustion, FGD – flue gas desulphurisation, IGCC – integrated gasification combined cycle, NERP – National Emissions Reduction Programme (under the EU Large Combustion Plants Directive).

Sources: IEA Clean Coal Centre CoalPower5 database and IEA analysis.

New boiler was made in Power station Arcelormittal 248 MW, 89 kg/s, 104 bar, 525 °C, Power station Třinec 125 t/h, smaller units in Dolni Benešov (8 and 4 t/h)

Fluidized bed Gasification

The Czech Republic has one operational integrated gasification combined cycle (IGCC) power station, Vresova IGCC, which is operated by Sokolovská Uhelná. The 400 megawatt electrical (MWe) IGCC power station consists of 26 Lurgi type **fixed-bed gasifiers**, using brown coal from local mines and a recent installed liquid gasifier from Siemens, which provides additional syngas from tars produced by the fixed- bed gasifiers.

The possibility to replace the fixed-bed gasifiers with more modern technology has been investigated; one of the options that have been considered is the High Temperature Winkler process, which is based **on the fluidised bed**. There is no plan to commission any additional unit operating on an IGCC basis. The coal supply serving the Vresova IGCC power plant will be available until approximately 2040. The potential usage of other fuels for this power plant after 2040 is being discussed.

Other uses of FBC

The research of combustion products as regards the mix of coal/biomass/waste is in the Czech Republic performed not only in a laboratory condition, but also in commercial conditions. Pilot plant models can provide basic parameters concerning the feasibility of mix fuels employment, and the chemical characteristics of solid as well as gaseous products from the point of view of major components.

There is a great interest here on alternative fuels and fuel mixtures.

Manufacturing

There is no company, which manufactured FBC.

A new large production group was created by Safichem, which took over the ISTROENERGO project and design office and intends to significantly expand the production portfolio in the classical energy sector

Fluid technology developed the INVET Servis CZ group, which derived a new type of fluidized bed boiler - 30 t/h, 100 t/h and 200 t/h with parameters up to 13 MPa, 535 °C, 215 °C.

The boiler 30 t/h were successfully implemented on brown and black coal in the Sezimovo Ústí heat plant, a boiler of 100 t/h for North Bohemian lignite at the ACTERM heating plant in Chomutov.

Boiler 200 t/h 13 MPa, 535 °C, 215 °C was offered in the version for the retrofit of K 700 in the UNIPETROL a.s. In Litvínov, which still uses powder boilers from the former PBS Brno boiler plant.

Research and development

The Czech research and development (R&D) system is centralised, with a nearly equal balance between public and private funding. Foreign companies play a dominant role in private R&D investment. Their share in total private R&D investment is one of the highest in the European Union (EU). Public R&D is carried out by institutions of higher education and the Czech Academy of Sciences.

Research, development and innovation (RDI) policy is implemented under the auspices of the Czech Parliament. The conceptual and strategic management of the policy is under the competency of the Prime Minister. The operational management is entrusted to the Research, Development and Innovation Council. Public funding is an integral part of the state budget, administered by the Ministry of Finance. The Council provides funds for research conducted at universities. The Ministry of Education, Youth and Sports (MEYS) is responsible for international R&D co-operation. MEYS and the Academy of Sciences represent the largest providers. The former provides funds for universities and is also responsible for international co-operation R&D. Energy research: focusing on reliability of energy distribution networks, including the integration of distributed energy sources and system security. At the same time, research will focus on new elements of network infrastructure for the supply of hydrogen or synthesis gas for the production of second-generation biofuels.

The priority areas of energy technology RDI are set out in the National Priorities of Oriented Research, Experimental Development and Innovations (NPOREDI) document, which was approved by the Czech government in July 2012. This document builds on the goals and activities of the NRDIP.

Now is a new Czech Technological Agency, which provide support of various project, incl. FBC/CFBC technologies, fuel quality, minimising of emissions, etc.

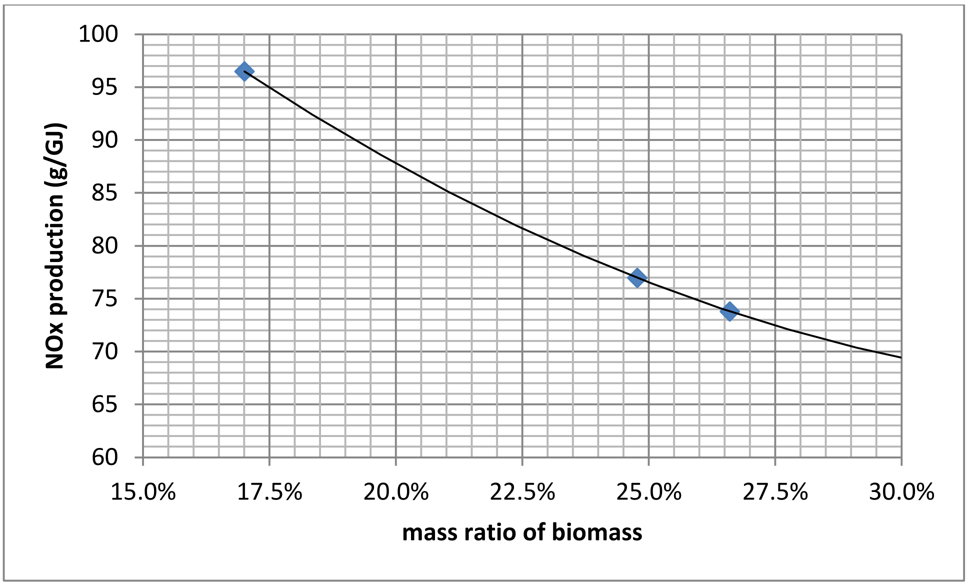
The main goals in the Czech Republic are similar like in the past period:

- Suitability of fluidised bed combustion at increasing the ratio of non-fossil fuel component in the mixture,
- Non-uniformity of combustion in the large space of fluidised bed combustor as influencing the composition of flue gases and specification in terms of minor constituents (NO_x, chlorine compounds, alkalis, etc.),
- Analogically the influence of the size or for that matter the influence of fuel granulometric distribution on the process,
- Chemical composition, crystallographic structures, and mechanical properties of combustion solid products (ash, fly ash, deposits),
- Long-term deposit formation on thermal exchanger’s walls,
- Analytical establishment of sulphur forms in fuel and combustion solid products, as well as element analysis for fuel and biomass,
- Detailed study for mineralogical and chemical composition of LP, UP, and the solid emission phase,
- Balance for volatile elements, Cl, S, Hg, Se, semi-volatile elements, V, Ni, Co, As, and some non-volatile elements, Cr a Sn. Based on these balances to calculate the content of these elements in emissions and compare these with the results of balance measurements,
- To use solid specimens sampled at various combustor levels for verifying condensation-evaporation model,
- Insufficient combustion as regards elements not found in the non-burnt share of fuel and biomass and waste,
- To perform leaching tests for combustion solid products, as regards combustion of individual fuel mix.

Active collaborations were carried out between TU Ostrava and several institutions including: the University of Toronto, the Technical University of Vienna, Southern Illinois University at Carbondale, the Technical University of Dresden, RWTH Aachen and a lot of real unit provider.

This work has led to a series of journal and conference publications.

Example - EVT 140 t/h fluid boilers with steam parameters 535 °C/12.5 MPa in Energo Škody Mladá Boleslav successfully tested co-combustion of biomass to 30% of heat input with a significant reduction of NOx production.



The FBC 88 MW, 9 MPa, 530 °C Otrokovice boiler has achieved a reduction of SO_2 emissions to 200 mg/m^3 with a controlled increased limestone load on Ca/S - 3,3

Conclusion

The complex of projects reflects the social need, as the gradual process of legislative unification before the admission of the Czech Republic into EU asks for the increase of the share of renewable energy resources in the overall energy balance of the country.

In the case of utilization of combined combustion of coal/biomass/waste, one may evaluate positively the fact that the existing facilities may be utilized with minimum costs for the reconstruction of boiler plants (stores, fuel conveyance) and at the same time emissions released into the air can be reduced (primarily sulphur and nitrogen oxides). Moreover, especially in the case that the waste fuel is of concern, the operation of equipment will be cheaper.

Financial savings with respect to the combustion of fossil fuels, mainly of coal, have made operators to use combined combustion processes for many years. In connection with the improvement of the environment this possibility is discussed primarily in recent years. By controlling the combustion process one may maintain the output of combustion equipment (up to portion of biomass max. 30 %), but at the same time we can significantly mitigate emissions of pollutants into the air.

Recently, the attention has been paid to cogeneration units not only from the side of experts, but also from the wide public. In its concept, a new technology of fluidized bed gasification in connection with cogeneration units with combustion engines for the utilization of biomass has been technically worked out for commercial utilization as well as. In the case of gasification of biomass there occur numerous problems concerning the disposal, and/or minimizing by-products, primarily tar vapours. The solution of technical details in connections with this issue will enable a faster application of cogeneration systems.

These units may be utilized in the areas and at the plants which are capable of providing the permanent utilization of not only generated electric energy (which in the majority cases is no problem), but mainly the produced heat energy. Under the conditions of market economy, but chiefly under a monopoly position of electricity distribution organizations, the sale of electric energy into distribution network would not be advantageous from the economic point of view.

Each material (raw material), which finished its service life, must be removed in an appropriate manner. Often, just burning or gasification of the waste is a very suitable way, however, it may be recommended only after all the other methods have been utilized, since the objective is the maximum avoidance of the origin of waste (the prolonged service life of materials), and/or recycling or minimizing the origin of this waste.

In the Czech Republic research on fluidized bed combustion and gasification is carried out mainly at the Technical University Ostrava and Prague University of Technology:

1. Energy Department, TU Ostrava, 17. listopadu 15, CZ - 708 33 Ostrava
2. Energy Department, ČVUT Praha, Technická 4, CZ – 160 00 Praha 6

Responsible persons (official delegates Czech Republic for IA IEA FBC):

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FINLAND

Prepared by Patrik Yrjas, Mikko Hupa and Maria Zevenhoven

Overview

Fluidized bed conversion continues to play an important role in the Finnish energy economy. Most of the boilers in Finland are bubbling beds, but some large ones are circulating fluidized bed boilers. The boilers burn a great variety of fuels and the role of biomass and waste derived fuels is remarkable. The largest boiler is still the Alholmen Kraft CFBC with a thermal power of 550 MW. The main fuels burned here are mixtures of coal, peat and bark.

Research in the FB technology continues to be active in Finland, and a number of research projects have been underway during the last years, for example FUSEC, 2011-2014 (Future Fuels for Sustainable Energy Conversion), CLIFF, 2014-2017 (Clustering Innovation Competence of Future Fuels in Power Production), ARVI/CLIC (2014-2016), EU-OnCord (2014-2017).

Also every year a “Flame day” (Liekkipäivä) seminar is arranged in Finland where most of the researchers meet to present their work on energy issues. Last time it was arranged in Lahti on February 4, 2016.

Furthermore, the 22nd International Conference on Fluidized Bed Conversion was arranged in Turku, Finland in June 2015, as was also the 70th IEA-FBC meeting.

Research centers

Aalto University (before Helsinki University of Technology)
Tampere University of Technology
Oulu University
Lappenranta University of Technology
Åbo Akademi University
University of Eastern Finland
VTT

Largest companies in Finland building FB boilers

Amec Foster Wheeler Energia Oy
Valmet Technologies Oy
Andritz Oy

Table 1. Fluidized bed boilers constructed in Finland since 2005.

Year	Place	Steam capacity, MWth	Steam pressure, bar	Steam temperature, °C	Fuels	Type
2017	Naantali	390	164	555	Forest residue, bark, sawdust paper fine reject	CFB
2016	Nokia	68	86	485	Forest residue, wood chips, peat sludge	BFB

2015	Lohja	88	81	520	Bark, forest residue, sludge, coal	CFB
2013	Järvenpää	69	117	527	Biomass, recycled wood, peat	BFB
2011	Kuopio	149	130	535	Peat, wood, coal	
2010	Keuruu	19	61	500	Biomass	BFB
2010	Jyväskylä	455	164	560	Biomass, forest residue	CFB
2010	Kaukas	385	115	550	Peat	CFB
2009	Hämeenlinna	52	27	400	Peat, biomass, coal, natural gas	BFB
2009	Joensuu	30	na	na	Biomass	BFB
2009	Kerava	73	77	480	Peat, forest residue	BFB
2008	Pori	177	84	522	Wood, peat, recycled fuel, coal	CFB
2007	Lapua	17	61	480	Peat, biomass	BFB
2007	Tornio	135	131	542	Peat (forest residue)	CFB
2006	Kemi	26	na	na	Biomass	BFB
2006	Juankoski	18	12	191	Peat, biomass	BFB
2006	Haapavesi	27	63	510	Peat, sludge	BFB
2006	Rauma	107	118	535	Bark, forest residue, peat, sludge, recycled fuel	BFB
2006	Lieksa	30	60	510	Peat	BFB
2005	Ilomantsi	19	45	460	Peat, wood chips	BFB

Also some **smaller companies** may be mentioned. For example Renewa Oy delivered many small BFBC's for different companies in Finland:

VS Lämpö Oy, 2015, 20 MWth, forest residue, waste wood and peat
Lappi Timber Group Oy, 2014, 12 MWth, bark, sawdust and peat
Nurmijärven Sähkö Oy, 2014, 10 MWth, forest residue
Suur-Savon Sähkö Oy, 2013, 18 MWth, forest residue, bark and peat
Ekokem Oy, 2013, 8 MWth, forest residue and waste
Loimaan Kaukolämpö Oy, 2013, 9 MWth, forest residue, sawdust and peat
Lohjan Biolämpö Oy, 2012, 26 MWth, forest residue and waste wood
Varissuon Lämpö Oy, 2011, 10 MWth, peat and forest residue
Orimattilan Lämpö Oy, 2010, 10 MWth, peat and forest residue
Vapo Oy, Vuokatti, 2009, 7 MWth, peat
Vapo Oy / Atria Oy, Nurmo, 2009, 13 MWth, peat
Saarijärven Kaukolämpö Oy, 2009, 4 MWth, peat and forest residue
Kokkolan Voima Oy, Kokkola, 2009, 15 MWth, peat and forest residue
Outokummun Energia Oy, 2008, 7 MWth, peat and forest residue
Nurmijärven Sähkö Oy, 2007, 11 MWth, peat and forest residue
Famifarm Oy, 2007, 3 MWth, peat
Suur-Savon Sähkö Oy, 2006 8 MWth, peat and forest residue
Kurikan Kaukolämpö Oy, 2005, 6 MWth, firing peat and forest residue
Ähtärin Lämpökeskus Oy, 2005, 4MWth, firing peat and forest residue
Fortum Lämpö Oy, Nakkila, 2005, 12 MWth Firing textile residues and forest residue
Loimaan Kaukolämpö Oy, 2005, 8 MWth, firing peat forest residue, sawdust

Koskisen Oy, 2005, 25 MWth, firing plywood residue

The publication activities have been extensive in combination with a relatively high number of doctoral theses involving FBC-technologies. These can be easily found by visiting sciencedirect.com and acs.org using the keyword: “Fluidised bed” and affiliation: “Finland”. Also the activities in the IEA-FBC can easily be found on: iea-fbc.org

GREECE

Prepared by Aris Nikolopoulos, CERTH/CPERI

The main activities on the FB technology, for the time period from 2011 to 2015 in Greece are described below:

Installation of RDF/SRF and biomass FB gasifiers

Helector S.A., a Greek Energy and Environmental applications company will build a 500kWel FB gasifier in Osnabrück, Germany. The unit will gasify 750 kg/h Refused Derived Fuel (RDF) / Solid Recovered Fuel (SRF).

