BENCHMARKING THE NORTH AMERICAN ATMOSPHERIC FLUIDIZED BED INDUSTRY

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ABSTRACT
Atmospheric fluidized bed combustion (AFBC) boilers are a mature, well established, and valuable technology. Their fuel flexibility, combustion efficiency, and relatively low emission levels have seen them attract new interest in recent times. In order to ensure plant sustainability it is important for AFBC plant operators to maintain a high level of operational performance and plant efficiency. Benchmarking is a tool that can aid the attainment of superior performance and efficiency levels. It has widespread use throughout many industries and allows managers to gauge how their company performs relative to similar firms and identify areas that are in need of improvement. Sponsored by Council of Industrial Boiler Owners (CIBO), this paper presents a set of North American AFBC industry benchmarks for the year of 2009. Focusing on both circulating and bubbling bed boilers, the benchmarks are intended to enhance the industry's overall efficiency and sustainability.

Keywords atmospheric fluidized bed combustion, benchmarking, fuel flexibility, emissions, biofuels, efficiency, environmental performance, outages

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AFBC TECHNOLOGY

AFBC technology was first introduced in the 1970's although technological development has occurred since the mid 1960's (Banales-Lopez and Norberg-Bohm, 2002; Koornneef, 2007). Bubbling bed boilers existed before circulating bed boilers and typically have a smaller power output. Circulating bed boilers have higher combustion efficiency, smaller furnace cross section, more efficient removal of SO_2, and fewer required feed points than the bubbling bed design; leading them to have higher levels of energy production. Fluidized bed boilers can be used for a variety of applications and use a variety of fuels including biomass and fossil fuel derivatives. These units are generally suited to smaller applications; typically AFBC plants are used as independent power generators or co-generators, rather than for utilities. AFBC units are known to be efficient and relatively environmentally friendly when compared with other power generating technologies (Banales-Lopez and Norberg-Bohm, 2002; Koornneef, 2007; Minchener, 2003).

AFBC boilers generate a range of emissions; depending on the fuel used these may include CO_2, CO, N_2O, NO_X, SO_2, particulates, and some heavy metals. At present emissions may be adequately controlled with the aid of pollutant technologies (Minchener, 2003). The operating conditions of AFBC boilers are naturally optimal for SO_2 capture with limestone. The lower combustion temperature of these units also incurs an intrinsic NO_X reduction quality (Banales-Lopez and Norberg-Bohm, 2002). Research is currently being conducted on the in-situ capture of CO_2 for biomass fueled AFBC reactors. This concept will enable AFBC plants to become a CO_2 sink, by means of a low temperature combustion process and CaO feedstock. Experimentation and modeling has shown this concept to be technically and conceptually feasible (Abanades et al., 2010).

AFBC units are attributed with being able to handle different feed sizes, having even temperature distribution, high heat transfer rates, and stable low temperature combustion operation. Their good air and bed material mixing properties allows them to burn fuels that have low energy content and high ash and moisture content. The fuel flexibility of AFBC units is an economic advantage as they are able to use cheaper low-grade and waste fuels (Banales-Lopez and Norberg-Bohm, 2002; Koornneef, 2007). The fuel flexibility of circulating bed boilers enables plant operators to select fuels based upon current market conditions and possibly generate a fuel blend that is the most economical, while still being able to provide adequate heat generation (Banales-Lopez and Norberg-Bohm, 2002). Some of the downfalls of AFBC technology include their requirement of very efficient solid-gas separation units, high levels of erosion on the boiler internals, high quantity of dust in the flue gas, and bed material agglomeration that causes defluidization problems (Khan et al, 2009).

BENCHMARKING

In order to ensure a company's sustainability it is imperative that they are able to outperform others on a quality, cost, and technological basis (Anand and Kodali, 2008). Benchmarking is a highly regarded technique for enhancing competitive advantage through improving business and operational performance. Organizations have been benchmarking for more than 25 years and it is now recognized as a useful management tool for growth potential rather than a fad that will fade away. Typically, organizations who utilize benchmarking outperform others (Adebanjo et al., 2010).

