ROLE AND CHALLENGES OF CFB IN A CHANGING ENERGY MARKET

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Abstract – The energy market is experiencing major changes to address the environmental demands of modern society. Ongoing and planned changes require ever higher plant efficiency and emission performance. Even more drastically, changes are pushing the energy sector towards Renewable Energy Sources (RES), which bring entirely new challenges in terms of security of power supply, reflecting in stricter demand on flexibility of power plants to grid requirements. The additional costs entailed by such demands are considerable, and savings must be found in every aspect of the plant management to assure a sustainable business for plant owners. Power plants digitalization can come to the rescue in this area, promising a holistic optimization of the plants during procurement, operation, and maintenance. But the rising environmental demands do not only bring new challenges, they also offer new opportunities, such as using the power sector to support the decarbonation of other sectors, and providing means within the power plants to store energy when in excess. All combustion plants, regardless of their technology, will need to address such issues. Circulating Fluidized Bed boilers (CFB) are also developing in these respects, focusing on the inherent strengths of this technology for added value in the tough competition for new installations and retrofit to existing plants.

INTRODUCTION

The energy market is experiencing major changes to address the environmental demands of modern society. Ongoing and planned changes require ever higher plant efficiency and emission performances. Simultaneously, in response to increasing shares of Renewable Energy Sources (RES, especially solar and wind), combustion plants are also expected to operate with higher grid flexibility, i.e. with faster ramping capabilities and lower minimum load operability. Digitalization, decarbonation, and energy storage are all very actual subjects which also bring new challenges and opportunities. This paper gives a quick overview on these topics, focusing on the challenges and strengths of Circulating Fluidized Bed boilers (CFB).

PLANT EFFICIENCY

Efficiency has been for long time a critical item in the energy business. Higher efficiency reflects in less resources needed to obtain a desired amount of energy: less fuel, smaller equipment, and ultimately less emissions and byproducts to handle. Higher efficiency also means lower emissions of carbon dioxide (CO_2). Higher plant efficiency can be obtained by several means: higher steam data, optimized steam cycle (e.g. reheat or double reheat), more heat recovery from the cold end, better control and lower losses from plant equipment.

The highest efficiency improvements have been achieved by rising steam parameters. While the first coal-fired CFBs of the early 1980s superheated steam to around 535°C, the first supercritical (SC) CFB unit in Łagisza (Poland) was designed for 563/582°C (SH/RH), and the first ultra-super critical (USC) CFBs in Samcheok (South Korea) are demonstrating operation with steam temperature of 603/603°C (Tab.1). Correspondingly, the plant net efficiency has increased from ~30% of the 1980s to figures currently exceeding 43%$_{LHV}$ (Fig.1).

Such achievements have required the use of more expensive materials, capable to handle the mechanical stresses and hostile conditions brought by higher temperatures. Further increases of temperature would require even more expensive materials. Many studies have been conducted to identify the best materials for the purpose, and to demonstrate their long-term reliability (e.g. AD700, COMTES700, ENCIO, MacPlus, MARCKO DE 2, MARCKO 700, and NRW PP700). Although some promising materials have resulted from these studies, the commercial interest in Advanced-USC CFBs with temperatures reaching 650 or even 720°C appears currently low. The benefits of increasing steam temperature up to 650°C are too low compared to the extra costs of needed materials, and materials proven suitable for 720°C are not commercially available.