The main goals of the company are to:

- Achieve at least 500 hours of operation in the Gasification plant (once being commercial, the Gasification plant will process/treat ≈ 3,500 tons/y of SRF-Stabilat or Stabilat/biomass mixtures).
- Achieve an overall energy efficiency (with regard to incoming Stabilat energy content integration into the MSW recycling plant to generate electricity and heat) of at least 50%
- Produce 3.5 GWhth/y of renewable electricity (assuming approx. 7,000 hours of operation annually).
- Produce 0,9 GWhth/y of process heat to partially cover the thermal needs of the existing Municipal Solid Waste (MSW) recycling plant in Osnabrück.
- Produce approx. 3,500 tons/year of High quality fuel, to be utilized in the industry. Moreover a bigger (2MWel) installation will be built by the same company in Imathia, Greece. The unit will gasify approximately 2.5 t/h of RDF/SRF and biomass under Fluidized Bed conditions. The company will undertake the detailed engineering of the units as well as construction, erection and commissioning.

WATT

W.A.T.T. S.A. is a company within the waste management industry, possessing management and executives that have admittedly demonstrated, technological achievements and impressive financial results over the last 15 years. They built a CFB gasifier for the gasification of Refused Derived Fuel (RDF). The circulating fluidized-bed reactor located at the premises of WATT is an atmospheric pressure, air-blown gasifier with a maximum thermal input of 105 kW_{th}. Its riser is a cylindrical tube made of stainless steel 316 L, with an inner diameter (ID) of 105 mm and a height of 6 m. The main air flow is introduced at the bottom of the riser via a perforated plate. One cylindrical silo is used for storage and the feeding rate through a screw feeder at its bottom. After this first screw feeder, there are two rotary valves in series. The screw feeders and the rotary valves are powered by electric motors. Char and bed material are separated from syngas by means a 170 mm ID cyclone and a height of 700 mm and return to the riser through a 95 mm ID downcomer tube. A nitrogen flow is used to assist recirculation and prevent char accumulation at the bottom of downcomer. In order to remove unburnt char and fly ash which are entrained by syngas after the first separation and at the end of heat exchanger, a second smaller cyclone (70 mm) is used. Prior syngas enters the second cyclone, it is cooled by passing through a heat exchanger type U. A slip-stream of product gas is continuously adsorbed, after the second separation and the cooling; it is driven to an analyzer. A ceramic filter prior to an impinger with isopropanol and a fiber filter prior to a silica gel column to capture moisture are used to purify syngas from any remaining by-products (particulates, tars, moisture).

Centre for Renewable Energy Sources and Saving (CRES)

The Centre for Renewable Energy Sources and Saving (CRES) is the Greek national entity for the promotion of renewable energy sources, rational use of energy and energy conservation. The Circulating Fluidized Bed Gasifier (CFBG), located at the premises of CRES, is a stainless steel 316L cylindrical tube with 78 mm internal diameter (ID) and 6.0 m in height. The gasifier is heated by cylindrical radiative electric resistances, which are placed along the bed height placed in electrically heated ovens consisting of cylindrical radiative electric resistances (KANTHAL-FIBROTHAL) that preheat and make up for heat loss from the bed. Fluidization air is also preheated and introduced to the bed through a distributor. The fuel mixture is fed well into the bed, at about 265 mm above the distributor. The feeding system consists of two hopper for the initial storage of the solid fuel and volumetric silos and its flow rate is adjusted by a dosimetric screw feeder. The second silo (near to gasifier) was modified because at preliminary gasification tests, it was observed that the temperature in feeding tube near the reactor was very high. The cooling jacket was necessary to avoid pyrolysis prior to the reactor in the part between silo and the reactor entrance. The air and nitrogen flows were regulated by mass flow controllers based on the thermal mass flow sensing technique. The flue gases were cleaned from particles by means of one cyclone which has an internal diameter 260mm and height 800mm. The unburned char and bed material return to the riser, through the downcomer with an internal diameter 30mm. The unit is used to test proper gasification conditions of various biomass types.

Research Activities (2011-2015)

CERTH/ISFTA and National Technical University of Athens are/have been involved in the following projects related to the Fluidized Bed technology:

Project Acronym: Cal- Mod (RFCS)

Full title: Modeling and experimental validation of Calcium Looping CO_2-capture process for near-zero CO_2 emission power plants

The CaL project research activity involves the development of advanced modeling and simulation tools required for implementing the Calcium Looping (CaL) process at commercial scale. Experimentation at particle level and at bench-scale systems have aided the development of sorbent models and CFD reactor models. Established reactor performance knowledge has led to realistic process and steam cycle models for the CaL process. The integration of a cement plant to the CaL process was also investigated. This integration was possible since CaO purge can be efficiently utilized for cement production. CERTH/ISFTA undertook the 3-D CFD modeling of the two coupled reactors (carbonator and calciner) with novel sub-grid EMMS schemes. Moreover, CERTH/ISFTA investigated, with steam cycle models, the proper integration of CaL process in power generation units and in cement industry.

Project Acronym: SCARLET (FP7)

Full title: Scale-up of Calcium Carbonate Looping Technology for Efficient CO_2 Capture from Power and Industrial Plants

One major goal of the proposed project is to perform long-term tests with different fuels in an upgraded 1 MW_{th} pilot plant, aiming mainly at optimization of operating conditions and operational reliability. The successful operation of the upgraded pilot will provide the important validation step between the 1 MW_{th} scale and a future 20 MW_{th} scale pilot plant. Process and CFD models will be developed and comprehensively validated against experimental data from 1 MW_{th} testing. These models will be applied to support the engineering for a 20 MW_{th} scale pilot plant. CERTH/CPERI is involved in the development and application of such 3-D CFD models, based mainly on the Eulerian approach, with main breakthrough the application of an advanced version of the sub-grid EMMS scheme. Finally, the project will provide a techno-economic as well as an environmental assessment of this high-potential technology for CO_2 capture from power plants as well cement and steel production plants, and provide the fundamental expertise needed for the scale-up and further technology development and integration.

Project Acronym: TE-RDF

Full title: Thermal exploitation of Refused Derived Fuel

The project addresses the energy exploitation of Refused Derived Fuel (RDF). Based on the characterization of Greek and Chinese RDF, its potential thermal exploitation in industrial sectors was investigated. MDI, Cement and power production were examined, based on specification of each sector and RDF characteristics. CFB gasification was investigated as a method of fuel upgrade. Within TE-RDF project, the experimental campaign for the Greek RDF was realized in WATTS's CFB gasifier. CERTH undertook the monitoring of the facility operation and the process simulation and optimization and the characterization of solid samples. Moreover, CERTH developed advanced 3D CFD tools by applying and comparing three different methodologies; the Eulerian-Eulerian approach, the Lagragian DEM method and finally the novel DDPM method. Finally, techno-economic and environmental assessment of RDF utilization was carried out.

Selected Publications (2011-2015) in International Journals

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HUNGARY

Prepared by Pal Szentannai, szentannai@energia.bme.hu

Commercial / Pilot / Experimental Fluidized Bed facilities in Hungary

The basic characteristics of the fluidized bed conversion utilities in Hungary are summarized in the next table, while their locations can be seen on the subsequent map. The dates of commissioning / refurbishment in the table show an intensive growth both in number and capacity in the period between 2011 and 2015. A special characteristic of the Hungarian situation is that a great deal of the FBC units contains dominant or at least significant amount of local knowledge and engineering manpower. A short introduction of the most important actors of this growths will be given in this section. (The Hungarian participation in the IEA-FBC working group started also within the reported period as Dr. Pal Szentannai signed the Implementing Agreement on 13th February, 2013 according to the designation by the Government of Hungary. It should be noted that this is the first time that Hungary, an IEA member country, has participated in an Implementing Agreement.)

Owner / Location	Year*	Type	Capacity	Fuels
MVM / Győr**	1984	BFBC	12 MW_{th}	brown coal
BAERT / Ajka	1993	HBFBC	4 x 88 MW_{th}	forest wood, coal, brown coal, wood chips, sawdust, bark, sunflower shell, straw
BME / Budapest	1996 / 2013	CFBC	80 kW_{th}	experimental facility for many traditional and challenging fuels like coal, biomass, and SRF
AES / Kazincbarcika**	2002	HBFBC	4 x 74 MW_{th}	forest wood, brown coal, sawdust, wood chips
Veolia / Pécs	2004	BFBC	140 MW_{th}	forest wood, biomass
MVM / Oroszlány**	2005	HBFBC	2 x 180 MW_{th}	brown coal, forest wood, biomass
Komlói Fűtőerőmű / Komló	2010	BFBC	18 MW_{th}	wood chips
Sinergy, GDHS / Tiszaújváros	2012	BFBC	500 kW_{th}	biomass, waste from agriculture and food industry
MVM / Göd	2015	BFBC	500 KW_{th}	alternative fuels
Tatabánya Erőmű / Tatabánya	2015	BFBC	2 x 37MW_{th} 18 MW_{th}	wood chips
Hamburger Hungária / Dunaújváros	2015	CFBC	172 MW_{th}	waste paper, wood chips, coal

* Year of commissioning / complete refurbishment (If more units, the first one. If a PC combustor was transformed into a FBC, that date.)

** Not in operation

BFBC bubbling fluidized bed combustor

CFBC circulating fluidized bed combustor

HBFBC hybrid bubbling fluidized bed combustor

The most important companies and research institutions being active on the topics Fluidized Bed Conversion in Hungary are the followings.

VEIKI (Institute for Electric Power Research)

This research institute developed, patented and took into operation a special construction called *Hybrid Fluid* (HBFBC) combustor. This solution was developed especially for retrofitting and upgrading existing pulverized-coal fired boilers into bubbling fluidized bed combustors. The bottoms of such boilers were completely reconstructed to bubbling fluidized bed combustors, while the upper parts with the burners were kept unchanged. The air distributor was divided into three bands so that a reinforced internal recirculation could be realized. This company exists no more in praxis.

GDHS (Ganz Danubius Hungarosteel Ltd.)

The company was founded in 1991. Its main field is manufacturing, installing and repairing parts and components for power plant boilers. GDHS built, commissioned and operates the BFBC unit in Tiszaújváros together with the company Sinergy. The basic knowledge accumulated in VEIKI was utilized by GDHS throughout the design and commissioning of this unit.

OVIT (MVM OVIT National Power Line Company Ltd.)

A special department within this company achieved excellent results in the design, manufacturing, and commissioning of small to mid-sized Fluidized Bed Combustors for utility operation in the last five years. The VEIKI knowledge basis was also utilized in the projects for Komló, Göd, and Tatabánya, thus, altogether five FBCs were put into operation in the reporting period.

Hamburger Hungaria Power Plant

Hamburger Hungária is a leading containerboard manufacturer in Europe. The two paper machines located in Dunaújváros produce annually about 650.000 tons of brown containerboard which accounts for 85% of all paper grades produced in Hungary. The new co-generation power plant, with a value of approximately EUR 150 mill., uses solid fuels, including the paper mill’s own residual waste from paper production, but also biomass and coal. The new plant generates both heat and electricity, thus ensuring the plant's energy self-sufficiency and the recovery of wastepaper that was earlier deposited at landfill sites in the vicinity. Hamburger Hungaria Power Plant and its highly qualified experts played active and significant roles in the procedures of setting up and commissioning of this new plant.

VALMET

The well-known international company was the supplier of the complete boiler to Hamburger Hungaria Power in Dunaujvaros. Valmet's net sales in 2015 were approximately EUR 2.9 billion, and Valmet's head office is in Espoo, Finland. The new power plant enables Hamburger Hungaria Power to use a wide range of solid fuels, biomass, coal as well as containerboard rejects and sludge in energy production instead of natural gas. The power plant has a capacity of 172 MW in used fuels, 158 MW in generated heat and 42 MW in generated electricity. Valmet's delivery included a complete boiler plant including a CYMIC boiler based on circulating fluidized bed (CFB) technology and flue gas cleaning to ensure low emissions.

BME (Budapest University of Technology and Economics)

Research and development activities on the applicabilities of renewable and challenging fuels, together with numerous further theoretical and practical issues of the topic FBC are carried out on the Department of Energy Engineering, Faculty of Mechanical Engineering of the Budapest University of Technology and Economics (BME). This institution set up and operates a 5 m high, 80 kW_{th} mid-scale experimental FBC facility, which was completely refurbished in 2013. This university department focuses also on the applications of advanced control techniques in order to assure more reliable and flexible operation of industrial FBC units resulting smoother operation and direct financial benefit.
http://fbc.energia.bme.hu/

Some publications

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ITALY

Prepared by Fabrizio SCALA (scala@irc.cnr.it, fabrizio.scala@unina.it)

COMMERCIAL FLUIDIZED BED FACILITIES IN ITALY (> 1 MWe)

The table below contains the most important features of the commercial fluidized bed combustors currently in operation in Italy. Most of the facilities have started operation between the end of the '90s and 2005. All the combustors fire either biomass or RDF, with the exception of the Sulcis plant owned by the Italian Electricity Company ENEL, which is the only one firing coal.

In the last five years (2011-15) only two new commercial fludized bed combustors have started up in Italy. In 2013 a biomass-fired bubbling fludized bed combustor (using a boiler design by EPI – now Outotec) with 18.7 MWe capacity was put in operation in Enna (Sicily) by IG Operation and Maintenance S.p.A. In 2015 a RDF-fired bubbling fludized bed combustor (using a boiler design by Ansaldo) with 14 MWe capacity was put in operation in Manfredonia (Puglia) by Energie Tecnologie Ambiente (Marcegaglia Energy Group). Some other projects of commercial fluidized bed combustors are currently under evaluation, but their real construction is still uncertain because of the opposition by local people and environmental organizations.

Up to now no commercial-scale fluidized bed gasification facility has been put in operation in Italy.

Owner/ Location	Start-up	Type (supplier)	Capacity	Fuel
AGSM Verona	1992	BFBC (Thyssen)	21.8 MWe	RDF
Tossilo Macomer	1994	***FICFBC*** (Ebara)	2 MWe	***RDF***
Veolia Pietrasanta	1999	BFBC (Kvaerner)	5.7 MWe	***RDF***
HERA Ravenna	1999	***BFBC*** (EPI)	6.5 MWe	***RDF***
Cartiere Burgo Mantova	1999	BFBC (EPI)	3.2 MWe	Paper sludge
Scarlino Energia Scarlino	1999	BFBC (Ex-Dorr Oliver)	19.5 MWe	RDF
Sicet Ospitale di Cadore	1999	FICFBC (AE Energietechnik)	20 MWe	Wood, Bark
Lomellina Energia Parona 1	2000	CFBC (Foster Wheeler)	15 MWe	RDF
Cartiere Burgo Verzuolo	2001	BFBC (EPI)	7 MWe	Paper sludge, wood waste
A2A Bergamo	2002	BFBC (EPI)	11.5 MWe	RDF
Marcegaglia Cutro	2002	BFBC (Fortum)	14 MWe	Wood chips
Marcegaglia Massafra	2003	BFBC (EPI)	12.3 MWe	RDF

Biomasse Italia Strongoli	2003	CFBC (SES Tlmače)	40 MWe	Biomass
A2A Corteolona	2003	BFBC (Kvaerner)	8.7 MWe	RDF
ENEL Produzione Sulcis	2005	CFBC (Alstom)	340 MWe	Coal, biomass
Ecologia Oggi Gioia Tauro	2005	BFBC (Kvaerner)	17.2 MWe	RDF
Lomellina Energia Parona 2	2007	CFBC (Foster Wheeler)	17 MWe	RDF
IG Enna	2013	BFBC (EPI)	18.7 MWe	Eucalyptus Wood Waste
Marcegaglia Manfredonia	2015	BFBC (Ansaldo)	14 MWe	RDF

BFBC bubbling fluidized bed combustor CFBC circulating fluidized bed combustor
FICFBC fast internally circulating fluidized bed combustor

RESEARCH CENTERS IN ITALY ON FBC/FBG

The table below reports the most important research centers in Italy where fluidized bed combustion and/or gasification are studied. Both theoretical/modeling and experimental activities are carried out. The experimental studies are performed both on the lab-scale (fundamental research) and on the pilot-scale (applied research).

