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Advancing grate-firing for greater environmental impacts and efficiency for decentralized biomass/wastes combustion

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Abstract

Biomass power is an important routine to source more energy needs from renewables and to mitigate global warming. This paper presents an overview of all the key technologies currently used for direct biomass co-firing for combined heat and power production, among which grate-firing is regarded to well suit decentralized biomass and municipal/industrial wastes combustion. This paper discusses with concrete examples how to advance grate-firing for greater efficiency and environmental impacts, e.g., use of advanced secondary air system, flue gas recycling and optimized grate assembly, which are of great interest and relevance for further development of this technology.

Keywords: Biomass; municipal and industrial wastes; direct co-firing; grate-firing; CFD

1. Introduction

Biomass is the largest renewable energy resource. Among various biomass conversion technologies, biomass power prevails. For example, for bioenergy-based transportation, the two leading technologies (i.e., cellulosic ethanol *vs*. electric vehicle batteries) are compared. Bioelectricity is found to outperform ethanol across a range of feedstocks, conversion technologies and vehicle classes [1]. Compared to the use of other renewable energy sources, biomass co-firing is normally significantly cheaper and can be implemented relatively quickly [2]. For European power generators, the current economic circumstances also greatly favor a change to biomass co-firing: an annual

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growth of 9-10% per year until 2020 has been projected. So far, biomass co-firing has been applied in over 240 plants worldwide. To further boost biomass power, the combustion technologies need to be advanced for greater efficiency, environmental impacts, and flexibility in terms of both the fuel range and operation range.

Abbreviation

BFB	bubbling fluidized bed	PA	primary air
CFB	circulating fluidized bed	PF	pulverized fuel
CFD	computational fluid dynamics	PVC	polyvinyl chloride
CHP	combined heat and power	RDF	refuse-derived fuel
EU	European union	REF	recovered fuel
FBC	fluidized bed combustion	RFG	recycled flue gas
FGD	flue-gas desulfurization	SA	secondary air
MSW	municipal solid waste	SCR	selective catalytic reduction
OFA	over-fire air		

2. Assessment of the three main biomass co-firing technologies

Figure 1, extended from [3], compares the fuel ranges of the three main combustion technologies, i.e., suspension-firing (or PF-firing), fluidized bed combustion (FBC) and grate-firing. Their key features, pros and cons in biomass/waste-firing for combined heat and power (CHP) are summarized in Table 1.