Increasing the degree of heat recovery from the cold end is a promising alternative toward higher efficiency. Flue gas heat can be recovered with heat exchangers at temperatures above the flue gas water dew point (i.e. 40 − 70°C depending on fuel), resulting in 0.5 - 1 %-points efficiency gain in power production (and more in CHP). Even higher gain in overall efficiency can be achieved with flue gas condensers (scrubbers), which may cool the flue gas even to approx. 30°C. While the technology for heat recovery has matured, sufficiently large heat sinks at appropriate temperature levels have to be found to optimize the process. In condensing turbine operation, the low-temperature condensate can be heated with recovered heat, decreasing the turbine steam extractions. Preheating of combustion air upstream of tubular (or rotating) air preheateres replaces auxiliary steam otherwise used for the purpose. In combined heat and power production (CHP), district heating (DH) return water provides an abundant heat sink.
Traditionally the flue gas exit temperature has been rather high (130 − 160°C) in solid fuel firing power plants, particularly due to concerns of sulfuric acid dew point corrosion. However, in CFB boilers fly ash is usually rich in alkaline and alkaline earth compounds, especially calcium, which readily react with acid gas vapors upon further cooling of the gas. This shifts the formation of acid-rich condensate toward lower temperatures. Corrosion resistant heat exchangers utilizing plastic tubes or high alloy tubes are already proven technology mainly at large high-efficiency condensing power plants producing electricity only, e.g. the Łagisza CFB unit. With such equipment flue gas can be cooled well below 100°C. Besides condensation of acid gases, fouling and corrosion under hygroscopic deposits (e.g. calcium chloride, $CaCl_2$) have to be taken into account, particularly with chlorine containing, moist fuels such as biomass or waste derived fuel. To keep fouling under control, such heat recovery coolers are provided with cleaning systems.

Flue gas condensing (FGC) recovers also the latent heat of flue gas that is substantial with moist fuels, and integrated scrubbing stage enables further purification of flue gases. The water balance is positive, and the excess water has to be purified before draining or utilization. Condensed warm water can also be used for humidification of combustion air, which further enhances the heat recovery process especially with drier fuel. In CHP applications, FGC is capable to increase the overall efficiency from near 90% to well above 100% (LHV). The main drawback, besides additional investment, is decrease in power output (e.g. -5%) resulting mainly from higher turbine back pressure. When FGC is combined with heat pumps that decrease the DH water inlet temperature, the gain in efficiency can be even 20 %-points, albeit with further loss of net power. In the Nordic CHP market heat production is favored over power production, and as new emissions regulations often call for additional investments in gas clean-up, FGC has become a standard solution. On the contrary, economics have not favored other heat recovery options such as fuel drying or Organic Rankine Cycle (ORC).

Lowering the losses from plant equipment is yet another way to increase efficiency. Losses can be reduced in furnaces by reducing the combustion air coefficient and optimizing fans setup and operation. These measures are simple, but require care to avoid costly side effects, e.g. furnace wearing due to local reducing conditions. CFBs can further benefit from the fine-tuning of air distribution through grid and along the furnace, and of the solids/gas separation at the cyclone. Although the contribution from each individual component may be small, the cumulative result from a systematic optimization of all equipment can add up to significant figures. Studies conducted at Amec Foster Wheeler have clarified that even starting from the best designs and practices in the industry, the power requirement for boiler auxiliary equipment could be still reduced by as much as 8-13%, depending on cases, contributing to an increase in plant net efficiency in the order of 0.15 - 0.25 %.

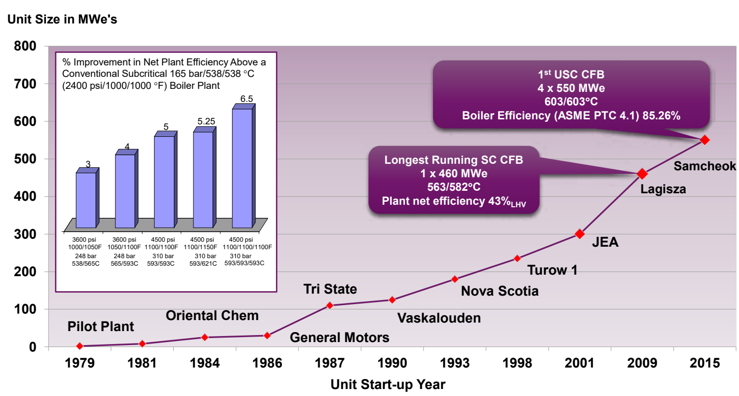

Fig. 1. Increase of plant efficiency with CFB boilers from the 1980s, and advantage of SC steam data.