INSTITUTION OR COMPANY	OWNER	MAIN ACTIVITY	WEB SITE	TYPE OF INTEREST IN FBC
CNR - Istituto di Ricerche sulla Combustione	Ministry of Education, University and Research	Research institute	www.irc.cnr.it	- Fundamental and applied research in fluidized bed combustion, gasification and pyrolysis
Università Federico II di Napoli - Dipartimento di Ingegneria Chimica, dei materiali e della Produzione Industriale	Ministry of Education, University and Research	Public University	www.dicmapi.unina.it	- Fundamental and applied research in fluidized bed combustion, gasification and pyrolysis - Fundamental research on SO_2 and CO_2 sorbent particle behavior
Seconda Università di Napoli - Dipartimento di Scienze e Tecnologie Ambientali Biologiche e Farmaceutiche	Ministry of Education, University and Research	Public University	www.distabif.unina2.it	- Fundamental and applied research in fluidized bed combustion, gasification and pyrolysis of wastes and biomasses - Fluidized bed processing of plastics for recycle
Università dell'Aquila - Dipartimento di Ingegneria Industriale e dell'Informazione e di Economia	Ministry of Education, University and Research	Public University	www.univaq.it/section.php?id=220	- Fundamental research on fluid dynamics and fluidized bed gasification

Università di Salerno - Dipartimento di Ingegneria Industriale	Ministry of Education, University and Research	Public University	http://www.diin.unisa.it/diin_en/index_en	- Fundamental research on fluidized bed torrefaction , pyrolysis and gasification of agri-food residues
Università di Teramo - Facoltà di Bioscienze e Tecnologie Agro-Alimentari e Ambientali	Ministry of Education, University and Research	Public University	www.unite.it/UniTE/Engine/RAServePG.php/P/25671UTE0451	- Fundamental and applied research on fluidized bed gasification of biomass
ENEA - Trisaia Research Center	Ministry of Economic Development	Research institute	www.trisaia.enea.it	- Applied research on fluidized bed gasification of biomass
ENEA – Casaccia Research Center	Ministry of Economic Development	Research institute	www.enea.it/it/centro-ricerche-casaccia	- Applied research on fluidized bed gasification of coal with CO_2 capture

MOST IMPORTANT ITALIAN PUBLICATIONS ON FBC/FBG (2011-2015)

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JAPAN

Prepared by Tadaaki Shimizu, tshimizu@eng.niigata-u.ac.jp

Summary

In the past 5 years (2011 - 2015), biomass combustion or co-combustion of biomass with other fuels such as coal in FBCs became popular in Japan and many new relatively small-scale FBCs have been built. Also construction cases of FBCs overseas by Japanese companies were found. A large scale pressurized BFBC and a large scale atmospheric BFBC are in operation. Incineration of municipal waste and sewage sludge is of great concern and various types of incinerators were constructed. Some R&D projects for utilization of low-grade coal and biomass subsidized by NEDO are introduced.

Large Scale Pressurized Fluidized Bed Combustors and Atmospheric Bubbling Fluidized Bed Combustor for Electric Power Companies

Karita 360 MWe bubbling PFBC owned by Kyushu Electric Power Co., Inc. is the largest PFBC in the world and the first FBC that employed supercritical steam condition. In 2014, there was a presentation of the state-of-art of PFBC operation[1)]. From the start of commercial operation in August 1999 to June 2014, the total operation time was 60021 hours with start-up of 155 times. They have burned about 5.3 million tons of coal, with limestone consumption of 0.5 million tons. The typical emissions were NOx: 47 ppm, SOx: 5 ppm, and dust: 1 mg/m^{3}N. The accumulated power output was 14340 GWh. Calculating from the above data, the averaged availability was about 46% and the averaged power output during operation was 240 MWe. They pointed out that challenges with PFBC operation are maintenance of boiler and erosion control of boiler tubes. The compact design of boiler, i.e., high density of boiler tubes, makes diagnosis of tubes difficult. Though direct contact of fluidized particles to boiler tube surface is favourable for heat transfer, attention should be paid to prevent tube erosion problems and countermeasure such as installation of protectors is required. Also fuel flexibility is a challenge for PFBCs because ash fusion and successive ash agglomeration may occur in the bed due to high partial pressure of oxygen. As a measure for early detection of ash agglomeration, they observe “apparent bed density” (=pressure drop of bed/bed height); with the increase in bed material size, the apparent bed density tends to decease. Also they withdraw bed material samples to measure the size distribution. Before they use a new fuel in PFBC, they need fuel evaluation under elevated pressure conditions but it takes time.

Osaki 250 MWe PFBC owned by The Chugoku Electric Power Co., Inc. stopped operation in December 2011[2)]. According to a report, the plant availability was low (43.6 % in FY2009) due to erosion/damage of boiler tubes (please see the previous country report (year 2011) for detail).

Takehara 350 MWe bubbling AFBC owned by J-Power has been working since its start of commercial operation in 1995. It will be replaced by USC coal-fired power plant in 2020[3)].

Recent Construction of Fluidized Bed Combustors

Table 1 summarizes fluidized bed combustors for electricity generation / industrial use completed in 2011 – 2015 and under construction (data source: press releases of manufacturers/plant owners, and courtesy of manufacturers). A trend in these five years is the increase in the number of biomass-fired FBC plants. This is attributable to the start of feed-in-tariff (FIT) program. Japan's feed-in-tariff program started in July 2012. The objective of the feed-in-tariff program is to accelerate investments in renewable energy by providing predictability regarding the recovery of investments. In addition to the construction in Japan, some manufacturers have been constructing FBCs in foreign countries / regions (Taiwan, Singapore, Korea, and Indonesia).

Table 1 Fluidized bed combustors for electricity generation / industrial use completed in 2011 – 2015 and under construction

Year of completion	Location (Pref.: Prefecture in Japan; underlined: foreign country/region)	Type of FBC	Fuel (Number: share of each component)	Electricity / steam rate / pressure/ temperature	Manufacturer / Remarks
2011	Kawasaki Biomass Power, Kanagawa Pref.	CFBC	Biomass (wood chip) 100	33MW(G) 137t/h 10MPa 513 ºC	Sumitomo Heavy Industries, Ltd.
2011	Agatsuma Bio Power, Gunma Pref.	ICFB (Internally circulating Fluidized-bed) Type BFB	Biomass	13.6MW (G) 11.6MW(net) 64 t/h 5.9 MPa 465 ºC	Ebara Corporation
2012	Asahai Kasei Nobeoka, Miyazaki Pref.	CFBC	Biomass (demolition wood) 60 +coal 30 +RPF 10	14 MW(G) 80 t/h 6.18 MPa 493ºC	Sumitomo Heavy Industries, Ltd.
2012	Green Thermal, Aizu, Fukushima Pref.	CFBC	Biomass100	5.7MW(G) 25t/h 5.4 MPa 453ºC	Sumitomo Heavy Industries, Ltd./ Small-scale CFBC (Modular CFB)
2012	Nippon Ghosei, Kumamoto Pref.	CFBC	Biomass(Wood) 60 + coal40	5.5MW 28 t/h 5.4 MPa 453ºC	Sumitomo Heavy Industries, Ltd./ Small-scale CFBC (Modular CFB)
2012	<u>Holi, Taiwan</u>	CFBC	coal82+TDF16+ Sludge 2	34MW 130 t/h 12.4MPa 541ºC	Sumitomo Heavy Industries, Ltd.
2012	<u>Tuas Power Ltd Singapore</u>	CFBC	Biomass (PKS*) 20+ Low-grade coal80	70 MW 450 t/h 10.5 MPa 510ºC	Sumitomo Heavy Industries, Ltd.
2012	Sizuoka Pref.	BFBC	Biomass	23.5t/h (No electricity)	TAKUMA Co., Ltd.
2012	Okayama Pref.	BFBC	Biomass	28.0 t/h (No electricity)	TAKUMA Co., Ltd.
2013	Miyazaki Pref.	BFBC	Biomass (Animal dung)	1.5MW 35t/h	TAKUMA Co., Ltd.
2013	<u>Tuas Power Ltd IIA Singapore</u>	CFBC	Biomass (PKS) 20+ Low-grade coal80	70 MW 450 t/h 10.5 MPa 510ºC	Sumitomo Heavy Industries, Ltd.
2013	Green Power Generation Oita, Oita Pref.	CFBC	Biomass	5.7MW(G) 25 t/h 5.4 MPa 453ºC	Sumitomo Heavy Industries, Ltd./ Small-scale CFBC (Modular CFB)

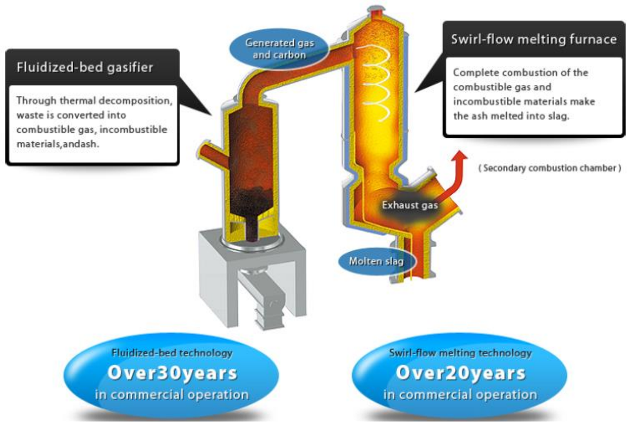
2013	eREX New Energy Tosa, Kouchi Pref.	CFBC	PKS, coal	20MW 105 t/h 10.2 MPa 541 ºC	JFE Engineering Corp. First designed as coal-fired CFBC but later modified to biomass-firing CFBC.
2014	Mie Enewood, Mie Pref.	BFBC	Woody Biomass	5.8MW 28t/h	TAKUMA Co., Ltd.
2014	Iwate Pref.	BFBC	Biomass	5.8MW 28t/h	TAKUMA Co., Ltd.
2014	Gifu Pref.	BFBC	Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2014	Shiga Pref.	BFBC	Recycled woody Biomass	3.55MW 22.6t/h	TAKUMA Co., Ltd.
2015	Matsue Biomass Hatsuden, Shimane Pref.	BFBC	Woody Biomass	6.25 MW 28t/h	TAKUMA Co., Ltd.
2015	Clean power Yamagata, Yamagata Pref.	TIF (Twin Interchanging Fluidized-bed) Type BFB	Industrial wastes, sludge, waste oil	700 kW(G) 11.8t/h 1.7 MPa 207 ºC	Ebara Corporation
2015	Hitachi Zosen Corporation, Ibaragi Pref.	BFB	Woody Biomass	5.8MW(G) 26 t/h	Hitachi Zosen Corporation
2015	Kumho Petro Chemical, Korea	CFBC	Coal (+Waste tire)	62 MW x2 400 t/h x2 12.6MPa 541ºC	Sumitomo Heavy Industries, Ltd.
2015	Chugokumokuzai, Miyazaki Pref.	CFBC	Woody Biomass	13t/h (No electricity)	TAKUMA Co., Ltd.
2015	Tsugaru Biomass Energy, Aomori Pref.	BFBC	Woody Biomass	6.25 MW 28t/h	TAKUMA Co., Ltd.
2015	ENE-VISON, Shimane Forest Generation, Shimane Pref.	CFBC	Biomass + PKS	12.7MW 53 t/h 6.3 MPa 483ºC	JFE Engineering Corp.
2015	Showa Shell Sekiyu K.K., Kanagawa Pref.	CFBC	Woody biomass, PKS	49MW 190t/h 10.3MPa 541 ºC	JFE Engineering Corp.
2015	Green Biomass Factory, Miyazak Pref.	CFBC	Biomass	5.75 MW (G) 25 t/h 5.4 MPa 453 ºC	Sumitomo Heavy Industries, Ltd./ Small-scale CFBC (Modular CFB)
2015	Ojimateria Co., Ltd., Shizuoka Pref.	CFBC	Biomass20 + coal40 + RPF40	57MW 230t/h 8.83 MPa 485ºC	Sumitomo Heavy Industries, Ltd.
2015	PT Antam (Persero) Tbk, Pomalaa, Indonesia	CFBC	Coal	30MW x2 125t/h x2 9.8 MPa 541ºC	Sumitomo Heavy Industries, Ltd.
2015	Nihonkaisui Co., Ltd., Hyougo Pref.	CFBC	Biomass100	18.5 MW (G) 77 t/h 10 MPa 513 ºC	Sumitomo Heavy Industries, Ltd.
2015	Oji Green Energy Nichinan, Miyazaki Pref.	CFBC	Biomass80 + coal20	25MW 100t/h 10.3MPa 541ºC	Sumitomo Heavy Industries, Ltd.

2015	Kouchi Pref.	BFBC	Woody Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2016 (under construction)	eREX New Energy Saeki, Ooita Pref.	CFBC	PKS, coal	50 MW 200t/h 10.2 MPa 513ºC	JFE Engineering Corp.
2016 (under construction)	Jeonju, Korea	Internal circulating BFB	Woody Biomass + RPF (Refuse paper & plastic fuel)	131 t/h	Kawasaki Heavy Industries/ Equipped with in-bed heat transfer tubes
2016 (under construction)	Green Energy Tsu, Mie Pref.	CFBC	Woody Biomass + PKS	20MW 85t/h 6.3 MPa 483ºC	JFE Engineering Corp.
2016 (under construction)	Summit Handa Power Corp., Aichi Pref.	CFBC	Biomass	75 MW,	Sumitomo Heavy Industries, Ltd.
2016 (under construction)	Fukui Green Power Co., Ltd., Fukui Pref.	BFB gasifier with combustion in freeboard	Woody biomass	7MW(G)	Kobelco Eco-Solutions Co., Ltd.
2016 (under construction)	Iwate Pref.	BFBC	Woody Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2016 (under construction)	Iwate Pref.	BFBC	Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2017 (under construction)	Daejeon, Korea	Internal circulating BFB	Wastes	50 t/h	Kawasaki Heavy Industries/ Equipped with in-bed heat transfer tubes
2017 (under construction)	Sigma Power Ariake, Fukuoka Pref.	CFBC	PKS, coal	185t/h 10.2 MPa 541 ºC	JFE Engineering Corp.
2017 (under construction)	Hokkaidou Pref.	BFBC	Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2017 (under construction)	Niigata Pref.	BFBC	Woody Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2017 (under construction)	Yamagata Pref.	BFBC	Woody Biomass	6.25MW 28t/h	TAKUMA Co., Ltd.
2018 (under construction)	Summit Sakata Power Corp., Yamagata Pref.	CFBC	Biomass	50 MW	Sumitomo Heavy Industries, Ltd.
2018 (under construction)	Tanjung Power Indonesia	CFBC	Low-grade coal	400 t/h x 2	Sumitomo Heavy Industries, Ltd.
2018 (under construction)	Hachinohe Biomass, Aomori Pref.	CFBC	Woody Biomass + PKS	12.4MW 55t/h 6.3 MPa 483ºC	JFE Engineering Corp.

