Industrial Combustion Boilers

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS** – Combustion boilers are widely used to generate steam for industrial applications and power generation. While all kinds of energy sources - fossil fuels, biomass, nuclear and solar energy, electricity - can be used to generate heat and steam, the scope of this brief is limited to combustion boilers using fossil fuels and biomass. Boilers can be grouped into two broad categories: *water-tube boilers* and *fire-tube boilers*. In the *water-tube boilers,* tubes containing water are heated by combustion gases that flow outside the tubes, while in the *fire-tube boilers* hot combustion gases flow inside the tubes and water flows outside. Key design parameters to determine the boiler size and power are the output steam mass flow rate, pressure and temperature. Since the first boilers were used in the 18th century, the design of boilers has evolved so as to increase efficiency as well as steam pressure and temperature. In the United States, the energy consumption of industrial boilers accounts for 37% of total energy use in the industrial sector. In the industrialised countries, more than 50% of the industrial boilers use natural gas as the primary fuel and about 76% of the total boiler population is older than 30 years. Boiler sales in 2002 amounted to 1/6 of the total sales in 1967.
- **PERFORMANCE AND COSTS** – The power of a boiler is determined by the required steam mass flow rate, pressure and temperature. The amount of input fuel depends on the fuel energy content and on the overall energy efficiency. New boilers running on coal, oil, natural gas and biomass can reach efficiencies of 85%, 80%, 75% and 70% respectively. Boiler efficiency can be improved by preventing and/or recovering heat loss. The construction of a large industrial steam generator can take between 22 and 48 months depending on the scope and framework. A boiler's annual availability ranges between 86% and 94% including planned outage. Unplanned outages are typically very small or non-existing. The costs of steam generation are usually referred to as a system cost covering the entire boiler life cycle. For a full-load steam system (86%-94% utilization), the fuel cost accounts for 96% of the total life-cycle cost while investment, operating and maintenance costs usually account for 3% and 1%, respectively. The cost structure clearly demonstrates that the energy efficiency is the main cost driver.
- **POTENTIAL AND BARRIERS** – Technology improvements for boilers focus on efficiency and low-cost design while giving increasingly more attention to air pollutant emissions. In the industrialized countries, specific emission standards exist or are being implemented for carbon monoxide, hydrogen chloride, mercury, particulate matter, selected metals (arsenic, beryllium, cadmium, chromium, lead, manganese, nickel and selenium) as well as greenhouse gases such as CO_2 and for SO_2 and NO_x. Emission standards depend on the primary fuel type, boiler size, load factor, and become more demanding over time. In the European Union, the directive 2001/80/EC of the European Parliament on the limitation of emissions of certain air pollutants from large combustion plants defines maximum emission levels for SO_2, NOx and dust, based on fuel type (solid, liquid, gaseous), input capacity (MW_{th}) and the year in which the operating license was requested. In some industrial applications, steam boilers based on renewable energy (biomass, solar energy) are becoming market competitors for the conventional fossil fuels-based boilers.

PROCESS AND TECHNOLOGY STATUS – A combustion boiler (or steam generator) consists of a fossil fuels or biomass burner and a heat-transfer system to boil water and generate steam. Steam generators also include systems and components for pressure control, heat recovery, steam delivery and distribution, condensate drainage, and separation of oxygen and non-condensable gases. [1] ■ **Fire-tube Boilers and Water-tube Boilers** – In the fire-tube boilers, hot combustion gases flow inside tubes immersed in a pressure vessel containing boiling water. In water-tube boilers, the boiling water flows inside tubes and hot combustion gases flow on the shell side. Fire-tube boilers were first developed in the 18th century. In the current designs, the technology of choice is the water-tube design which is more suited to high-pressure steam generation as small tubes can withstand high pressure better and are less vulnerable to fracturing and failure.[1] ■ **Saturated, Superheated and Supercritical Steam** – Steam pressure and temperature are the key parameters that characterize the boiler performance. *Saturated steam* is steam at saturation (i.e. boiling) temperature for a given pressure (water-steam equilibrium). If further heat is provided and the steam temperature rises above the saturation temperature at a given pressure, then the steam is referred to as *superheated steam*. (e.g. steam at T > 100°C, P= 1 bar). *Supercritical steam* [1] is steam at a pressure and temperature above the water critical point (i.e. 374.15 °C, 218.3 atm) where changes of phase (boiling) no longer occur. Steam in supercritical conditions is often used in power generation.