Tab.1. First world supercritical CFB and Ultra-supercritical CFB, by Amec Foster Wheeler.

	Łagisza	**Samcheok**
Electric Output (MWe)	460	4 x 550
Total Heat Output (MWth)	966.3	4 x 1166
Steam Flow (kg/s)	361/306	437/356
Steam Pressure (bar (a))	275/50.3	257/54
Steam Temperature (°C)	563/582	603/603
NOx (mg/Nm^3)	200	103
SO2 (mg/Nm^3)	200	143
PM (mg/Nm^3)	30	20
Start up	2009	2016

Tab. 2. Emission limits (mg/Nm^3, dry, 6% O_2, unless specified differently) planned in EU for new plants firing coal over 300 MWth. Simplified table.

Pollutant	**Technology**	**IED**	**BREF** (daily)	**BREF** (yearly)
SOx	PC	150	25 - 110	10 - 75
	BFB	150	25 - 110	20 - 75
	CFB	200	200	
NOx	no PC	150	80 - 125	50 – 85
	PC	200	200	65 - 85
PM		10	3 - 10	2 - 5
NH3		-	-	< 3 - 10
Hg (μg/Nm^3)		-	-	<1-2
HCl		-	-	1 - 3
HF		-	-	<1 - 2

GASEOUS EMISSIONS

Gaseous emissions are another long-term critical item in the energy business. However, the challenges have reached a whole new dimension during the last decade. While the early-days recommendations in US and Europe targeted only main emissions of sulfur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM), nowadays emissions are regulated in most countries around the globe, covering a broader range of pollutants, and often address emissions during low load operation of plants.

Regulations in the European Union (EU) can be used as example. In 2013 the Industrial Emission Directive (IED) superseded earlier directives, setting "safety net" limits for traditional emissions (DIRECTIVE 2010/75/EU). More critically, the IED established the key role of binding documents known as the BREFs (Best Available Technology Reference documents). Among those, the most important for CFB applications is the Large Combustion Plants BREF (LCP-BREF). The LCP-BREF sets further emission limits, which local authorities should respect while granting environmental permits to plants. This includes stricter limits on SOx, NOx, and PM, but also add limits on new pollutants, namely NH_3, Hg, HCl, and HF. The BREF does not set limits for CO, though it provides some indicative levels and the requirement to monitor it, for future regulations. Different limits are set for different fuels (coal, lignite, biomass, and peat among the solid fuels), boiler sizes (50-100, 100-300, and over 300 MWth), and in special cases also for different technologies. An example is given in Tab. 2, which shows the limits set in the IED and the LCP-BREF for new plants firing coal above 300 MWth. The application of the LCP-BREF is scheduled for late 2017 to early 2018, after which new plants will have to comply and existing plants will have up to 4 years to comply.

The lowest emission levels may demand for dedicated post-cleaning equipment such as scrubbers for acid gases, SCR catalyst for NOx, and bag filters for PM and heavy metals. However, the CFB technology will still benefit from its widely recognized advantages of low temperature (low NOx) and sulfur capture in furnace (low SOx) inherently from fuel or with limestone additive. Therefore, CFB boilers allow one more degree of freedom compared to other technologies, allowing to choose whether to focus the control for each emission in furnace, at the back end, or share it between the two locations to best accommodate the needs of the operator.

Amec Foster Wheeler has worked relentlessly on the improvement of emissions control, in furnace and downstream. Efforts went to further decrease NOx in furnace, thus allowing to minimize the need of SCR catalyst and additives. These efforts showed potential for over 20% NOx reduction in mid-scale coal-fired CFBs without SO_2 penalty, and as much as 35% reduction with a certain SO_2 penalty, easily manageable downstream (Fig. 2), and without additional risk for erosion, corrosion, or other side effects. Concerning the downstream options, considerable efforts are still devoted to further improve the effectiveness of Circulating Fluidized Bed Scrubbers (CFBS), which decrease the need for additives and improve the effectiveness in capturing not only SOx but also other acid gases and heavy metals (Tab. 3).