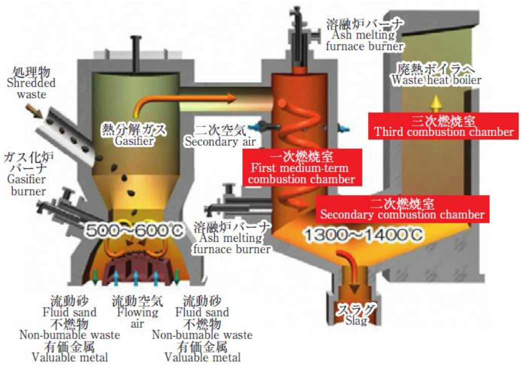
* PKS: Palm Kernel Shell

Trend in Fluidized Bed Municipal Waste Incineration

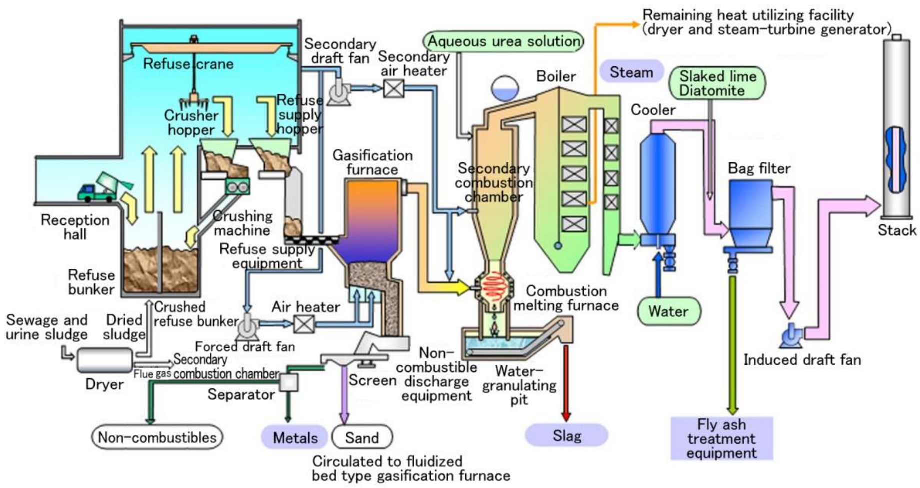
Previously, simple waste incineration using fluidized bed was considered to be not favourable to suppress the formation of dioxins and to minimize the landfill of fly ash. Thus fluidized bed waste gasifiers equipped with ash melter in the downstream were developed because ash melter can destroy dioxins (their precursors) at high temperatures and the volume of melted ash is much smaller than the original ash. The vitrified ash is favourable to extend the lifetime of landfill sites. Also the vitrified ash can be used as construction material if it meets the standard. Different types of fluidized bed gasifier – ash melter systems have been developed and constructed. Fig. 1 shows some examples of fluidized bed gasifier – ash melter systems with different combination of fluidized bed type and high-temperature gas combustor for ash melting. After experience of commercial operation for two decades, fluidized bed gasifier – ash melter systems achieve stable operation, for example, continuous operation for 226 days [4]. Thus these systems are regarded as mature technology and widely employed for municipal waste incineration as listed in Table 2.



(a) Combination of bubbling fluidized bed gasifier and ash melter with downward gas swirl flow (courtesy of KOBELCO ECO-SOLUTIONS Co., Ltd.)



(b) Combination of internally circulating fluidized bed gasifier and ash melter with downward gas swirl flow [5]



(c) Combination of bubbling fluidized bed gasifier and ash melter with upward gas swirl flow [6]

Fig.1 Some examples of gasifier-ash melter systems

Table 2 Recent fluidized bed municipal waste incineration plants completed in 2011 – 2015 and under construction

Year of completion	**Conversion type**	**Fluidized bed type**	**Fuel**	**Feed rate**	**Energy output /steam condition**	**Manufacturer**	**Owner or location (underlined : foreign country)**	**Remarks**
2012	Waste gasifier with ash melter	BFB	municipal waste	160t/d	2850 kW /4.0MPa, 400 °C	Mitsubishi Heavy Industries Environmental & Chemical Engineering	Sanjyo, Niigata Pref.	
2012	RDF incinerator	TIF (Twin Interchanging Fluidized-bed) type BF [7)]	RDF	Approx. 1900t/d[8)]	70 MWe[8)]	Ebara Corporation	<u>Frankfurt, Germany</u>	
2013	Waste incinerator	TIF (Twin Interchanging Fluidized-bed) type BFB	municipal waste and sludge	315 t/d	5900 kW (G)	Ebara Corporation	Hiratsuka, Kanagawa Pref.	Ash is vitrified in external facilities
2014	Waste gasifier with ash melter	BFB	municipal waste	143 t/d	1970 kW	Kobelco Eco-Solutions Co., Ltd.	Haga, Maoka, Tochigi Pref.	
2014	Waste gasifier with ash melter	BFB	municipal waste	117t/d	1900 kW	Kobelco Eco-Solutions Co., Ltd.	Nishi-Akikawa, Akiruno, Tokyo	
2014	Waste gasifier with ash melter	BFB	municipal waste	52 t/d	750kW	Hitachi Zosen Corporation	<u>Namyangju, Gyeonggi, Korea</u>	Design, construction, and support of test runs
2015	Waste gasifier with ash melter	BFB	municipal waste	300 t/d	7 650kW /4.0MPa, 400 °C	Mitsubishi Heavy Industries Environmental & Chemical Engineering	Aomori, Aomori Pref.	
2017 (under construction)	Waste gasifier with ash melter	BFB	municipal waste	150 t/d	3100kW /4.0MPa, 400 °C	Mitsubishi Heavy Industries Environmental & Chemical Engineering	Yamagata, Yamagata Pref.	
2017 (under construction)	Waste gasifier with ash melter	BFB	municipal waste	369 t/d	7700 kW, Generation efficiency =22.5%	Kobelco Eco-Solutions Co., Ltd.	Koufu-Kyoutou, Fuefuki, Yamanashi Pref.	
2017 (under construction)	Waste gasifier with ash melter	BFB	municipal waste	200t/d	3200 kW, Generation efficiency =18.7%	Kobelco Eco-Solutions Co., Ltd.	Sen-nan, Miyagi Pref.	

However, the government's policy of ash melting has been changed as:

1997: Ash vitrification (ash melter) is required for each newly built waste incinerator [9].

2003: Ash vitrification (ash melter) is not necessary for exceptional cases under specified conditions such as reuse of ash as raw material for cement and construction, sufficient remaining capacity of ash disposal site (15 years or longer), and isolated islands.

2005: Ash vitrification (ash melter) is not necessary to obtain subsidy from the government to construct waste incineration plant[10].

2010: Existing ash melters that were built with subsidy from the government between FY1997 and FY2004 are allowed to stop operation and can be disposed[11]. The reasons of this change are improvement of combustion technologies to suppress formation of dioxins, reduced amount of waste by recycling, and necessity of CO_2 emissions reduction by reducing additional energy for ash melting.

After the change in the government's policy, fluidized bed incinerator becomes one of the choices for waste incineration again. As shown in Table 2, City of Hiratsuka employed fluidized bed incinerator, though they send the produced ash to external ash-vitrification facilities (melting ash in reducing atmosphere) to reuse the ash as resource.

In spite of the change in government's policy, gasifier-ash melter systems are still attractive because of reduced ash volume. Local governments that have only limited landfill spaces need systems with ash melter to reduce ash volume. An additional approach to extend the lifetime of the landfill site is melting the landfilled combustible wastes. A waste gasifier with ash melter in Nishi-Akikawa, Tokyo, is designed to burn mixture of municipal waste and landfilled wastes [12]. The landfilled waste consists of ash from stoker incinerator that contains 8.5% combustibles, 64.3% ash, and 27.3% water, with LHV of 3040 kJ/kg. They expect that the end of landfill to be delayed from year 2017 to year 2043 by reducing the volume of landfilled ash by treating in the ash-melter. Though ash-melters sometimes need additional fuel (usually kerosene) to maintain the temperature at the slag outlet, efforts have been made to reduce fuel consumption by achieving stable operation of gasifier (stable feed of waste) to keep constant flow of combustible gas to the ash-melter[13]. Stable and long-term operation is also needed to reduce the energy consumption of start-up / shut-down and the maintenance cost. Operation with low air ratio reduces power consumption of fans [13].

Some manufacturers are active to construct waste incineration plants in foreign countries based on their own technologies. Ebara Corporation's 1900t/d RDF-fired plant in Frankfurt, Germany, was the largest Waste-to-Energy plant in Germany at the time of completion. A waste gasifier with ash melter was also constructed in Korea in 2014 based on the design of Hitachi Zosen Corporation.

Sewage Sludge Conversion by Fluidized Bed Processes

Sewage sludge is a kind of biomass resource but its utilization is not easy because of high moisture content. Recently, newly developed fluidized bed processes have been put into practice, namely pressurized incineration, incineration with energy recovery by binary cycle generation, and fluidized bed carbonization to produce alternative fuel. In addition of energy recovery, reduction of N_2O

(nitrous oxide, strong greenhouse gas) emissions from sewage sludge incineration is of concern because nitrogen content in sewage sludge is high.

1) Pressurized (turbo-charged) fluidized bed incineration of sewage sludge

Pressurized fluidized bed sewage sludge incineration has been developed in Japan as a low-energy consumption incineration process. The fluidized bed is operated under elevated pressure conditions (100 – 140 kPa-gauge) so that the hot flue gas can drive a turbine-compressor system (turbocharger) to convert thermal energy to high pressure air. Thus the power consumption to drive fans can be reduced by 40 – 60% because the turbocharger supplies sufficient compressed air for fluidization. Because of high combustion rate per unit cross sectional area under elevated pressure conditions, heat loss through the reactor wall can be reduced, i.e. auxiliary fuel demand can be reduced by about 10%. In addition, since the thermal decomposition of N_2O in freeboard is favoured under elevated pressure and high temperature condition, N_2O reduction of about 50% can be achieved. Though the capital cost of the pressurized system is higher than the conventional atmospheric incinerators, reduction of total cost is expected by reducing power consumption. By now, total nine plants (including plants under construction) have been employed by local governments as summarized in Table 3. Though this process does not supply energy to outside, this process is regarded as an energy-conversion system to convert thermal energy to mechanical energy in the form of compressed air.

Table 3 Pressurized fluidized bed sewage sludge incineration plants

Year of completion	Feed rate	Manufacturer	Location	Remarks
2013	60 t/d	Sanki Engineering Co. Ltd.	Asakawa, Tokyo	The first plant of this technology
2014	300 t/d	Tsukishima Kikai Co., Ltd.	Kasai, Tokyo	Total plant construction cost 3400Million JP Yen
2014	100 t/d	Tsukishima Kikai Co., Ltd.	Sagami-river Kanagawa Pref.	Total plant construction cost 3600Million JP Yen
2015	100 t/d	Tsukishima Kikai Co., Ltd.	Aigawa-river, Osaka Pref.	Total plant construction cost 1700Million JP Yen
2015	250 t/d	Sanki Engineering Co. Ltd.	Shin-Kawagishi, Tokyo	
2016	60 t/d	Tsukishima Kikai Co., Ltd.	Kofu City, Yamanashi Pref.	Total plant construction cost 1620Million JP Yen (excl. tax)
2017 (under construction)	300 t/d	Tsukishima Kikai Co., Ltd.	Miyagi, Tokyo	Total plant construction cost 3920Million JP Yen (excl. tax)
2018 (under construction)	70 t/d	Tsukishima Kikai Co., Ltd.	Chiba, Chiba Pref.	Total plant construction cost 2190Million JP Yen (excl. tax)
2019 (under construction)	205 t/d	Tsukishima Kikai Co., Ltd.	Hokubu, Osaka Pref.	Total plant construction cost 2350Million JP Yen (excl. tax)

2) Incineration with energy recovery by binary cycle generation

Ministry of Land, Infrastructure, Transport and Tourism, Japan has subsidized R&D projects for efficient utilization of sewage sludge as "Breakthrough by Dynamic Approach in Sewage High Technology Project (B-DASH)". One of the B-DASH R&D projects was energy recovery from sewage sludge incineration by binary cycle generation. Binary cycle generation is considered to be suitable to convert relatively low-temperature heat to energy, compared with conventional Rankine cycle using water. In Minami-Tama, Tokyo, they plan to recover heat from hot water of 140 °C using 245fa as working fluid and produce electricity of 120 kW (after subtracting power consumption in this unit) by using binary cycle [14)]. This energy recovery is equivalent to about 20% of energy in sewage sludge [14)]. Table 4 is a list of sewage sludge incineration/gasification plants equipped with binary cycle power generation.

Table 4 Fluidized bed sewage-sludge incineration/gasification plants with binary cycle power generation

Year of completion	Conversion type	Fluidized bed type	Feed rate	Energy output	Manufacturer	Location	Remarks
2014	Incinerator	FB	25 t/d	25 kW	METAWATER Co., Ltd.	Ikeda, Oaka Pref.	B-DASH project
2016 (under construction)	Gasifier	Circulating FB	110t/d	120kW *	METAWATER Co., Ltd.	Minami-Tama Inagi, Tokyo	*equivalent to about 20% of energy in sludge [14)]

3) Carbonization of sewage sludge by fluidized bed reactor to produce char

Carbonization of sewage sludge by fluidized bed reactor to produce char is also put into practice. The product, carbonized sewage sludge char, can be sold as an alternative fuel to coal. Table 5 is a list of sewage sludge carbonization plants.

Table 5 Fluidized bed carbonization plants to produce char as alternative fuel

Year of completion	Conversion type	Fluidized bed type	Feed rate	Product	Manufacturer	Location	Remarks
2015	Carbonization Furnace	FB	80t/d	Char 8 t/d	METAWATER Co., Ltd.	Kosei Ohtsu, Siga Pref.	
2017 (under construction)	Carbonization Furnace	FB	75t/d	Char 7 t/d	METAWATER Co., Ltd.	Nakashima Mishima, Shizuoka Pref.	

4) Partial combustion followed by secondary combustion chamber to reduce N_2O

Combustion at high temperature is favourable for destruction of N_2O in gas phase, thus installation of secondary combustion chamber in which gas temperature is increased by burning fuel gas is an approach to destroy N_2O without considerable increase in NOx. However, such system often requires auxiliary fuel. One approach is burning sewage sludge in oxygen-deficient atmosphere to produce combustible gas and burning the unburned gas in the secondary combustion chamber. Table 6 shows some example of partial combustion - secondary combustion chamber system.

Table 6 Partial combustion followed by secondary combustion chamber to reduce N_2O

Year of completion	Fluidized bed type	Feed rate	Manufacturer	Location	Remarks
2011	Circulating FB	290 t/d	Kobelco Eco-Solutions Co., Ltd.	Himeji, Hyougo Pref.	
2014	Circulating FB	120t/d	Kobelco Eco-Solutions Co., Ltd.	Kusatsu, Siga Pref.	

Research and development

1) Development of dual-fluidized bed coal gasification technology by IHI Corporation [15)]

IHI Corporation has been developing dual-fluidized bed coal gasification technology called “TIGAR” that gasifies low grade coal such as brown coal under atmospheric pressure at lower temperatures. The final product is H_2 for ammonia synthesis. This process consists of dual-fluidized bed gasifier followed by tar reformer (by O_2 injection at high temperature), heat recovery, dust removal, gas shift reactor to convert CO to H_2, and acid gas removal process. They constructed pilot-scale plant (6 t/d) in 2006. After collecting basic data from the pilot-scale plant, they constructed a demonstration plant (50 t/d) in Indonesia in 2014. Since 2015 they have been doing demonstration operation. The coal tested is local low-grade coal with high moisture content (3 400 kcal/kg GAR at 43% moisture). The final goal is to develop commercial plants of 300 – 1000 t/d scale suitable for ammonia production of 1000 t/d. This project is partly subsidized by NEDO.

2) NEDO’s R&D projects of fuel production processes from biomass using fluidized bed reactor [16)]

Biomass is regarded as carbon-neutral energy source. There are different ways to utilize biomass, combustion, gasification, and liquefaction. NEDO has been subsidizing R&D activities for biomass utilization in a framework of “Strategic Development of Next-generation Bioenergy Utilization Technology”. Among the R&D projects, there are fluidized bed conversion technologies as briefly described below.

2-1) Advanced Biomass Co-gasification Next-generation Biomass Liquid Fuel Technology (FY2012-2013)

This research project was carried out by a join research group of Japan Coal Energy Center and Gifu University with re-entrustment to National Institute of Advanced Industrial Science and Technology (AIST). This project includes development of three-tower circulating fluidized bed gasification technology with tar reformer, R&D of tar- and H_2S-resistant FT-synthesis catalyst, and research on matching system for gasification and FT-synthesis. The process is illustrated in Fig. 2. Biomass and auxiliary fuel are fed to a circulating fluidized bed gasifier with CaO bed material. Conditioning biomass gasification, tar reforming, desulfurization and the ratio of H_2/CO in a circulating fluidized bed gasifier simplifies the gas purification process after gasification. Gasification gas cleaned by a water scrubber is introduced as synthesis gas to a liquefier. Liquid fuel is then produced by FT synthesis using newly developed catalyst that has resistance to tar and sulfur.