Boilers account for a significant share of industrial energy consumption and are the key components in power generation and industrial plants [9]. Quantitative information on the importance of boilers from the energy and industrial point of view in industrialised and emerging countries, can be obtained from a 2005 study by the US Energy and Environmental Analysis Inc. (EEA, [2]).

[1] A supercritical fluid is a fluid at a temperature (T) and pressure (P) above its critical point. Close to the critical point, small changes in T and P result in large changes in density, allowing key fluid properties to be "tuned". Supercritical fluids are used in industrial applications and power generation

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■ **Boiler capacity** – The EEA estimates that the United States boiler population consists of approximately 43,000 units with an aggregated capacity of 439 GW input. Boiler capacity is concentrated in five industries (i.e. chemicals, paper, food, refining, metals), which represent 82% of total boiler capacity (Fig. 1). ■ **Boiler fuels** – Energy consumption of industrial boilers accounts for 37% of the total industrial energy consumption (some 6,823 PJ/year). Some 51% of the US industrial boiler capacity is designed to use natural gas as the primary fuel. Other primary fuels are coal, oil and wood (Fig. 2). Boilers are only partially fuelled by primary fuels (e.g. natural gas) and make large use of industrial by-products that, typically, may represent some 50% of the boiler fuels. Figure 3 shows the boiler fuel share used in the US industry. ■ **Boiler market and existing population** – Historical data on boiler sales show a steady decline in the US market from 1964 to 2002 for both fire-tube and water-tube types. Figure 4 shows an overview of US boiler sales data. Due to decreasing sales, the average age of boilers is increasing. Some 76% of the existing boilers are older than 30 years (66% of the very large boilers). Figure 5 presents an age distribution of the US boiler population. The US study clearly demonstrates that the boiler market grows fast during the industrial development of a country and tends to decline to a stable substitution market after the industrialisation. Thus, growing boiler markets are currently located in the emerging countries such as China and India while in more advanced countries the market is basically driven by substituting aging capacity with more efficient and clean equipment.

PERFORMANCE AND COSTS – The energy efficiency is a major cost drive for boilers as the fuel cost accounts for more than 90% of the boiler overall costs on a life-cycle basis ■ **Efficiency** – In general, boilers can generate steam with different pressure and temperature, using diverse fuels and equipment [11]. To assess and compare the boiler efficiency, the US Department of Energy proposes benchmark values based on feed-water temperature, operating pressure, and fuel (see for instance Tables 1 and 2).

Table 1 - Energy (kJ) required to produce 1 kg of saturated steam, [4]					
	Feed-water temperature, (°C)				
Pressure (kPa)	**10**	**38**	**66**	**93**	**121**
1034	2740	2624	2507	2391	2272
3103	2761	2645	2528	2412	2293
4137	2754	2638	2521	2405	2289

Table 2 - Efficiency for boilers with feed water economizers, air pre-heating, and 3% O_2 in flue gas, [4]	
Fuel type	**Combustion efficiency, %**
Natural gas, GJ	85.7%
Distillate/No. 2 Oil,	88.7%
Distillate/No. 6 Oil,	89.6%
Coal	90.3%

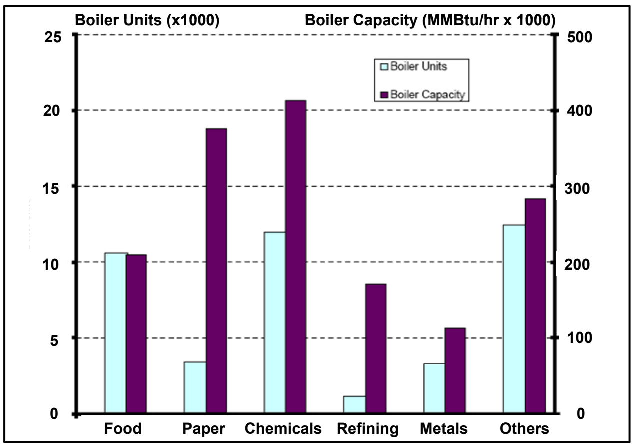

Fig. 1 - Number of boilers and boiler capacity[2] in the US, by industry sector [2]