Benchmarking essentially identifies the industry best practices that lead to superior performance. It allows for learning about the environment, reduces uncertainty, and provides insights to the changes that would most benefit the company (Adebanjo et al., 2010; Banker and Khosla, 1995; Lere, 2009). The Benchmarking process consists of assessing performance, making comparisons to other facilities, prioritizing investments, efficiency investments, identifying opportunities, and justifiably setting targets for improvement. This process highlights where a company falls behind best practices; accordingly identifying the best places for optimization of operational efficiency and effectiveness. Giving plant operators the power to make sound decisions and control costs (Garris, 2008). This paper reduces the barriers of benchmarking as data has already been collected from across the industry, analyzed, and presented. The industry benchmarks offered here are process and performance based, key competitiveness factors within a power generation industry (Adebanjo et al., 2010).

Benchmarking is widely utilized across many industries, by organizations of various sizes. For meaningful results it is important to compare companies that are similar to one another. Business operations and cultures often vary greatly between countries which is why benchmarking usually focuses specifically on geographical areas or business sectors. The research presented here only considers AFBC plants from North America; their similarity therefore allows for valuable results (Adebanjo et al., 2010; Anand and Kodali, 2008; Lere, 2009).

Characterization of industrial competitiveness should be studied though multiple criterion, to provide a broad view of a company's performance (Guan et al., 2006). It is important that the benchmarks are relevant and that the organizational goals set through the benchmarking process are realistic (Jensen, 2011). Correspondingly, multiple benchmarks were developed for this research; they were designed to incorporate the factors most likely to influence operational performance and efficiency of AFBC plants. It is expected that the optimization of day to day operations and maintenance issues will yield best results from this process.

Benchmarking should be utilized on a continuous basis for sustained success and improvement. Consequently there is a need to adapt a benchmarking culture when there is a desire for change within a company (Metri, 2005). Involving all levels of the workforce in seeking continuous improvement is key to high quality management practices. This may be facilitated by worker empowerment where both ownership and accountability are given to employees for set tasks (Banker and Khosla, 1995). To ensure acceptance and proper execution of the benchmarking process employees must understand the objectives, motivation, and potential benefits of benchmarking. Communication of benchmarking progress and results is important for continued support (Garris, 2008). As a part of good benchmarking practice, the development of AFBC industry benchmarks is conducted on an annual basis (Fuller and Bessette, 2007; Fuller and Ayre, 2011a; Fuller and Ayre, 2011b; Fuller et al., 2006; Fuller et al., 2004; Fuller et al., 2005).

BIOFUELS

Rising environmental concerns over the use of fossil fuels has led to an ongoing search for greenhouse gas emission reduction solutions. One sustainable option is the use of biofuels, which are likely to become a vital contributor to future energy demands. Biomass appears to have the potential to help alleviate some social, environmental, and economical problems as its emissions is considered to be neutral. The rush to use biofuels in the power generation industry is being made more urgent by the rising cost and quickly depleting supply of fossil fuels (Khan et al., 2009; Metri 2005; Scala and Chirone, 2004).

While biofuels are quite versatile in that they may be obtained from and used in many locations, their diversity makes them complex to use; although AFBC technology is still capable of burning them (Khan et al., 2009). Difficulties of use arise from their widely varying chemical and physical properties, which leads to varying combustion behavior. Biofuels are typically more porous, structurally fragile, anisotropic, and intrinsically reactive than traditional fossil fuels. The high volatile content of these fuels allows them to have higher amounts of heat release. Indeed, if the residence time is long enough, combustion efficiencies may also be higher than that of coal (Scala and Chirone, 2004). Biofuels generally have a high ash content which can cause problems like slagging, agglomeration, deposition, and fouling. Cost savings arise from the use of biofuels through the displacement of other fuels like coal and from the costs that would have otherwise been incurred for fuel disposal (Khan et al., 2009).

RESEARCH AND IMPROVEMENTS

Recent developments in the AFBC industry have addressed environmental and scale up issues. Future developments are likely to improve upon plant construction, operations, efficiency, and reduce operating costs. Koorneef et al. (2007) predict that the three most important research and development issues in the future for AFBC boilers will be material handling, boiler reliability, and the reduction of environmental impact. Bubbling fluidized bed research issues are expected encompass the use of biomass (Koornneef et al., 2007).