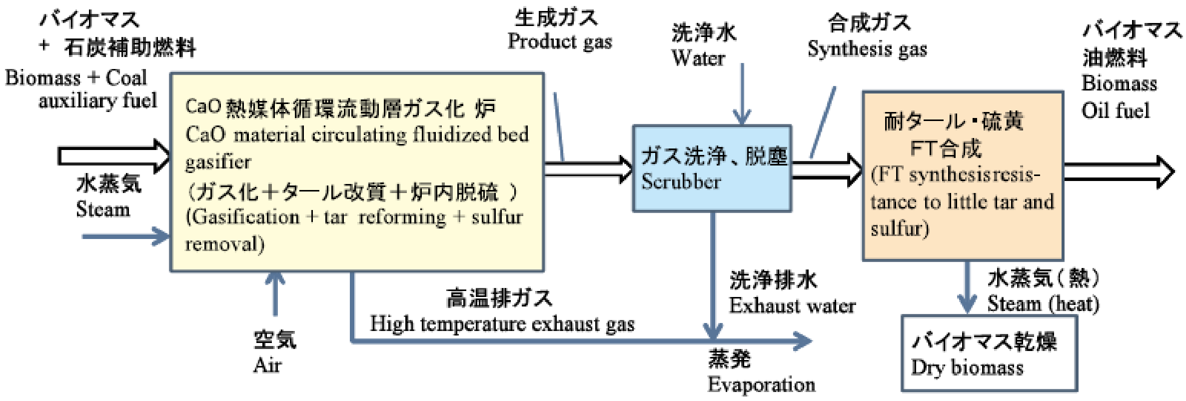


Fig. 2 Flow sheet of "Advanced Biomass Co-gasification Next-generation Biomass Liquid Fuel Technology"

2-2) Development of Steam Gasification /Hydrogenation Hybrid Processes for High-grade Fuel Production from Biomass (FY2012-2015)

This research project was carried out by a join research group of Gunma University and Kinsei Sangyo Co., Ltd. with re-entrustment Oyama National College of Technology. The objective of this R&D is to establish economically efficient plants through the development of small-scale biomass conversion processes, which produce high-grade fuel and electricity that meet local needs. This project includes production and demonstration of hybrid process, elucidation of catalyst poisoning behaviour and identification of usable biomass, evaluation of liquid fuel and identification of optimal production conditions, and improvements and demonstration of the total test plant. A feature of this project was to develop a three-compartment internally circulating fluidized bed system, which consisted of three bubbling beds connected by solid transportation lines. The three reactors were combustor, pyrolyzer, and gasifier as shown in Fig. 3.

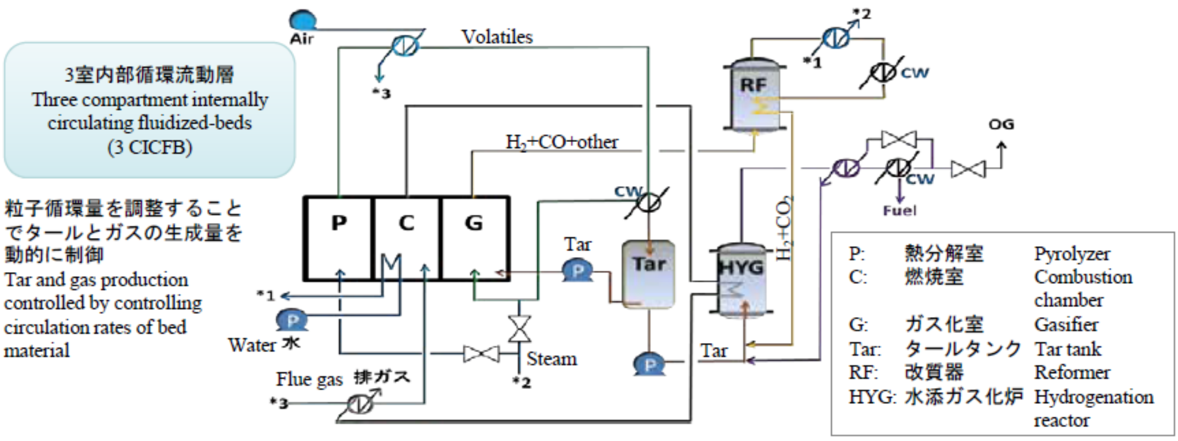


Fig.3 Three compartment internally circulating fluidized-beds for co-production of liquid fuel (biomass oil) and electricity.

2-3) Technology for Production of New Biofuels using Catalytic Fast Pyrolysis (FY2011-2014)

Joint research group of Tokyo University and Meiwa Co., Ltd. with re-entrustment to National Institute of Advanced Industrial Science and Technology (AIST), and Japan Advanced Institute of Science and Technology, conducted research project to produce low-cost and high-quality biofuel via catalytic fast pyrolysis using two-stage fluidized-bed reactor. One of the problems of liquid fuel (bio-oil) production from biomass via pyrolysis process is high oxygen content in the product. Thus this project includes R&D on multi-function catalyst for upgrading psyrolysis oil, development of advanced catalysts for hydrodeoxygenation and Water-Gas-Shift reaction, R&D of two-stage fluidized bed reactor for catalytic fast pyrolysis to produce upgraded bio-oil, and optimization of reactor. The concept is shown in Fig.4.

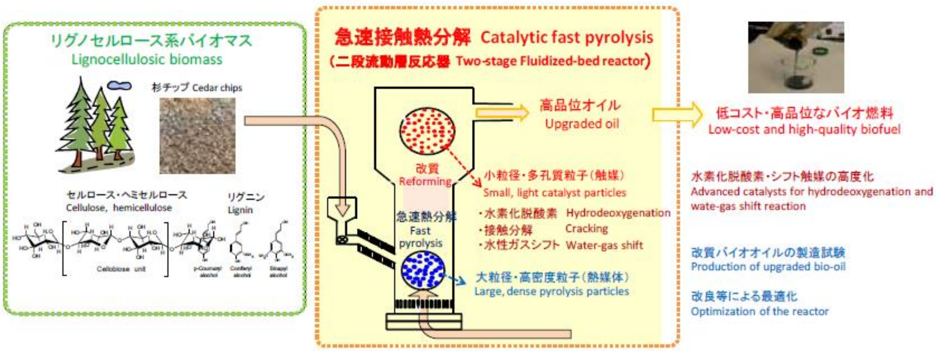


Fig.4 Concept of Production of New Biofuels Using Catalytic Fast Pyrolysis

2-4) SNG Production from Woody Biomass Using Gasification Process (FY2012-2014)

This research project was carried out by a join research group of IHI Corporation and Hitachi Zosen Corporation. The objective of this R&D is to establish a highly efficient process for SNG production from woody biomass by combining dual fluidized bed gasification with a novel methanation process under atmospheric pressure. This project included optimization of dual fluidized bed gasifier, development of highly efficient tar reformer, and development of methanation process. The concept is illustrated in Fig.5. The atmospheric dual-fluidized bed gasifer consisted of a riser reactor in which char is burned using air, and a bubbling bed gasifier where biomass is pyrolyzed/gasified. The produced gas is finally converted to SNG in methanation reactor and fed to city-gas pipeline.

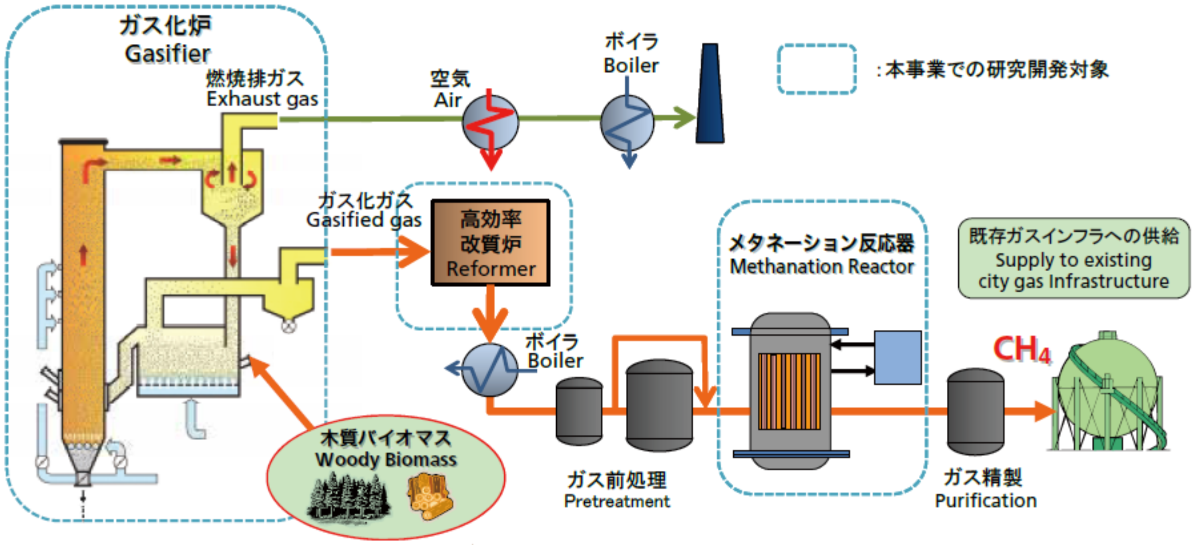


Fig.5 SNG production from biomass using atmospheric dual-fluidized bed gasifer followed by reformer and methanation process.

3) Academic activities

The Society of Chemical Engineers, Japan has Fluidization Research Group in Fluid & Particle Processing Division. This research group has been organizing "Symposia on Fludization & Particle Processing" annually since 1995.   In 2011 – 2015, 17th (Nagoya), 18th (Sakai), 19th (Kiryu), 20th (Okayama), and 21st (Kitakyushu) symposia were held. Previously a lot of papers were presented in the sessions on energy conversion and waste management, not so many presentations were found recently in these fields. Indeed, in 2015 (20th), only 8 papers were related to energy/waste management among total 44 papers.

Besides the symposia series, this research group has been doing training courses for these three decades in cooperation with AIST, Japan. This training course is open once a year for mainly young engineers in industry. This course includes lecture on basics of powder technology, bubbling and circulating fluidized beds, and fluidized bed combustion. Also training experimental courses using small scale plants are included. Some universities offer opportunities to operate their fluidized bed experimental apparatuses such as dual-fluidized bed hot model as "Satellite courses". The interest of industry for these series of training course is stable and total 25 participants joined the course in year 2015.

Acknowledgement

The author of this report expresses his thanks to the members of Technical Group of Environment, Energy and Fluidization of The Association of Powder Process Industry and Engineering, Japan (APPIE), for their cooperation in data collection. Also the help by the manufacturers of fluidized bed systems is deeply appreciated.

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KOREA

Prepared by JongMin Lee, KEPCO Research Institute (jm.lee@kepco.co.kr)

Introduction

Recently, there has been increased interest in effective fuel utilization in Korea as its energy consumption is largely dependent on imported resources. Moreover, the issues of CO_2 reduction in the industries using fossil fuels have been on the rise. So, the utilization of biomass and wastes fuels in these sectors have been increased steadily over the last few years, because of its carbon neutrality.

One of the successful technologies of the fuel utilization is a circulating fluidized bed combustion because of its capability of firing various fuels, such as SRF (solid refuse fuel), bio-SRF (bio solid refuse fuel) as well as low quality coals. Besides, the capacity and efficiency of the CFB technology have been more and more improved by successful achievement of large scale SC/USC (super critical/ultra super critical) CFBs as shown in Figure. 1 [1]. This would be also able to contribute the reduction of CO_2 emission.

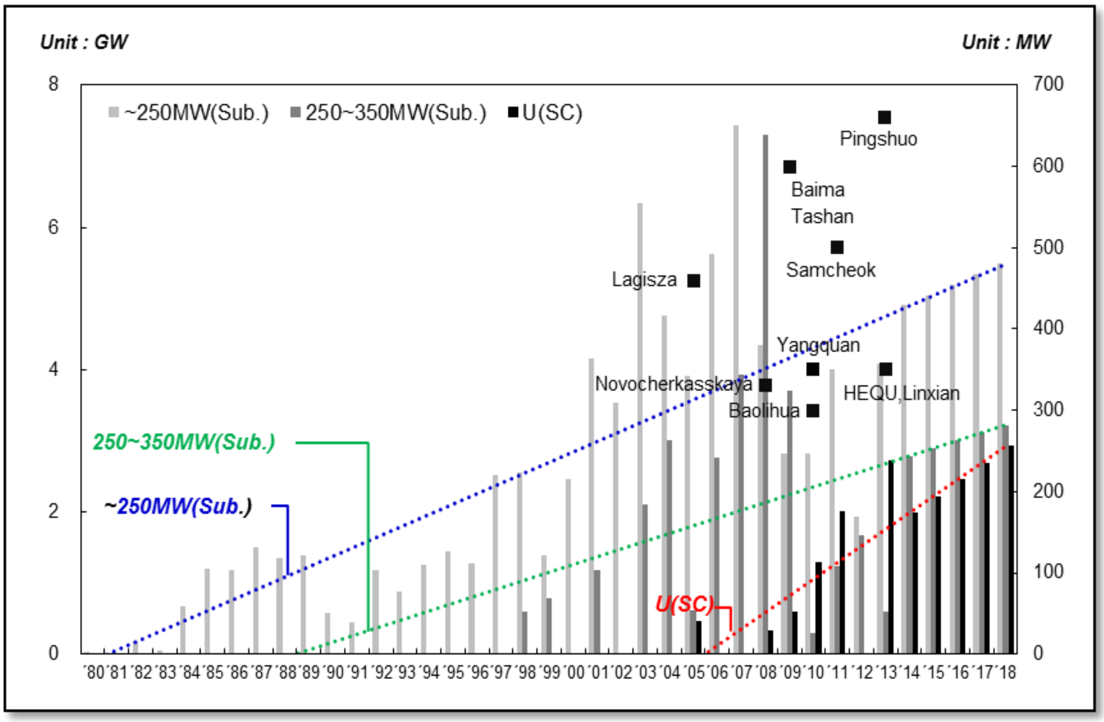

Figure 1. CFB total unit and capacity from 1980 to 2013 (1,145 units, 116.5 GW) and SC/USC CFBs [based on construction starting year, Ref. '14 McCoy report Data]

For these reasons, co-firing of biomass and wastes with coal in many CFB boilers in Korea has been carried out over the last several years. The Donghae (200MWe x 2 units) and Yeosu CFB (340MWe) boilers are typical co-combustion examples, where about 10% bio-SRF is co-fired with coal. The new several CFB boilers for only biomass or SRF have been also constructed and operated recently. Typically, there can be GS-EPS biomass CFB boiler (100MWe) at Dangjin city in Korea, which has been operated successfully since 2015.

On the other hand, Samcheok USC-CFB boilers (500MW x 4 units) are being commissioned aiming at completion late 2016. These boilers are also expected to reduce the operating cost and CO_2 emission through the improvement of the plant efficiency and the biomass co-combustion. Separately, Korea started the research for the development of USC-CFB boilers at 2016 with the goal of commercializing 600MW USC-CFB. The research will continue by the end of 2018.

Fluidized Bed Combustion

In Korea, 34 units of CFB boilers are being operated and 8 units of CFB boilers are under construction for cogeneration and electric power generation. As shown in Table 1, the trend of the CFBs cofiring biomass and SRF is on the rise. Especially, Samcheok USC-CFB plants, which are the first and the largest once-through CFB type in Korea, will be completed at the end of 2016 and is shown in Fig. 1 [2].