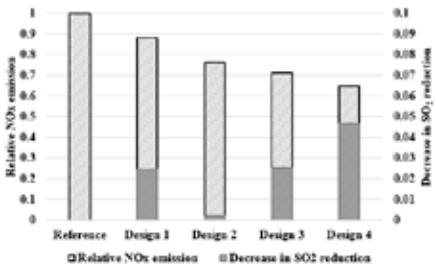

Fig.2. NOx reductions in a coal fired CFB unit using different design changes (Kipinoinen et al., 2017)

Tab. 3. Performance of Amec Foster Wheeler's commercial Circulating Fluidized Bed Scrubber (CFBS)

Pollutant	Stack Emission Level (dry, 6% O_2)	Removal Rate
SO_2	10 – 200 (mg/Nm³)	85 – 99%
SO_3	0.1 – 1(mg/Nm³)	90 – 99%
HCl	< 1 (mg/Nm³)	99+%
HF	< 1 (mg/Nm³)	99+%
PM FF	2 – 20 (mg/Nm³)	
PM ESP	20 – 50 (mg/Nm³)	
Total Hg	3 – 50 (µg/Nm³)	60 – 80%
	1 – 35 (µg/Nm³)	80 – 90%
	1 – 30 (µg/Nm³)	90 – 99%
Dioxins/Furans	0.009 – 0.08 (ng/Nm³)	95 – 98%

PLANT FLEXIBILITY

Until recently, plant flexibility has been synonymous of fuel flexibility. Nowadays, plant flexibility has taken an additional meaning, focusing on the flexibility of the plant to satisfy the demands from the electric grid.

Fuel flexibility has been always a stronghold of fluidized bed technology. Especially CFB boilers have been fully capable to operate efficiently and reliably with a vast variety of fuels and their mixtures, ranging from fossil fuels, to biomass, and various wastes (Coda Zabetta et al., 2013). During the last 15 years CFBs designed for coal have successfully co-fired major shares of biomass (e.g. Kobyłecki et al., 2005, Khan et al., 2009, Leffler et al., 2016), and new CFB units have entered operation to fire ever broader varieties of residuals (e.g. Natunen et al, 2013), so much so that the superiority of CFB in fuel flexibility has remained undisputed.

As for the flexibility to electric grid requirements, this is a fairly new story for utilities. Recent energy policies have revolutionized the energy market. Under the impulse of incentives, the share of Renewable Energy Sources (RES) on the energy market has exploded. In Europe, for example, objectives have been set to reach 20% RES share by 2020, and 27% by 2030. EU's Energy Roadmap 2050 considers that the RES share in electricity consumption could reach 97% by 2050. This revolution is happening mostly though the installation of solar and wind power. Both these sources are highly intermittent, hardly predictable in the mid-term with 3-6% accuracy 1 hour ahead, and unpredictable in the longer term with 6-8% accuracy 1 day ahead (Alobaid et al., 2016). As a consequence, the same large combustion plants that were earlier securing the base load to the electric grid, now are required to compensate for the variability of RES sources. To cover their new role, combustion plants need to ramp up and down more rapidly, and need to be operable at lower minimum load.

Depending on fuels (solid), current CFBs can typically ramp up and down at a rate of 2-5% (MCR) within 30 seconds under primary control, and a rate of 2,5 – 4% per minute under secondary and tertiary control (Fig.3). Most units can maintain minimum load operation down to 30% MCR. Future targets to accommodate grid requirements are expected to go as high as 10% within 10 seconds by primary control, 5% per minute by secondary and tertiary controls, as well as to allow minimum load operation down to 15-20% MCR. This should be achievable by applying advanced controls, by improving the balance between boiler and turbine so that both participate in ramping, and by fully utilizing the energy stored within the process, possibly including extra storage (Kovacs et al., 2017). The larger thermal inertia of CFBs allow more reliable ramping and minimum load when fuel quality or feeding are inconsistent.