Enhanced economic performance can be achieved by learning about AFBC technology. Modeling is, therefore, used as a tool to generate foresight and determine optimal operating conditions for these units (Koorneef et al., 2007). This is achieved by investigating the effects of various operating parameters like fuel type, fuel load, excess air used, and operational velocity (Gomez-Barea and Leckner, 2010; Gungor, 2010; Li et al., 2010). Modeling can save time and money when being used to support the design and real-system experiments (Gomez-Barea and Leckner, 2010). Exergoeconomic analysis is another tool used to optimize AFBC plants operations. It is capable of identifying the most cost effective ways of improving plant efficiency (Ozdemir, 2010).

Technological innovation for AFBC plants can reduce the cost of operations and their environmental impact. A major technical barrier to the operation of AFBC units is the reliability of fuel feeding systems and waste material disposal. Banales-Lopez and Norberg-Bohm (2002) suggest that third party research programs, like the benchmarking offered here, are capable of making significant contributions to the introduction of new technologies to the industry. It is hoped that this paper enables plant operators to engage in innovative adaptations utilizing the reduced risk that benchmarking offers (Banales-Lopez and Norberg-Bohm, 2002).

BENCHMARKING ANALYSIS

The following section presents a set of AFBC benchmarking data collected for the year of 2009. Data for the benchmarks were collected via a survey from CIBO members and other firms who operated an AFBC on-site in 2009. The survey contained questions pertaining to general plant, efficiency, environmental performance, and plant operation information. Multiyear data were requested for some sections of the survey. This was done to identify trends in the data and to establish multiyear averages. Multiyear data in this research pertains to data collected for the years 2004 through 2009. Engaging in the benchmarking process, plants will be able to identify where they fall short of industry standards and begin to implement change to correct this. The benchmarks and corresponding data may be found in Tables 1, 2, and 3.

Table 1: Benchmark Descriptions

Benchmark	
1	Total gross boiler heat rate, BTU/gross kW·h (per boiler)
2	Total net boiler heat rate, BTU/gross kW·h (per boiler)
3	Individual boiler start-up date
4	Number of FBC boilers in facility
5	Plant efficiency or heat rate, BTU/kWh (per plant)
6	Boiler efficiency percent (per boiler)
7	Steam used by customers for purposes other than to generate electricity, million BTU
8	Fly ash used for beneficial purposes (per boiler)
9	Fly ash sold to third parties (per boiler)
10	Bottom ash used for beneficial purposes (per boiler)
11	Bottom ash sold to third parties (per boiler)
12	Ca/S ratio (per boiler)
13	Number of full time staff per million MW·h
14	Number of full time management per million MW·h
15	Man-days of lost time accidents in 2009
16	Respondents who have begun addressing the new boiler MACT with respect to Mercury emissions
17	Percent of time boiler/plant available
18	Percent of outage hours that were forced
19	Percent of outage hours that were boiler related

Table 2: 2009 Benchmark Results (for Benchmarks 1-16)

Benchmark	Number of Responses	Group		
		Overall	>40 MW net	≤40 MW net
1	12	11,019	13,766	10,014
2	13	13,149	16,803	11,322
3	32	1988	1983	1993
4	18	1.8	1.4	2.1
5	10	12,884	13,940	12,038
6	16	87%	85%	89%
7	11	505,456	404,369	626,759
8	28	50%	62%	42%
9	32	4%	0%	7%
10	27	66%	60%	72%
11	32	0%	0%	0%
12	16	2.6	2.4	2.7
13	18	34	33	35
14	18	5.7	4.3	7.1
15	10	18	16	22
16	17	40%	29%	50%

Table 3: 2009 Benchmark Results (for Benchmarks (17-19)

Benchmar k	Time Period	Group				
		Overall	Coal	Gob	Pre-1990	1990-Post
17	2009	89%	83%	95%	92%	85%
	Multiyear	90%	89%	95%	89%	91%
18	2009	38%	20%	54%	12%	44%
	Multiyear	34%	28%	35%	35%	33%
19	2009	83%	89%	70%	92%	84%
	Multiyear	87%	88%	91%	83%	91%

The benchmarks are ultimately aimed at generating superior operational performance and therefore sustainable competiveness for both the individual AFBC plants and the industry as a whole.