Table 1. Status of CFB boilers in Korea (2016)

Company / Location(City)	**Year**	**Capacity (steam t/h or MWe)**	**Fuel**	**Category**	**Supplier /Design**
Oriental Chemical / Incheon	1984	120 t/h	Coal	Co-Gen	Hyundai HI[1)]/ Ahlstrom
SK / Suwon & Ulsan	1988/89	25/200 t/h	Coal	Co-Gen	Hyundai HI/ Ahlstrom
LG / Yeocheon	1989	210 t/h	Coal	Co-Gen	Hyundai HI/ Ahlstrom
Hyundai Oil / Daesan	1989	120 t/h	Coke	Co-Gen	Hyundai HI/ Ahlstrom
Petrochemical Service Co./Ulsan	1990	250 t/h	Coal	Co-Gen	Hyundai HI/ Ahlstrom
Dyeing Complex / Busan	1991	80×2 t/h	Coal	Co-Gen	Daewoo HI
Korea Energy / Onsan	1991	175 t/h	Coal	Co-Gen	Doosan/Lurgi
Sam Yang GENEX / Incheon	1990	60 t/h	Coal	Co-Gen	Hyundai HI/ Ahlstrom
EWP/ Tonghae	1998/99	693 t/h ×2 (200 MWe ×2)	Anthracite /Biomass	Electric	Doosan/ Alstom
Kumho Petrochem. / Yeosu	2003	305 t/h	Coal	Co-Gen	Hyundai HI
Dyeing Complex / Daegu	2004	160 t/h	Coal	Co-Gen	Hyundai HI
Gunjang Energy / Gunsan	2007/ 2010	200 t/h × 2 / 250 t/h	Coal	Co-Gen	Hyundai HI
Hanhwa Energy / Yeosu	2009	400 t/h × 3	Coal	Co-Gen	F/W
BASF/ Gunsan	2009	180 t/h	Coal	Process	Hyundai HI

Hansol[2] / Jeonju	2010	10 MWe	Biomass/ RPF	Co-Gen	AF Sweden
Gunjang Energy #3, #4 / Gunsan	2011/ 2014	250 t/h × 2	Coal / Pet. Coke	Co-Gen	Hyundai HI
KOSEP / Yeosu	2011 / 2016	1040 t/h × 2 (340MWe × 2)	Coal/ Biomass	Electric	Doosan
Yeosu Co-gen Plant / Yeosu	2012	350 t/h × 2	Coal	Co-Gen	Hyundai HI
Hyundai Oil Bank #8, #9, #10 / Daesan	2012/ 2014/ 2017	220 t/h × 2 330 t/h × 1	Pet. Coke	Co-Gen	Hyundai HI
Gimcheon Community Energy / Gimcheon	2012	330 t/h	Coal	Co-Gen	Hyundai HI
Han Ju Corp. / Ulsan	2015	250 t/h	Coal	Co-Gen	Hyundai HI
GS EPS / Dangjin	2015	105 MWe	Biomass	Electric	FW
KOMICO / Wonju	2015	10 MWe	RDF	Co-Gen	Hansol Seentec/ KIER
OCI/ Gunsan	2015	150MWe × 2	Coal	Co-Gen	Doosan /FW
KOSPO / Samcheok	2016	1,572 t/h × 4 (500MWe × 4)	Coal/ Biomass	Electric	Hansol Seentec /FW
Hansol[3] / Jeonju	2017	30 MWe	Biomass/ RPF	Co-Gen	Kawasaki
Hanhwa Energy / Gunsan	2018	100MWe	Coal	Co-Gen	FW

1) HI: Heavy Industries, 2) Hansol : BFB type, 3) Hansol : ICFB type

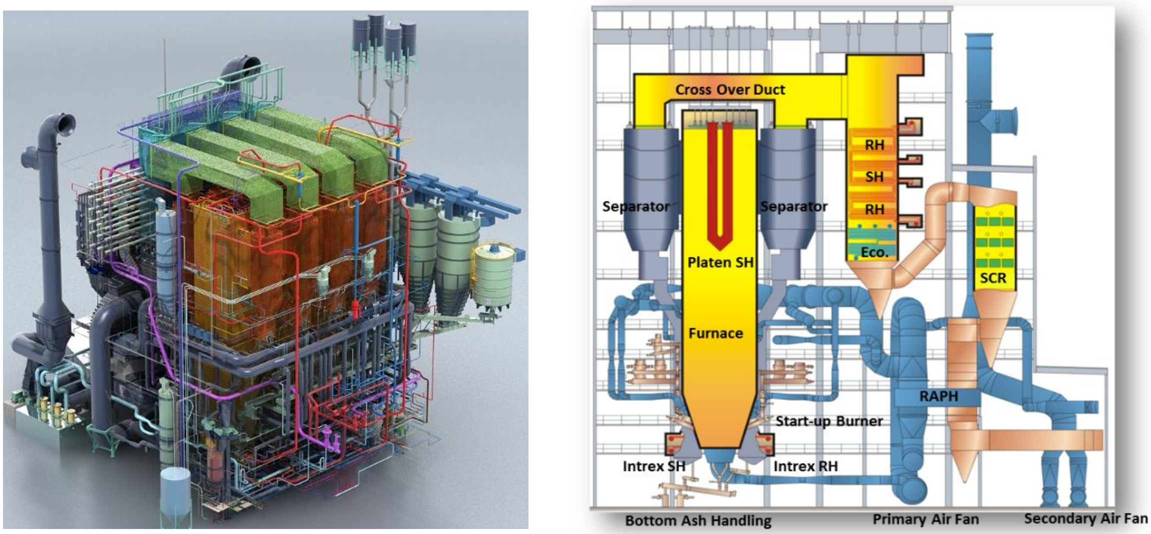

Fig. 1. Samcheok USC-CFB feature.

Fluidized Bed Gasification

There is not any commercial fluidized bed gasifier in Korea. However, many researches are going on to develop the fluidized bed gasifier for production of syngas and chemical feed stock from coal, biomass and wastes. Instead of fluidized bed gasifier, the first IGCC plant for electric power generation, based on Shell technology, is in commissioning period at Taean city in Korea, which is of 300MWe capacity and will be operated by Korea Western power co. Ltd..

Manufacturing

There are two major manufactures of FBC equipment in Korea. One is Doosan Heavy Industries & Construction and the other is Hyundai Heavy Industries. Doosan Heavy Industries & Construction can fabricates relatively large CFB boilers, more than 200MWe with its own technology through acquiring AE&E Lentjes in late 2011. Hyundai Heavy Industries usually manufactures relatively small CFB boilers around 50~200MWe. Additionally, these days Hansol-Seentec is emerging as a fluidized bed boiler manufacturer and supplier in the field of small scale fluidized bed for biomass and wastes fuels [3].

Each manufacture's web site is www.doosanheavy.com, www.hhi.co.kr and www.hansolseentec.com, respectively.

Research and Development

KEPCO research institute (KEPRI) started a new project for "Development of USC-CFB technology" supported from several power generation companies, which will be carried out for 3 years from 2016. In this project, the design and operation technologies of USC-CFB using various fuels will be developed with the goal of commercializing 600MWe USC-CFB boiler in the near future [4].

On the other hand, a national research roadmap in the field of thermal power generation is newly being established for realizable technology in 2020. In this roadmap, the development of USC and Oxy CFB technologies is involved as well as fuel diversification.

Also, CLC, CLG and CO_2 post capture process using fluidized bed technology are being developed around several research institutes (KEPRI, KIER, KIMM and KITECH) in Korea. For example, CO_2 post capture process using FB technology with a capacity of 10MWe was accomplished by KERPI and KIER, and was verified as connecting the commercial thermal power plant. This process will be continuously developed on a large scale (100MWe) [5].

Fluidized bed gasifiers have been studied by KITECH and SK energy in Korea. KITECH has developed a 1 t/d pilot scale dual fluidized bed gasifier and has experimented with various fuels to secure the design technology of the 1MW scale gasifier for commercialization [6]. SK energy has also developed a 3 t/d gasifier producing syngas from low grade coals through technical cooperation with KBR [7].

On the other hand, KIER started a new project for development of 2MWe USC-Oxy-CFB technology through cooperation with several institutes in 2016. The objective of the project is to achieve the high efficient and eco-friendly power generation system.

Conclusion

There have been lots of activities as regards fluidized bed technology in Korea, from 2011 to 2015. Particularly the fuel diversification into biomass and wastes in the CFB boilers, and the improvement of the efficiency through introduction of USC CFB became an object of attention recently, because the issue of the reduction of CO_2 emission has been on the rise. In near future, the technologies of fluidized bed for Oxy, CLC, CLG and CO_2 capture and so on will also come into the spotlight in Korea.

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RUSSIA

Prepared by Georgy Ryabov, georgy.ryabov@gmail.com

Commercial Facilities in Russia

The basic characteristics of the fluidized bed conversion utilities in Russia are summarized in the table 1. Most of FBB boilers were installed on pulp-and-paper plant (PPP). Some of them were made as FB furnace extension (gasifier) connecting the existing or new boilers (engineering by ENEKO ltd, produced by Belgorod boiler manufactory). Other projects are typical FBB as Russian – Finish cooperation projects (Outocompy, Kvarnier, Metso).

There are more than 5 small size drum type FB boilers for coals and some agriculture and forest residues (less than 1 MWth) designed by Tambov State University and Bisk boiler manufactory.

More than 30 years ago 420 t/h BFBC (300 MWth) for lignite firing was designed and constructed. The design was prepared by CBTI (“Central Boiler and Turbine Institute”) and JSC “Sibenergomash”. But now that boiler is not in operation.

Table 1 - The basic characteristics of the fluidized bed conversion utilities in Russia

Location	Year*	Type	Capacity	Fuels
Vuoborgskiy PPP	1988	BFBC	14	bark and wood waste
Suktuvkarskiy PPP	1996	BFBC *	60 MW_{th}	bark and wood waste
Archangelskiy PPP	2000, 2004	BFBC	2*60 MW_{th}	bark and wood waste, liquid wastes
Solambalsky PPP	2000	BFBC *	60 MW_{th}	bark and wood waste
Bratskiy PPP	2001, 2004, 2011	BFBC * + BFBC	2 * 60 + 72	bark and wood waste
Svetogorsk PPP	2002	BFBC	120 MW_{th}	waste paper, liquid wastes
Ust-Ilimskiy LPK	2004	BFBC *	60 MW_{th}	bark and wood waste
Segedskiy PPP	2004	BFBC	80 MW_{th}	bark and wood waste
Kondogskiy PPP	2006	BFBC	60 MW_{th}	bark and wood waste
Beluy Ruchey TPP	2007	BFBC	2 x 15 MW_{th}	wood chips, wood waste
Rudnevo MIP	2003	ICFBC	3*15 MW_{th}	Municipal solid wastes
Novocherkasskay TPP	2015/2016	CFBC	330 MWe (800 MWth)	Anthracite culm

BFBC - bubbling fluidized bed combustor
CFBC - circulating fluidized bed combustor
ICFBC - internal circulation fluidized bed combustor (ROWITEC technology)
* FB furnace extension (gasifier)

Municipal wastes incineration plant at Rudnevo (Moscow region, Russia) started up in operation in 2003. The two swirl fluidized bed furnaces (ROWITEC technology) were delivered by Lurgy (Germany). Due to two years intensive investigations and improvements all guaranty data were confirmed. The maximum fuel capacity was raised to 19 t/h and steam rate after boiler was about 30t/h (nominal – 25 t/h). The complete burning (CO concentration less than 10 mg/m3, O_2 – 11% and mechanical combustion losses are about 0,3%) was provided even for very height ash and moisture content (33% and 50%, heat value – 1200 kKal/kg) of municipal wastes.
The project of the new Unit № 9 330 MW with OTU CFB boiler of Novocherkassk TPP is the determining for the wide use of CFB technology in Russia. CFB boiler was constructed by Foster-Wheeler and EM-Alliance (Russian boiler manufacture). The Unit is designed for combustion of the Anthracite culm, Kuznetskiy lean coals and coal slurry. It is typical FW design with compact cyclones and INTREX ash heat exchangers. The CFB boiler efficiency is by 3% higher as compared to that practically achieved at similar coal-fired boilers. Also, NOx and SO_2 emissions are as lower as 3-4 and 10 times. The construction of the unit was finished in 2015, nominal capacity have reached just now.

Pilot / Experimental Fluidized Bed facilities in Russia

There are 3 CFB pilot facilities in Russia. All of them are not in operation at the moment. The largest pilot CFB was built in Taganrog (5 MWt), but constructed was not finished (control system and some auxiliary equipment). Ural Federal University, All-Russia Thermal Engineering Institute (VTI) and Tambov State University has small size laboratory test rig. VTI has 2 cold models, one of them with dual CFB – FB reactors. The laboratory CLC test rig (10 – 20 kW) was completed for natural gas and syngas firing. The main design parameters of the unit are: fuel flow 0.2 – 0.4 g/s, air flow 4.12 – 8.5 g/s, oxidizer diameter 0.07 m, reducer diameter 0.148 m and unit height 2.2 m.

The most important companies and research institutions being active on the topics Fluidized Bed Conversion in Russia are the followings.

- **VTI (JSC "All-Russia thermal Engineering Institute"**)

VTI is leading engineering and research organization in CFB technology in Russia. For more than 20 years the Institute is working on field of fluidized bed combustion. From 1988 there is an active research going on concerning CFB combustion of solid fuel. Combustion phenomena, fluid dynamics and heat transfer from highly loaded particle flow have been studied in various test rigs. A large cold model, small size firing test rigs and pilot plant are operated. VTI carrying out the investigation on co-firing and combustion of biomass and wastes. Other direction of VTI researches is a municipal wastes combustion. At the moment the Institute take part of startup operation on Rudnevo plant (near Moscow region). These investigations cover a wide range of processes concerning combustion, deposits formation and corrosion in the furnaces and recovery boilers as well as emission generation and suppression. The latest investigations were made in field of CO_2 capture, oxyfuel and chemical looping combustion (CLC). Some new data focus on the solids circulation rate, standpipe and loop seal behavior, pressure profiles of the DCFB depending on selected operating parameters such as fluidization gas flow rate, loop seal fluidization, and solids inventory.

- **CBTI ("Central Boiler and Turbine Institute"**)

CBTI have a good experience in designing and operation of FBB boilers in Russia in range of 1 – 10 MWth. There are typical boilers for coal firing constructed in 1960 – 1970 years. Other projects were made for FB gasifiers and CFB boilers (preliminary design for 225, 330 MW units.

- **EM-Alliance** (JSC “EM-Alliance, Taganrog Boiler “Krasny Kotelschik”)

Taganrog Boiler “Krasny Kotelschik” is the largest boiler manufactory in Russia. EM-Alliance is a supplier of OUT CFB boiler (with FW) for # 9 Unit of Novocherkasskay TPP. EM-Alliance participated in preliminary design of domestic CFB boilers with steam capacity 600 – 1000 t/h.

- **Belgorod boiler manufactory**

Belgorod boiler manufactory and some connected Companies produced FBB boiler for pulp-and-paper plant and BFB boiler for wood chips.

- **INEKO Ltd**

Engineering Company INEKO specialized on designing of FBB gasifier connected to the existing or new boilers.

- **Bisk boiler manufactory**

Bisk boiler manufactory is the largest Company in Russia to produced small and medium size solid fuel boilers. There has some project for coal and biomass FBB boilers.

- **JSC “Sibenergomash”**

JSC “Sibenergomash” in cooperation with Central Boiler and Turbine Institute produced the largest in USSR FBB boiler 420 t/h BFBC (300 MWth) for lignite firing. But now that boiler is not in operation. JSC “Sibenergomash” constructed FBB boilers for Segedskiy pulp-and-paper plant.

- **Ural Federal University (UrFU)**

Ural Federal University is the oldest scientifically institute in field of FB technology. A lot of investigations of hydrodynamics, heat exchange, combustion and NOx formation were made. UrFU. UrFU has a good experimental equipments, laboratory test rigs and FB pilot plant.

- **Tambov State University**

Tambov State University have a good experience in engineering and designing of small size drum type FB boilers for biomass and coal firing with heat production.