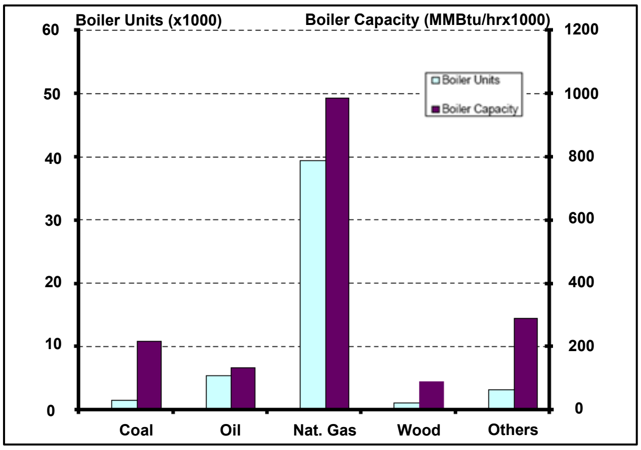

Fig. 2 – Boilers' primary fuels in the US industry [2]

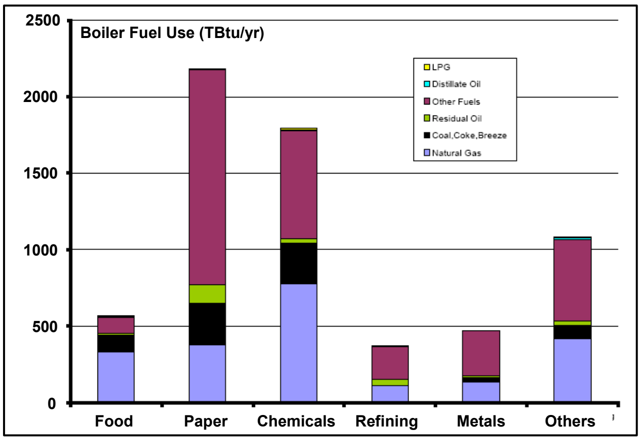

Fig. 3 – Boiler fuel use in the US industry by sector [2]

Benchmark efficiencies can be achieved by boilers being equipped with a set of efficiency improvement systems. The efficiency of a steam generation can be improved by preventing or recovering energy losses. Feed water pre-heating using an economizer to extract

[2] To convert to KJ (GJ) energy expressed in Btu (MMBtu) multiply by 1.0551.

heat from a boiler exhaust can increase the efficiency from 1% to 7% (typically 5%). Combustion air pre-heating using a boiler exhaust recuperator can provide between 1% and 2% (typically 1%) efficiency increases. Heat recovery from blow-down waste to pre-heat feed-water can provide an additional 1%-2% efficiency (typically 1%). Blow-down waste can also be used in a flash tank for de-aeration or for processes that require low-pressure steam. Depending on existing insulation levels, the insulation of pipes and valves can also increase efficiency. Fire-tube boilers can have turbulence promoters inserted into tubing to increase heat transfer. This may result in an additional 1%-2% (typically 1%) efficiency. Oxygen trim controls are used to ensure an optimal fuel/oxygen mix in the burner, with a 1% increase in efficiency [5] [6]. The US Department of Energy offers online tools for efficiency improvement calculations such as the Steam System Scoping Tool, Steam System Assessment Tool, and 3E Plus. Actual efficiencies of new boilers running on coal, oil, gas and biomass at full load – Maximum Continuous Rating, MCR – can reach about 85%, 80%, 75% and 70%; at low load efficiencies drop to 75%, 72%, 70% and 60%. [21] ■ **Availability** – In general, boilers offer high availability ranging between 87% and 94%. Planned outage ranges from 4% to some 14%. Unexpected failure in large steam generators is very low [14]. ■ **Construction Time** – The construction time of a large boiler often depends on the construction time and scope of the power or the industrial plant the boiler is part of. For example, the contract for the Weston unit 4 supercritical pulverized coal plant in Wasau, Wisconsin (1,652 ton/h steam at 26 MPa) was obtained in 2004 and commercial operation started in 2008 [12]. However, construction time can be significantly shorter as shown by the 22-month reconstruction of the Hawthorn 5 unit pulverized coal facility in Kansas City, Missouri (1,814 ton/h steam at 20 MPa), following its initial destruction due to a malfunction [13].

■ **Boiler Costs** – As already mentioned, a life-cycle approach is often used to analyse the costs of a steam generation system. Over the entire life-cycle, the fuel accounts for some 96% of the overall cost while capital, operation and maintenance (O&M) costs may represent as little as 3% and 1%, respectively [1] [3] [5]. The **overnight investment cost** can vary widely according to output steam parameters such as flow rate, temperature and pressure. In addition, the steam generator is often part of a larger technology system (e.g. a power plant) and its cost may depend on specific operational conditions. A typical cost of a gas- or oil–fired packaged fire-tube boiler that generates some 4695 kg/hr steam at 1.034 MPa is approximately $ 60,000 (2008 US$). An additional mass flow rate of 1565 kg/hr may result in a cost increase of around $ 5500. This cost does not include components such as water softener, feed water system, chemical treatment equipment, economizer, blow-down equipment, condensate return system and fuel supply equipment. Nor does it include the installation cost, which may add between 50% and 100% to the investment cost [15]. Information on investment, installation, operating and maintenance costs for power generation in the European Union can be found in the European commission staff working document *Energy Sources, Production Costs.*