Even though higher grid flexibility of plants is technically viable, it remains a serious economic burden, as expensive and complex installations are used to produce energy for only a limited time and at limited capacity. To make things worse, their maintenance costs are likely to increase due to the additional stresses and wears caused by erratic operation. A tempting alternative could be to multipurpose these plants, and widen their scope from heat and power generation, to the generation of other sellable goods (energy-to-products), allowing to operate the plant and generate profit also when the electric grid does not need input (Bocin et al., 2013; Hendriks et al., 2013). Amongst other opportunities in this area, fuel upgrade seems a viable option, where extra energy during the picks from RES sources can be used to upgrade the fuel for the combustion plant, a better fuel allowing higher response and lower load operation of the plant when needed (Fig.4). Other opportunities may be in decarbonation and energy storage, as discussed below.

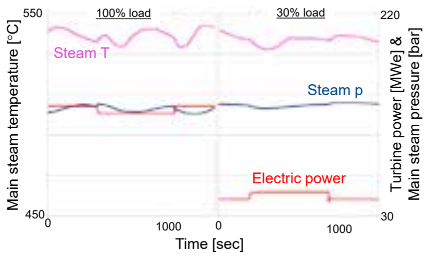

Fig. 3. Primary grid support in a 300 MWth CFB firing lignite at full and minimum load (based on Kovacs et al., 2015)

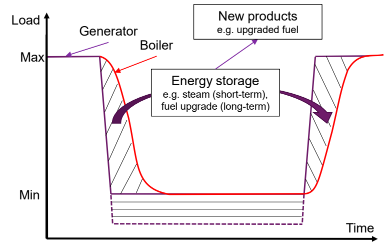

Fig. 4. Example of increased plant flexibility by storing/utilizing excess energy from the ramp-down phase to boost the ramp-up phase.

DECARBONATION

Decarbonation is the action to reduce the buildup of carbon dioxide from human activities in the atmosphere. Decarbonation from the energy sector has been largely addressed by replacing combustion sources that use fossil fuels with Renewable Energy Sources (RES). As discussed in the section about plant flexibility, however, a complete transition is not possible within the coming 20-30 years because reliable and dependable sources of electricity are needed on demand to secure the electric grid. A more interesting approach looks at combustion plants not as the problem, but as part of the solution to decarbonation.

Intense developments have been made for the last 15 years in the capture of carbon (dioxide) from combustion of fossil fuels and sequestrate it, the technique going with the name Carbon Capture and Storage (CCS). The technically feasibility of CCS has been proven, and the CFB technology has its contribution in this via the Flexi-Burn® technology (Eriksson et al., 2009 & 2013). However, the economics of CCS are just not right, at least as long as the value of CO_2 credits remains below 20-30 €/ton CO2 (e.g. Nuortimo et al., 2017).

In order to turn the economy right, CCS has been turned to Carbon Capture and Utilization (CCU). Now, instead of having a costly operation to sequestrate CO_2, the CO_2 can become integral part of sellable goods. The role of CFB remains unchanged from CCS to CCU, as Flexi-Burn® can supply CO_2 of a grade suitable for further utilization, whether that is production of new fuels (energy-to-fuels such as methanol or methane), desalination of ground water, mineralization, or others (Bocin et al., 2013). High expectations from CCU are confirmed by the generous funds recently secured by the European Commission though its Horizon 2020 programs (Hendriks et al., 2013).

CCU can help to reach the targets adopted in the Paris Agreement (COP21, 2015) and implemented in November 2016 (COP22), i.e. to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. However, several experts have argued that the only way to pursue such target is to go CO_2-negative, i.e. to create sinks for CO_2. Here again, the CFB technology is a great asset. A biomass-fired CFB boiler with Flexi-Burn® technology can remove CO_2 generated from biomass for storage or utilization, effectively setting the CO_2 balance to negative.