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SPAIN

Prepared by Sanchez Hervas, Jose Maria and Colleagues from CIEMAT
(josemaria.sanchez@ciemat.es)

The main data of the fluidized bed conversion utilities in Spain are summarized in the next table. The dates of commissioning/refurbishment in the table show a little activity in the period 2011-2015.

COMMERCIAL/DEMONSTRATION INSTALLATIONS

Owner/Location	Year	Type	Capacity	Boiler	Feedsotck
La Pereda/Mieres	1994	CFBC	50 MW	Foster Wheeler	Hard coal, 65 % ash
Betejar/Cordoba	1995	BFBC	12.5 MW	Foster Wheeler	Orujo (olive waste) 65% moisture
Tirmadrid/Madrid	1996	BFBC	30 MW		MSW
Mora de Ebro/Tarragona	1997	BFBG	0.5 MW	Energia Natural de Mora	Almond Shell
Sogama/La Coruña	2002	2 CFBC	50 MW		MSW
Dacsa/Valencia	2002	BFBC	2 MW	Vulcano	Rice husk
INERCO/Sevilla	2007	BFBG	3 MWth	Inerco	Wood pellets, olive stones, rapessed
Guascor/Vitoria	2008	BFBG	1 and 2 MWth	ENAMORA	Agro-industry wastes
Guascor/Vitoria	2008	Multistep gasifier	670 kWth	GUASCOR	Lignocellulosic biomass
ENCE BIOMASA Navia, Asturias	2009	BFBC	36,7 MW	Andritz	Wood chips/bark eucalyptus, forest/agricultural biomass
CIUDEN/León	2011	CFBC, OXY	30 MWth	Foster Wheeler	Coal+biomass
CIUDEN/León	2011	BFBG	3 MWth	Inerco	Biomass, wood chips, pellets
La Pereda CO_2/Oviedo	2011	CFBCL	1.7 MWth	CSIC	Coal
ENCE BIOMASA Huelva	2012	BFBC	50 MW	Andritz	Wood chips/bark eucalyptus, forest/agricultural biomass
Biomasa de Cantabria	2013	BFBC	10 MW	Foster Wheeler	Biomass wastes
MOVIALSA /Campo de Criptana, (Ciudad Real)	2011	BFBG	6 MWe	EQTEC	*Orujillo*, (olive oil bagasse), grape marc, almond shell, olive stone,..
Cerámicas Mollá/Xátiva (Valencia)	2010	BFBG	1.55 MWe	NECER-CARECO	Biomass, chips
IDERMA (Ejea de los Caballeros, Zaragoza)	2011	BFBG	2 MWe	NECER-CARECO	Biomass, chips

BFBC bubbling fluidized bed combustor; CFBC circulating fluidized bed combustor; BFBG bubbling fluidized bed gasifier; CFBG circulating fluidized bed gasifier; CFBCL circulating fluidized bed Ca looping; * co-combustion with gas from oxy-gasification

CENTERS OF RESEARCH AND TECHNOLOGICAL DEVELOPMENT

A description of the main R&D groups working on FBC in Spain is given below. Information is exclusively based on a survey conducted over last year to update information and therefore should not be regarded as fully comprehensive. The information contained in this report rests on that provided by researchers at the respective R&D Centers

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT). Unit for Energy Valorization of Fuels and Wastes, Combustion & Gasification Division, Department of Energy.
Location: Madrid

Overview
Over the last two decades, the objective of the Unit, as part of the Energy Department, is to generate knowledge to support the development and implementation of advanced combustion and gasification systems, focusing especially on FB technologies and gas treatment systems, gas cleaning and upgrading in response both to technological and environmental demands.

R&D Activities in Fluidised Bed Conversion:
- Co-firing coal and biomass under oxy-firing conditions aiming to characterize pollutant generation, ash composition and deposition on heat exchanger surfaces.
- Coal, biomass and waste FB combustion process
- Analysis of the fate of mercury during oxy-firing in a bubbling fluidized bed.
- Kinetic studies and theoretical development
- Gasification of biomass and waste in bubbling and circulating fluidized bed reactors

Facilities:
- 3,5 MWth bubbling fluidized bed combustor for solid fuels
- 1 MWth bubbling fluidized bed combustor for solid fuels
- 5 kWth bubbling fluidized bed combustor combustion and oxyfuel
- 0.5 MWth circulating fluidized bed gasifier for biomass and waste gasification coupled to dry and wet gas cleaning systems
- 100 kwth bubbling fluidized bed gasifier for biomass and waste gasification

Bioenergy Group, Chemical and Environmental Engineering Department, Escuela Superior de Ingenieros (University of Seville)
Location: Sevilla

Overview
The Chemical and Environmental Engineering Department of University of Seville has been carrying out research on thermal and catalytic conversion of fuels, including coal, biomass and wastes for more than twenty years. The activities related to Fluidized bed conversion are conducted within the Thermochemical Conversion Group of the Bioenergy Group of the University of Seville (TCG-BEGUS) founded in 2006.

R&D Activities
- Biomass/waste gasification in fluidised bed: Demonstration of gasification of biomass and wastes

- Design of new gasification systems based on innovative concepts and gas cleaning strategies for tar removal and conversion systems by primary and secondary measures. Development a new concept for FB gasification of dirty fuels (urban waste).
- Thermochemical Bio-refineries and biofuels production (BTL) by the thermochemical path (gasification and catalytic synthesis): production of ethanol and higher alcohols (HAS), thermochemical biorefinery based on dimethyl ether (DME) as a platform chemical, polygeneration of electricity, fuels and chemicals (methyl acetate, ethyl acetate, acetic anhydride) , and the production of butadiene from ethanol.
- Development of tools for modelling and scaling up: Modelling, design and simulation of thermochemical conversion of biomass processes for producing either heat & electricity, chemicals or biofuels. Economic and feasibility studies using process simulators (Aspen Plus) for comparison of different alternatives. CFD software for optimisation of hardware details and operation performance.

FBC facilities Installations on biomass/waste gasification include:

- BFB lab plant (5 kWth, 0.5 kg/h) situated in the university campus. It is a flexible BFB system allowing gasification of very different fuels with a number of gasification agents (air, steam and oxygen, and mixtures thereof).
- BFB pilot plant (100 kWth, 15-20 kg/h), situated in the university campus
- Three-stage FB pilot plant (75kWth, 10-15 kg/h), situated in the university campus
- Catalytic laboratory with 2 bench-scale reactors for catalyst testing and process optimization
- Fluidized bed conversion coupled with pyrometry to track detailed fuel conversion process
- Bench scale supercritical reforming for the valorization of liquid residual organic fractions
- Several laboratory rigs for investigation of biomass gasification, devolatilization and fuel reactivity, including an accredited laboratory for fuel analysis (fixed bed reactors, TGA, ovens, …)

Fundación Ciudad de la Energía (CIUDEN)

Location: Ponferrada, Leon

Overview

The "Fundación Ciudad de la Energía", CIUDEN is a public state foundation, the purpose of which is to strengthen economic and social development in the Bierzo region by means of activities related to energy and environment.

R&D Activities:

- Oxy-firing of coal in CFB and direct/indirect oxy-co-combustion of coal and biomass
- CO_2 capture technology development based on oxy-combustion processes

Facilities:

- 30 MWth CFBC, oxycombustion of a wide range of coals and direct/indirect co-combustion of coal and biomass
- 3 MWth FBG demonstrationunit: Biomass gasification with CO_2/O_2

CENER – Second Generation Biofuel Centre (CB2G)

Location: Aoiz (Navarre, Spain)

Overview:
The main goal is the production of a fuel gas suitable for the following cleaning and synthesis processes of 2nd generation biofuels. To that aim a gasification unit based on the technology of atmospheric bubbling fluidized bed (ABFB) with two operating modes: using air as gasifying agent or using steam/oxygen as gasifying agent is in operation since 2012. This unit is designed to work with a wide range of biomass (with bulk densities between 80-800 kg/m^3 and moisture content below 50%) and a wide range of bed materials and additives (with bulk densities between 1.000-5.000 kg/m^3 and particle size below 1 mm).

R&D Activities:

- Feeding system development and optimization for alternative raw materials.
- Optimization of the gasification process mainly through testing bed materials and additives to improve in bed tar conversion and to reduce ash sintering.
- Develop hot and cold gas cleaning processes for syngas. Plant layout has been carefully design to facilitate the possibility to test hot and cold gas cleaning equipment on site with real syngas using slip streams from the main gas stream

FBC facilities:

- Atmospheric Bubbling fluidized bed gasifier, 2 MWt, study of a wide range of biomass, bed materials and additives is feasible, thermal oxidizer and flue gases treatment.

ICB, Instituto de Carboquímica de Zaragoza, Department of Energy and Environment, Combustion and gasification Group, ICB-CSIC
Location: Zaragoza

Overview
The ICB-CSIC is a public research center belonging to the Chemical Sciences and Technologies of the Spanish National Research Council.

R&D Activities:

- Oxy-fuel fluidized bed combustion: To understand the process of sulfur capture under oxy-fuel operating conditions to optimize the sulfur retention in fluidized bed combustors working at oxy-fuel conditions.
- Chemical looping combustion: The main objective of the activities is development of the Chemical Looping Technology for gas, solid and liquid fuels as a promising way of reducing CO2 emissions in energy production, such as heat, power o hydrogen.

Facilities:

- 3 kWth bubbling fluidized bed combustor.
- 1 kWth circulating fluidized bed combustor for gaseous fuels.
- 10 kWth circulating fluidized bed combustor for gaseous fuels.
- 1 kWth circulating fluidized bed combustor for liquid fuels.
- 1 kWth circulating fluidized bed combustor for solid fuels.
- 50 kWth circulating fluidized bed combustor for solid fuels.

CIRCE-Centre of Research for Energy Resources and Consumption
Location: Zaragoza

Overview

Carbon capture and storage (CCS) is the main alternative to avoid CO_2 emission from power plants. Aiming to contribute to the increase of knowledge related to CCS, in 2007, CIRCE decided to build its own laboratory to study two different technologies to carry out CCS, oxy-firing and calcium looping. In both cases, fluidized bed reactor was considered the most suitable technology.

R&D Activities

- Characterization and modelling of fluid-dynamics, combustion and heat transfer of anthracite, bituminous coal and lignite oxy-firing with different O_2/CO_2 blends
- Study of desulphurization by limestone addition and operation with secondary gas to limit SO_2 and NO generation during oxy-firing anthracite and lignite with different O_2/CO_2 blends (from 21% O_2 to 60% O_2).
- Analysis of the fate of mercury during oxy-firing in a bubbling fluidized bed.
- Co-firing coal and biomass under oxy-firing conditions aiming to characterize pollutant generation, ash composition and deposition on heat exchanger surfaces.
- Fluid-dynamic characterization of two interconnected circulating fluidized bed.

FBC Facilities:

- Oxyfuel 100 kWth O_2/CO_2 BFBC
- Cold-flow dual CFBR for solid looping systems

INCAR, Instituto del carbón, energy Processes &Emissions Reduction

Location: Oviedo

Overview

The “Instituto del Carbón” (ICB) is a public research centre belonging to the Chemical Sciences and Technologies of the Spanish National Research Council (Consejo Superior de Investigaciones Científicas, CSIC). It is divided into three Areas, Chemical Processes for Energy and the Environment, Chemistry of Materials and Coal, Energy and the Environment

R&D Activities

- Utilization of coal and renewable fuels for CO_2 emissions reduction and H_2 generation
- CO_2 capture in combustion and gasification processes
- development of new materials for H_2 storage
- CO_2 Capture from combustion flue gases using CaO Carbonation/calcination loop

FBC facilities

- 30 kW carbonator reactor test facility Ca-looping experimental facility

Based on the facility and concept above, Endesa, Hunosa and CSIC have built a 1 MW pilot dedicated to carbonate looping, close to a CFB power plant

Numerical Fluid Dynamics Group, University of Zaragoza

Location: Zaragoza

Overview
The Numerical Fluid Dynamics Group is a research group of the University of Zaragoza. It is part of the Fluid Mechanics Group, Department of Materials and Fluids Science and Technology, University of Zaragoza, Spain, as well as the Laboratory for Research in Combustion Technology (LITEC-CSIC)

Capacities
- Development of Eulerian-Eulerian multiphase models for fluidized beds
- Simulation of bubbling and circulating FBC
- Modelling and simulation of polydisperse gas-fluidized beds with particle size distribution
- Modelling and simulation of drying and devolatilization of solid fuels fed into fluidized beds
- Modelling and simulation of combustion and gasification in fluidized beds
- Simulation postprocessing features for quantitative analysis of vertical and lateral segregation in polydisperse beds
- Simulation postprocessing features for quantitative analysis of distribution of species and reactions in fluidized bed reactors
- Modelling and simulation of heat transfer in convective sections
- Modelling of pneumatic transport
- Modelling of fouling

Facilities
- In-house, academic (OpenFOAM, MFIX) and commercial CFD codes and expertise
- High-performance-computing equipment

Universidad Politécnica de Madrid, (UPM), Higher School of Industrial Engineering Environmental Technologies and Industrial Resources
Location: Madrid

Overview
The research group Tecnologías Ambientales y Recursos Industriales (TARINDUSTRIAL) belongs to the UPM and comprises a multidisciplinary team of 16 people from the Higher School of Industrial Engineering and the Higher School of Mines and Energy. The diverse academic training of its members (industrial engineering, mining and chemistry, environmental science, geology and chemistry) allows them to address a wide variety of projects for the industrial sector. The TARINDUSTRIAL members maintain an active relationship with some research groups from other countries favouring our international mobility.

R&D Activities
- Waste recovery: gasification, anaerobic digestion, composting
- Air quality: emissions inventories, sampling and analysis of pollutants in both indoor and outdoor environments, air quality modelling
- Industrial processes improvement and pollution prevention: water management, flue gas cleaning processes, life cycle assessment (LCA), industrial ecology and clean combustion technologies.

FBC facilities
- Laboratory scale plant (Fluidised bed gasifier), air (or air/steam mix) gasification, stainless steel fluidised bed reactor (AISI 316 L), 700 mm high and 32 mm inner diameter.

Catalonia Institute for Energy Research (IREC). Thermochemical conversion group
Location: Tarragona

Overview
IREC is an institute that focuses on basic research and technology transfer, intending to offer companies and entrepreneurs the technological innovations resulting from the Institute's research.

R&D Activities
- Assessment of characteristics of biomass and wastes for their valorization via thermochemical processes.
- The thermochemical processes: focus on pyrolysis and gasification, covering the different aspects that allow improving the efficiency and reducing the process cost (feedstock pretreatment, study of reaction mechanisms, design of novel reaction concepts, development of bed materials, syngas cleaning strategies, ash issues).
- The Catalysts for Synthetic Fuels Laboratory is focused on the design, synthesis and characterization of novel catalysts aimed at the production of synthetic fuels from renewable biomass and assimilable resources.

FBC facilities
- High pressure lab-scale fluidized bed reactor (pyrolysis and gasification) (0.4 kWth).
- 6 kWth atmospheric lab-scale fluidized bed gasifier.

Carlos III University of Madrid, Energy System Engineering Research Group (ISE)
Location: Leganés (Madrid)

Overview
The ISE Research Group is part of the Thermal and Fluid Engineering Department at Carlos III University of Madrid, School of Engineering. The aim of the ISE research is to apply lab scale experimental evidence and mathematical modelling to the industrial challenges of energy generation, in an efficient and sustainable way.
In the last 7 years, ISE research group has focused his efforts on the use of biomass as a source of energy. The main processes studied for the biomass conversion in the research group, have been the gasification and pyrolysis. As a previous step for the biomass thermochemical conversion, ISE research group has laboratory for biomass characterization, BIOLAB, which is part of the network of Laboratories of Comunidad the Madrid.