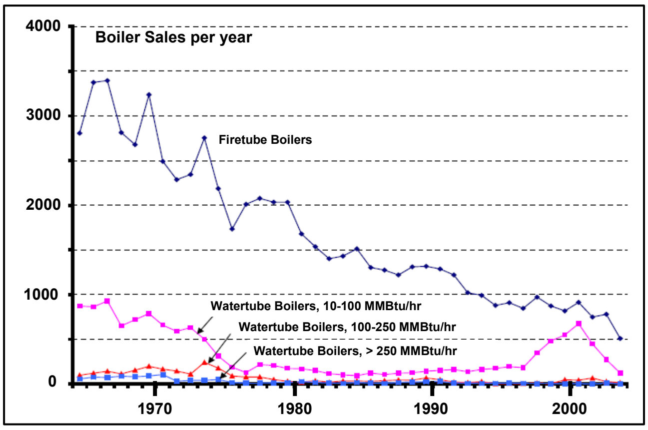

Fig. 4 – Boilers' sales in the US [2]

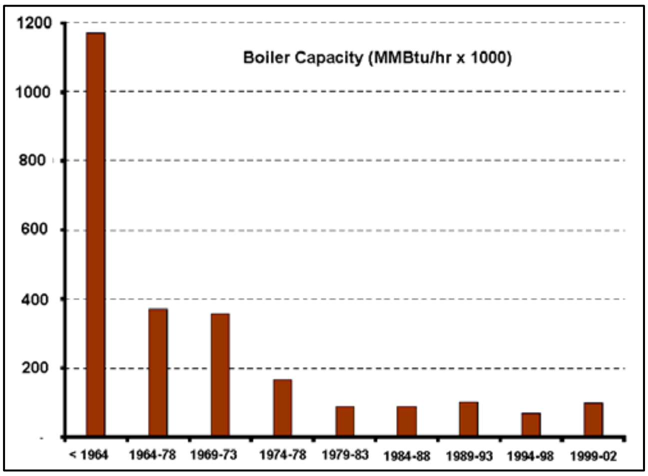

Fig. 5 – Installation year of the US boiler population [2]

and Performance of Technologies for Power Generation, Heating and Transport [16]. In this document, costs are for the entire facility, not merely the steam system. For example, the investment cost of a pulverized coal combustion power plant amounts to $1706/kW[3], with O&M costs of $81/kW (2008 US$) [16]. In comparison, a 2003 study by the Babcock and Wilcox company on the possible replacement of an existing coal plant with a supercritical coal plant provides an investment cost of $1381/kW, a fixed O&M cost of $12 million/year and a variable O&M cost of $1430/kWh (2008 US$) [17]. In 1979 PEDCo-Envrionmental, Inc. prepared a comprehensive study on investment and O&M costs for industrial boilers. Cost correlations were obtained and used by the Office of Air Quality Planning and Standards as input for their computer models. The correlations offer an overview of different boiler types (fire-tube, package water-tube, field-erected water-tube, stoker coal-fired, and pulverized coal-fired) using a variety of fuels (coal, distillate oil, residual oil and natural gas). The costs used for deriving at the correlations are given in US$ 1978, but the study can still provide a valuable insight in relative terms or by using GDP deflators [18, 20].

[3] 1000 $2008 = 1083 $2005, [20]

POTENTIAL & BARRIERS - Technological research on boilers aims to improve efficiency, and reduce emissions and construction costs. An example of cost reduction is the vertical tube, variable pressure furnace for supercritical steam boilers. The Babcock and Wilcox Company in cooperation with the US Department of Energy are testing a boiler design which tries to combine the low-cost vertical tube building scheme with the advantages of variable pressure, efficient on/off cycling and rapid load changing. [7] An effort to improve efficiency and reduce emissions is the Super Boiler Research Program of the Gas Technology Institute. First generation performance tests point towards an increased thermal efficiency of 94% and reduced emissions in NOx, VOC, CO and CO2. [8] ■ **Emissions Standards –** In the United States, boiler emission standards exist for carbon monoxide (CO), hydrogen chloride (HCL), mercury (Hg), particulate matter (PM) and selected metals including arsenic, beryllium, cadmium, chromium, lead, manganese, nickel and selenium. Current standards depend on fuel type, boiler size and use, and the year of construction (boiler age) [10]. Emission caps for large, high capacity factor boilers, which were built after January 2003, are given in Table 3.