SURVEY RESPONDENTS

The survey had 18 AFBC plant respondents, with plant size ranging from six through 569 net megawatts (MW). Four of these plants had a size of less than 40 net MW and 12 had a size of greater than 40 net MW. There were a total of 32 boilers included in the survey as some plants have multiple boilers onsite. The average number of boilers on site was 1.8. Four bubbling fluidized bed (BFB) boilers and 28 circulating fluidized bed (CFB) boilers were included in the survey. Seventeen plants provided fuel source information; 10, 5, 1, and 1 plant(s) use coal, gob, culm, and wood as their fuel source, respectively. Three plants use a secondary fuel source, including natural gas, wood, and biomass.

PLANT INFORMATION

The 18 plant respondents had an average of 0.71 full time staff per gross MW capacity. This value varied from 0.7 through 1.81 for individual plants. The average number of full time management employees per gross MW capacity for these plants was 0.13, varying from 0.01 to 0.55. For 11 respondents, an average of 18 man-days of lost time was incurred from accidents in 2009, varying from 0 to 91 for individual plants.

EFFICIENCY

The total gross boiler heat rate was determined from the 12 plants that responded to this section of the survey. Overall the average heat rate was 11,019 British thermal units per total gross kilowatt hours (BTU/kW·h). For plants greater than 40 MW in size this average was 10,104 BTU/kW·h.

For the 16 plants that responded to this section, the overall average boiler efficiency in 2009 was 86.1%; this ranged from 75% to 99% for individual boilers. Plants larger than 40 MW in size also had an average boiler efficiency of 89%; while smaller plants had a slightly higher average efficiency of 85%.

ENVIRONMENTAL PERFORMANCE

The calcium to sulfur (Ca/S) ratio of the fuel mixture affects the desulfurization ability of an ABFC unit. Ca/S ratio data was obtained for 16 boilers. This ratio varied from 1.8 to 3.3 for individual boilers and had an average value of 2.6. AFBC boiler ash byproducts may be used in secondary applications like backfilling a mine or as an input to concrete production. Recycling byproducts reduces disposal costs and occupied landfill space. Using data supplied for 27 boilers it was determined that an average 50% of fly ash and 66% of bottom ash was used for beneficial purposes in 2009. For individual boilers this value ranged from 0 through 100% for both fly and bottom ash.

The United States Environmental Protection Agency regulates mercury emissions for stationary power plants according to the Clean Air Act. This act stipulates that mercury emissions be controlled by the maximum achievable control technology (MACT); compliance with this act was required by December 2007. The survey showed that an average of 40% of 17 respondent plants were currently addressing this issue.

PLANT OPERATION

A benchmark for plant availability was created for the year of 2009. This was achieved by subtracting the total outage hours for each plant from the total hours in one year and averaging these values for all plants. The overall average percent of time that plants were available in 2009 was 89%, ranging from 85% to 92% for individual plants. For the years 2004 through 2009 this overall value has remained between 89% and 91%. Plants constructed before 1990 (pre-1990, herein) were available an average of 92% of the time in 2009, this value was 85% for plants constructed from 1990 through present (1990-post, herein). This was unusual as for the years 2004 through 2008 pre-1990 plants consistently had a lower average annual availability than those constructed more recently.

Data collected for 2004 through 2009 demonstrated that on average plants that use coal as fuel consistently had a lower annual availability than gob fuelled plants. For these years coal fuelled plants had an average availability of 89% and gob fuelled plants had an availability of 95%. During 2009 coal fuelled plants and gob fuelled plants were available for 83% and 95% of the time, respectively.

Forced outages were investigated by the survey. A forced outage benchmark was created for each plant by subtracting planned outage hours from total outage hours and dividing this value by the total outage hours. Individual plant percentages were then averaged. Forced outage hours represented an average of 38% of the total outage hours for all survey respondents in 2009. This may be compared with the overall multiyear average of 34%. For 2009 forced outage hours represented 20%, 54%, 12%, and 44% of total outage hours for coal fuelled plants, gob fuelled plants, pre-1990 plants, and post-1990 plants, respectively. The average forced outage hours in 2009 for plants by construction year varied significantly from their multiyear average. The multiyear averages for pre-1990 plants and post-1990 plants are 35% and 44%, respectively. The multiyear data showed no clear trend for forced outage hours between the types of fuel used or the age of the plant.