R&D Activities
- Study of the performance of fluidized beds and their application as gasifiers, pyrolyzers and combustors to transform biomass
- agglomeration phenomenon in both cold and hot facilities using pressure fluctuations signals
- gasification and pyrolysis
- combustion mechanics and use of biomass as an energy source

FBC facilities
- Lab-scale BFB gasifier of 52 mm inner diameter and a total length of 1480 mm

University Complutense of Madrid (UCM). Faculty of Chemistry, Department of Chemical Enginnering, Group of Physical Chemistry of the Environmental and Industrial Processes
Location: Madrid

Overview
UCM's Department of Chemical Engineering has 8 Professors around 400 undergraduates and 20 postgraduate students. It has a lot of specialized laboratories and a building for pilot plants.
Within the Group of Physical Chemistry of the Environmental and Industrial Processes, the thermochemical Conversion Research Group is dealing with fluidized bed conversion technologies for over 30 years.

R&D Activities
- The team is able to carry out experiments concerning gasification and combustion of biomass, waste and/or other fuels. Moreover, this team has several years' experience on catalytic hot gas cleaning from gasifiers and combustors.
- Main research interests are focussed about the valorization of waste and biomass residues by gasification processes.
- Main topics of interest: Biomass gasification, waste gasification, tar abatement, valorization of energy crops, catalytic gas cleaning.

FBC facilities
- Pilot plant consisting of a bubbling fluidized bed gasifier (BFBG) (D=15 cm, H= 4.2 m), primary air and secondary air injection, two cyclones in series, and a catalytic (monolithic) reactor. The gas flow to the monolithic reactor can be made independent of the total gasification gas flow produced

Universidad Politécnica de Madrid, (UPM), School of Agricultural Engineering
Location: Madrid

Overview
Grupo de Agro-energética (Agroenergy group) is a research group based on the College of Agricultural Engineering at UPM, but it also includes researchers of the College of Industrial Engineering. Their research interest focuses on four lines: Bioenergy, Sustainability, Plant Production and Phyto-depuration.

R&D Activities
- Capacities: biomass production; engineering; chemistry; thermal processes
- Research interests: Bioenergy, Analysis of energy systems and Life Cycle Analysis (LCA); Plant Production; Phyto-depuration.
- Topics: the topics most related to Developments in FBC are the following: Biomass, energy crops, sustainability, Life Cycle Analysis (LCA), charcoal, gasification, pyrolysis, carbonization, torrefaction.

FBC facilities
- Laboratory scale fluidized bed reactor (1 kg/hour) with micro-GC for fast pyrolysis, gasification and combustion
- Bench scale 2D and 3D fluidized bed simulator

Universidad de Extremadura (UEX), Department of Apllied Physics, Group for Comprehensive utilization of waste biomass and Renewable Energy, GAIRBER.

Location: Badajoz

Overview

Research conducted at GAIRBER group focuses on the use of biomass waste for energy purposes as well as techniques that add value to biomass

R&D Activities

- Technical consultancy on different uses of wastes for added value materials, including exploitation of biomass, production of biofuels and activated carbons
- Technical advisory to biomass boiler manufacturers, agriculture producer, government, consulting and engineering companies.
- Biomass exploitation using techniques such as combustion, pyrolisis, hydrothermalcarbonization, and gasification.
- Study and development of agro-crops.

FBC facilities

- Pilot gasification installation consisting of a bubbling fluidised bed reactor, operating slightly below atmospheric pressure. It is an 80 kW autothermal reactor, made of a carbon steel with internal refractory lining, circular in cross-section with an inside diameter of 400 mm and with a height of 2050 mm.

SWEDEN

Bo Leckner, Jan Kjärstad, Filip Johnsson
Department of Energy and Environment, Chalmers University of Technology, Sweden

Background

This is an update of a previous study reported in 2011 [1]. The data presented are based on official data from the Swedish Energy Agency [2], the manufacturers of FBC boilers [3] and Chalmers power plant database [4].

Electric power and fuels

The electric power generation system of Sweden is dominated by hydro and nuclear power as seen in Figures 1 and 2. Data has been taken from [2].

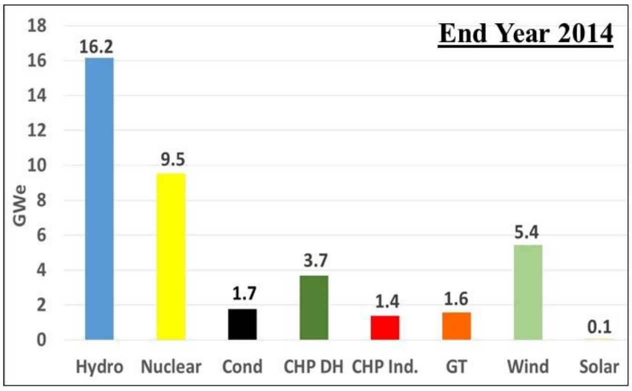

Figure 1. Installed power in the Swedish electricity generating system at the end of 2014.

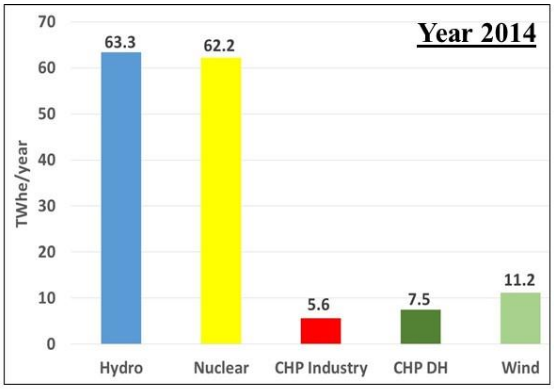

Figure 2: Produced electric power in Sweden in 2014

The fuels burnt to generate non-nuclear power and district heat (DH) in Sweden in 2014 are given in Figures 3 and 4, respectively. Data has been taken from [2].

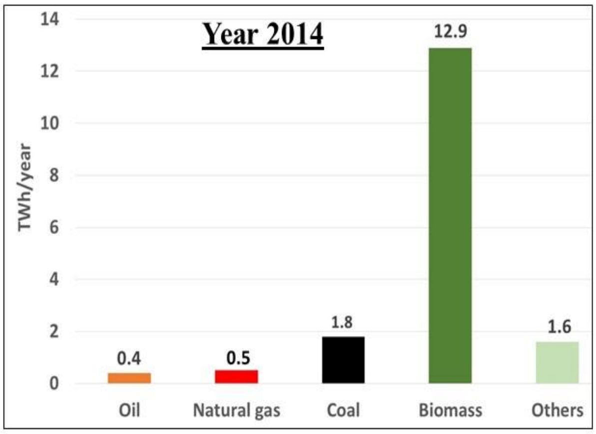

Figure 3: Non-nuclear fuels for power generation 2014, TWh/year

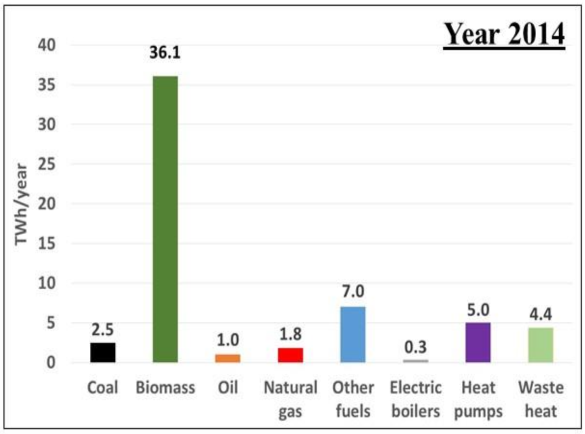

Figure 4: Fuel and energy sources for production of district heat in 2014, TWh/year

Fluidized Bed Combustion

Data shown exclude some fluidized bed boilers supplied by Andritz since verified lists have not been received from this company. Yet, FBC boilers supplied by Andritz are registered in the database (see Table 1).

As of January 2016, a total of 119 FBC boilers with a combined thermal capacity of 6,920 MW_{th} have been installed in Sweden. Total power generation capacity of the Combined Heat and Power (CHP) plants that have installed an FBC boiler is 2,273 MW_e. At least 22 of the FBC boilers are installed in heating plants, i.e. no electricity is produced. Their total thermal capacity is nearly 510 MW_{th}. Figure 5 shows the geographical spread of the FBC boilers in Sweden. BFB boilers are shown as blue circles and CFB boilers as red squares.

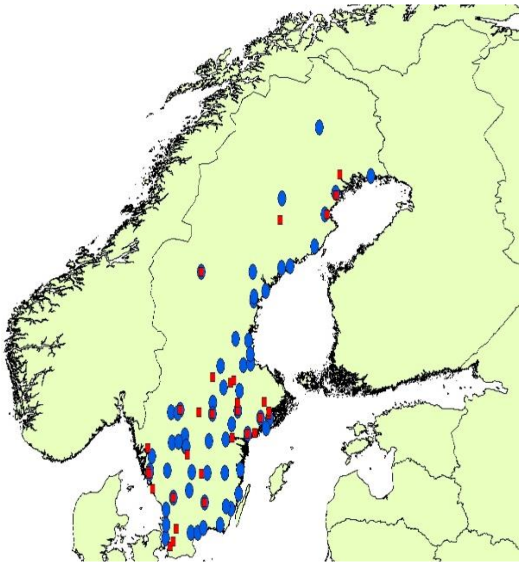

Figure 5: Geographical distribution of Fluidized Bed Boilers in Sweden. BFB boilers are shown as blue circles while CFB boilers are shown as red squares.

78 of the boilers are BFB with a combined thermal capacity (steam or hot water) of 3,743 MW_{th} and electric power generation capacity of 1,158 MW_e. The mean thermal capacity per BFB boiler is 48 MW_{th}. Nine of the BFBs are grate-fired boilers converted to fluidized bed in paper and pulp mills. Their combined thermal capacity is 913 MW_{th}.

40 of the boilers are CFB with a combined thermal capacity of 3,092 MW_{th} and a combined electric power generation capacity of 1,115 MW_e. Thus, the mean thermal capacity per CFB boiler is considerably larger than the corresponding value for BFB, namely 77 MW_{th}.

Additionally, a 35 MW_{th} CFB gasifier was delivered by Valmet (Kvaerner) in 1987 but this device has been decommissioned.

Figures 6 and 7 show total thermal capacity and, in parenthesis, corresponding number of units for fluidized bed boilers installed in Sweden and sorted by installation year (Figure 6) and by main fuel (Figure 7). The CFB gasifier has not been included.

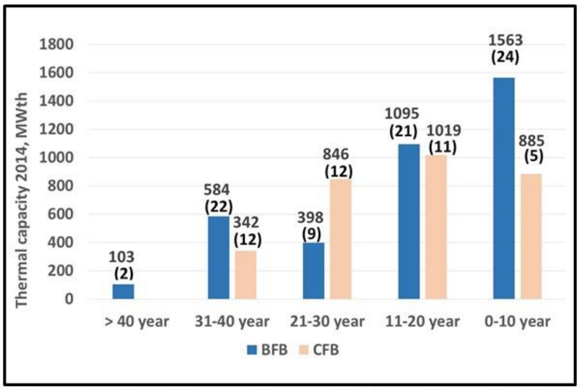

Figure 6: Total thermal capacity (number of units) of FBC boilers installed in Sweden by end of 2015 sorted by installation year.

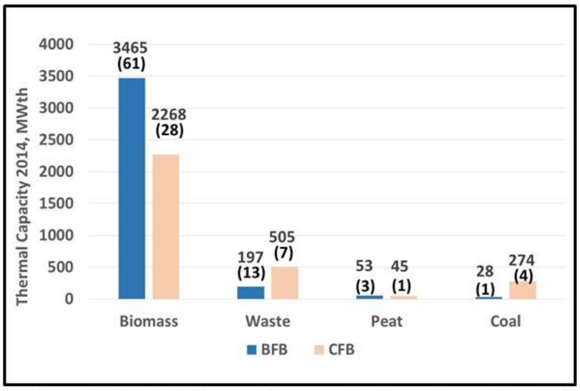

Figure 7: Total thermal capacity (number of units) of FBC boilers installed in Sweden by end of 2015 sorted by main fuel.

It is not known how many of these boilers that are presently in operation, but it is clear that the two oldest ones (> 40 years) are actually grate-fired boilers converted to BFB 1994-95.

It is interesting to note that mean thermal capacity per boiler has increased continuously since the first FBC boilers were supplied to the Swedish market in the 1970s, and this is shown in Figure 8.

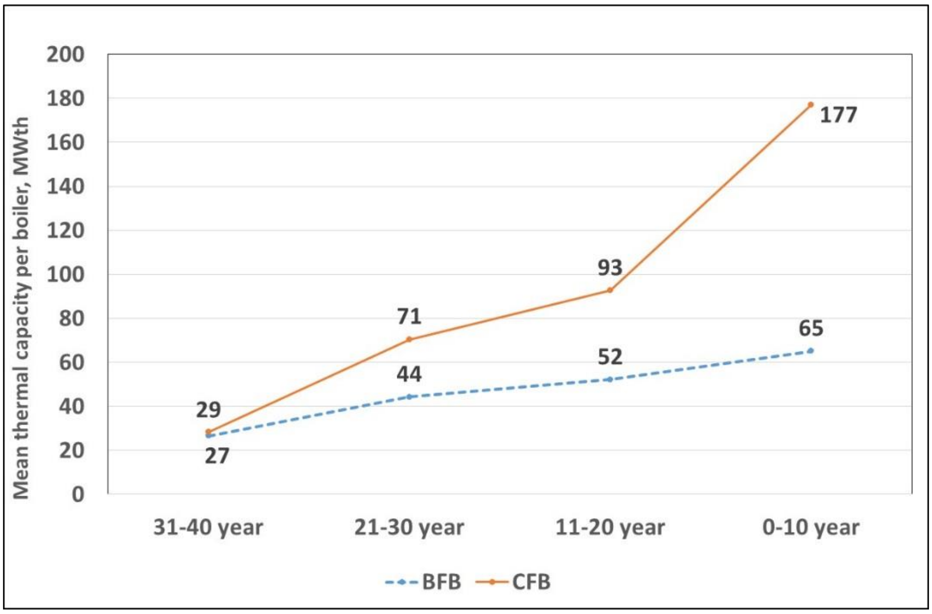

Figure 8: Mean thermal capacity per boiler as function of installation year at the end of Year 2015

Table 1 shows the thermal capacity (number of units) of the FBC boilers sorted by supplier. The CFB gasifier has not been included in the table.

Table 1: Suppliers of FBC boilers by thermal DH capacity, MW_{th}, (number of units)

	BFB	**CFB**
Foster Wheeler	840 (18)	1,519 (16)
Kvärner/Metso/Valmet	2,400 (47)	808 (19)
Andritz	266 (5)	280 (1)
Unknown	237 (8)	485 (4)
Total	**3,743 (78)**	**3,092** (40)

CFB from Kvärner/Metso/Valmet excludes the 1x35 MW_{th} CFB gasifier.

Trends and conclusions

During the five years from the previous study [1] the following trends can be seen:

1) The power system and its electricity generation is about the same but there has been a substantial increase in wind energy. (Figures 1 and 2).

2) Oil, gas, and coal for power production have decreased further from already low values. (Figure 3). However, the use of biomass in district heat (and power) has increased by about 30% (Figure 4).

3) The number of FB boilers, particularly BFB has increased considerably during the last ten years. They, and the CFB boilers, are quite small boilers for district heating or industrial systems using biomass (Figure 6 and Figure 7).

4) Figure 7 shows a doubling of the use of biomass in FBC boilers during the last five years.

FBC boilers under construction

Sobacken, Borås CHP, Värmekällan block 4, Skövde and Nybro (waste) CHP. Total electric power 57 MW_e and heat capacity (district heating) 138 MW_{th} are presently under construction and not included in the above diagrams or tables.

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[3] Personal communications with Alstom, Babcock and Wilcox, Foster Wheeler and Valmet including the former Metso/Kvärner.

[4] Chalmers Power Plant Database is a continuously updated database on all power plants in Europe with a capacity of 1 MW_e or more. The database contains almost 16,000 units (as of March 2016) and plants are usually registered on block level.