ENERGY STORAGE

Energy storage is yet another necessity rising from the massive introduction of RES sources. As their input to the grid is erratic and somewhat unpredictable, it would be highly convenient to store energy from RES when generated in excess, to be promptly available during shortage periods. Many technologies – e.g. pumped hydro, flywheel, battery, compressed air, chemical, thermo-chemical, and thermal energy storage – are commercially available to store electrical energy at different rated capacity and discharge time, but no technology is fully proven or commercially viable for the scales and times required in the energy sector (Luo et al. 2015, Hameer et al. 2015). For example, electric batteries are a largely proven and available technology, but the cost of their deployment is very high, and this is unlikely to change any soon. Today, energy storage in batteries is mostly decentralized, and relegated to users keen to make such investment. Other ways, including the conversion of power into high energy density product (e.g. power-to-gas technologies), the utilization of district heating system as energy “battery”, or the production of higher grade fuels (e.g. Fig.4) provide alternative solutions.

CFB technology can be combined with numerous storage techniques, and has a clear advantage when it comes to store heat in process solids. Using extra energy to heat circulating material in CFBs would not only provide an alternative to energy storage, but would also enhance the grid flexibility of CFBs as cold startups could be largely replaced with hot startups, and could also allow lower minimum load.

DIGITALIZATION

Digitalization is the latest revolution in the power business. It comes from a much broader revolution, covering all sectors of society, from individuals, through households, to industry and services. The broad idea here is to connect digitally anything that can be connected, and to measure anything relevant and use the information to provide services with added value. In the power sector this means services to help developing new projects and retrofits, design, fabricate, and erect such projects, as well as tuning, operating, and maintaining new and existing projects. The idea is not new in itself. Early examples can be found from over a decade ago: for instance, Amec Foster Wheeler marketed an early form of such service with the name SmartBoiler™ (Soininen et al., 2003). As information technology has made major advances, however, the potential in this area is considerably higher today.

CFB technology can benefit from digitalization like any plant technology, possibly more since the CFB combustion process has more variables that can be optimize compared to some other technologies, e.g. gas combustors. Owners and operators of CFB plants can benefit from a large variety of services for outages and their planning (repairs, inspections), boiler tuning and maintenance over time of optimal boiler operation, and maintenance strategy. Such services are even more relevant when taking into account plant flexibility (see related section), as the experience necessary to optimize the plant for new types of grid requirements or fuels may differ considerably from the experience of local O&M departments. The knowhow necessary to manage such changes must come from a much deeper and holistic experience from CFB references.

Amec Foster Wheeler can count from the experience of over 460 CFB references, their design and supply, alongside their fuel data, process data, reliability/availability/maintenance data (RAM) to name a few. This is the solid backbone over which digital tools are built, tools that will help owners to increase the revenues and cut the maintenance costs from their units.

CONCLUSIONS

This paper offers an overview on the challenges and opportunities for Circulating Fluidized Bed (CFB) boilers in the currently changing energy market. Efficiency, emissions, flexibility, decarbonation, energy storage, and digitalization have been addressed. Higher efficiency, traditionally attained by rising steam parameters, today is pursued also through the increase of heat recovery from the cold end, and by lowering losses from the plant equipment. CFBs still benefit from their inherently lower emissions. For the tightest requirements, reduction of emissions can be optimally balanced between the furnace and cleaning equipment downstream. CFBs still offer unmatched fuel flexibility, and efforts are being made to increase its flexibility to more demanding grid requirements, including faster ramping and lower minimum load. Through Flexi-Burn® technology, CFBs can contribute to the planetary decarbonation targets not only via Carbon Capture and Storage (CCS), but also via Carbon Capture and Utilization (CCU). CFBs can also participate in the energy storage needs caused by Renewable Energy Source (RES), with unique advantages. Finally, CFBs can benefit from digitalization like any boiler technology, possibly more since CFBs have more parameters for optimization. However, real value can be gained only with digital services developed by highly experienced suppliers, which have access to deep knowhow and extensive data.

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