CO_2 emissions are based on input fuel emission factors corrected for the boiler efficiency. Basic fuel emission factors are 50.29 kg CO_2/TJ for natural gas, 69.33 kg CO_2/TJ for distillate fuel oil, 74.69 kg CO_2/TJ for residual fuel oil, and 89.08 kg CO_2/TJ for coal [6]. The European community has adopted the directive 2001/80/EC of the European Parliament and the European Council of 23 October 2001 on the emissions limits for certain pollutants from large combustion plants including industrial combustion boilers. The directive provides emission limits for NOx, SO_2 and dust depending on fuel type (solid, liquid, gaseous), input capacity (MWth) and the year in which the operation license was granted. For installations granted with a license after 27 November 2002 and/or in operation after 27 November 2003, the emission limits are given in Table 4, 5 and 6 [19]. Note that there are still exceptions to the tables shown for outermost regions, gas turbines, yearly utilization rate, etc. [19].

Table 3 – High capacity factor, Industrial Boiler MACT, [10]

Fuel	PM	TSM	HCL	HG	CO
	ppm	kg/GJ	kg/GJ	kg/GJ	ppm
Solid	0.04	0.00003	0.0069	0.0000011	200
Liquid	0.068		0.00019		200
Gas					200

Table 4 - SO_2 Emission limits for new installations, (mg/Nm³); [19]

	Plant size, MWth		
Fuel type	50 - 100	100 - 300	> 300
solid general (6%O_2)	850	200	200
biomass (6%O_2)	200	200	200
liquid (3%O_2)	850	400 to 200 linear	200
gaseous general (3%O_2)	35		
liquified gas (3%O_2)	5		
low LHV gases from coke oven (3%O_2)	400		
low LHV gases from blast furnace (3%O_2)	200		

Table 5 - NOx emission limits for new installations (mg/Nm³), [19]

	Plant Size, MWth		
Fuel type	50 - 100	100 - 300	> 300
solid general (6% O2)	400	200	200
biomass (6% O2)	400	300	200
liquid (3% O2)	400	200	200
gaseous general (3%O2)	200		200
natural gas (3%O2)	150		100

Table 6 - Dust emission limits for new installations (mg/Nm³) [19]

	Plant Size, MWth	
Fuel type	50 - 100	> 100
solid general (6% O2)	50	30
liquid (3% O2)	50	30
gaseous general (3%O2)	5	
blast furnace gas (3% O2)	10	
gases produced by steel industry (3% O2)	30	

Table 7 – Summary Table - Key Data and Figures for Industrial Boilers

Technical Performance	
Energy input	Gas, Coal, Oil, Wood and other fuels
Output	Steam
Benchmark combustion efficiency, %	Coal 90.3%, Oil residual 89.6%, Oil distillate 88.7%, Natural Gas 85.7%,
Actual efficiency, full load, %	Coal 85%, Oil 80%, Natural Gas 75%, Biomass 70%
Actual efficiency, low load, %	Coal 75%, Oil 72%, Natural Gas 70%, Biomass 60%
Construction time, months	22 months – 48 months (large industrial boilers)
Technical lifetime, yr	25 years – 40+ years
Max. (boiler) availability, %	86.6% - 94.2%
Typical (capacity) size, GJ/hr	Small < 11 GJ, large 11 – 264 GJ, very large > 264 GJ
Environmental Impact	**Air pollution**
total selected metals (TSM), kg/GJ	0.00003
HCl, kg/GJ	0.00019-0.0069
Hg, kg/GJ	0.0000011
CO, kg/GJ	0.14-0.25 (200 ppm)
SO_2, Mg/Nm³	5 – 850
NO_x, Mg/Nm³	100 – 400
Dust, Mg/Nm³	5 – 50
CO2	Input fuel dependent
Costs	
Capital cost, overnight	3% of the life-time cost The typical cost of a gas- or oil–fired packaged fire-tube boiler that generates some 4,695 kg/hr steam at 1,034 kPa may be approximately around $ 60,000 (US $ 2008). Incremental mass flow rate of 1,565 kg/hr may result in cost increase of some $5,500.
O&M cost (fixed and variable)	1% of the life-time cost
Energy/fuel cost	Dependent on fuel type, market price of fuel type and utilization, constitutes up to 96% of life time cost
Economic lifetime, yr	25 – 40
Interest rate	Sector dependent

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