Boiler related outage hours gives an indication of how auxiliary units are performing against boiler units, although scheduled maintenance hours and should also be considered. Overall boiler related outage hours represented an average of 83% for all plants in the survey in 2009. In 2009 the average boiler related outages comprised 87% and 89% of the total forced and planned outages, respectively. This was unusual since the average boiler related outages of forced outages is usually lower than for that of planned outages. The multiyear average for boiler related outages of forced outages is 77%. Between 2004 and 2008 this value only ranged from 68% to 80%. The multiyear average for boiler related outages of planned outages is 90%. In 2009, pre-1990 plants had 92% of their total outages boiler related, which may be compared with the multiyear average of 83%. Post-1990 plants had an average of 84% of their total outages boiler related in 2009, with a multiyear average of 91%. For the years 2004 through 2008, pre-1990 plants had more annual boiler related outages than post-1990 plants. Boiler related outages represented an average of 89% and 70% of total outages for coal fuelled and gob fuelled plants respectively. This is contradictory to the trend for the years 2004 through 2008, as coal fuelled plants consistently had lower boiler related outages than gob fuelled plants.

Data were collected regarding the causes of forced outages. The top three causes were combustor pressure parts, fuel handling or feeding systems, and ash handling systems, accounting for an average of 46%, 26%, and 16% of the total forced outage hours, respectively. Please refer to Table 4 for more detail on the causes of forced outages in 2009.

Table 4: Causes of Forced Outages in 2009

Contributor	2009
Combustor Pressure Parts, Including Tube Failure	46%
Fuel Handling and Feeding Systems	26%
Ash Handling Systems	16%
Turbine and Electrical Systems	14%
Refractory	11%
Steam or Electrical Generation Load Restriction	7%
Cyclone and U-beam Separation	4%
Backpass Pressure Parts, Including Tube Failure	3%
Other includes the following events: 1. Fan trip and coal motor shaft break 2. Disturbances of electrical grid 3. FD fan motor bearing failure 4. ID fan trip 5. Sorbent injection system failure 6. Utility curtailment 7. Generator protective relay trips 8. Lightening strike caused loss of DCS communication	29%

Table 5: Future Boiler Operations and Management Concerns for 2010

Concern Issue	Concern Priority
Ash Regulations	6.9
Ash Disposal	6.2
Fuel Quality	5.5
Ash Handling	5.3
Fly Ash	5.2
Pressure Parts	5.1
Tube Erosion	5.1
Fuel Handling/Crushing	4.8
Refractory	4.4
Boiler Combustion	4.2
Refractory	4.2
Loop Seals	4.2
Expansion Joints	4.2
Turbine/Electrical Systems	4.1
Cyclones	3.9
Electrical & Controls	3.8
Bed Ash	3.8
NSR definition Changes	3.8
Cyclone Refractory	3.6
Air Heater	3.5
Refractory: Combustor	3.5
Fuel Feeding	3.4
Seasonal Emissions	3.4
Boiler Backpass	3.3
Ash Cooling	3.2
Other	1.0

Plants participating in the survey were queried about their future boiler operations and management concerns for 2010. Plants were presented with a list of 26 possible issues and asked to rank them on a scale of 1 through 10, corresponding to how highly concerned they were about these issues for the year of 2010 (with 10 being of highest concern). Overall the three biggest concerns were for ash regulations, ash disposal, and fuel quality issues. Please refer to Table 5 for more detail on 2010 boiler operations and management concerns.

CONCLUSIONS

Survey respondent data was used to create 2009 performance and efficiency benchmarks for the AFBC industry. Multiyear data were collected, permitting the identification of trends for some of the benchmarks. Future operating and management concerns for the year of 2010 were also assembled. The biggest concerns were for ash regulations and ash disposal. This research is aimed at enabling plant owners and operators to identify where their plant falls short of industry standards, so that they may take appropriate steps to address these issues. The sharing of information between plants in this way allows plants to improve their overall operational performance, ultimately aiding in the development of a more competitive and efficient power generation industry.

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