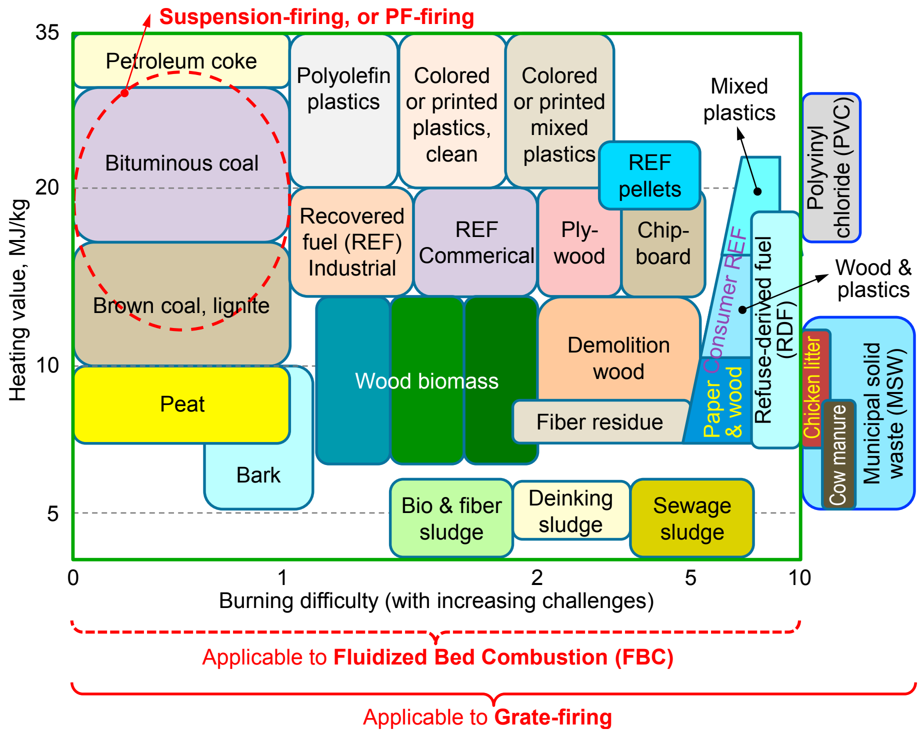

Fig. 1. Fuel range comparison of the three combustion technologies: PF-firing *vs*. FBC *vs*. grate-firing.

An evaluation of biomass co-firing in Europe shows that PF-firing is the most widely used direct co-firing technology, followed by BFB, CFB and grate-firing [2]. PF-firing has witnessed great success in co-firing of woody biomass at low thermal shares [2,4]. As more problematic feedstocks are employed and the biomass thermal share increases, the applicability of direct PF co-firing will be compromised since it is difficult to grind the raw biomass or biomass pellets to sufficiently fine particle sizes as required by PF-firing [5,6]. The low ash melting temperatures of biomass fuels may also impose challenges to high-temperature PF co-firing. FBC has great fuel flexibility and is widely used for biomass combustion. However, some wastes (e.g., PVC and MSW) are generally considered not applicable to FBC as seen in Fig. 1, due to, e.g., high polycyclic aromatic hydrocarbon emission. The EU directive on waste incineration requires the gas and particles after the last injection of combustion air to be raised to 850 °C (or 1100 °C for wastes with more than 1% of halogenated organic substances, expressed as chlorine) for at least two seconds [7], which may not be readily attained in FBC boilers. FBC is also very sensitive to bed agglomeration. Using silica sand as bed materials, bed de-fluidization is reported when firing some biomass feedstocks (e.g., coffee husks, cotton stalk, coconut shell), although the problems may be mitigated by using special additives or bed materials [8]. Grate-firing, which could be underrated for its applicability, economics, environmental impact and operation experience in [2], is not subject to all the above obstacles. Nevertheless, grate-fired boilers need to be further improved in terms of efficiency and overall environmental impacts.

Table 1. Main combustion technologies and their application to biomass and municipal/industrial wastes combustion.

	Suspension- or PF-firing	FBC	Grate-firing
Fuel flexibility	Poor	Very good	Very good
3T (temperature, turbulence, time)	High-temperature, very good mixing, very short residence time	Low-temperature, very good mixing, long residence time	Intermediate temperature, poor mixing, very long residence time
Excess O_2 (vol%)	Typically 4–6%	3–4% for BFB; 1–2% for CFB	5–8%
Efficiency	High	High	Low
Environmental impacts	Low NO_x emissions with efficient air-staging and mixing	Low NO_x emissions due to low-temperature, air-staging (and char in recycled bed material for CFB); easy capture of sulfur	Low NO_x emissions need special technology in old units, and can be achieved in modern units via advanced secondary air systems
Economics	Highest capital cost (with FGD and SCR), highest operation cost	High capital cost and high operation cost	Low capital cost (for plants <20 MW_{th}) and low operation cost
Use in existing biomass-fired CHP plants	About 50% equipped with PF-boilers; mainly co-firing woody biomass at low thermal shares	Nearly 40% based on FBC (either BFB or CFB boilers); can fire pure biomass or waste	About 10% using grate-firing; often fire pure biomass/waste of all types, small scale 0.3–175 MW_{th}
Obstacles for use in biomass and wastes combustion	(1) low fuel quality, (2) hard to mill biomass to similar sizes to coal, (3) low ash melting temperature of biomass	(1) Potential bed agglomeration and de-fluidization, (2) hard to meet the directive on waste incineration for some feedstocks	No inherent obstacle, but grate-firing generally needs to be advanced for higher efficiency and lower emissions

3. Towards an improved grate-firing technology of greater efficiency and environmental impacts

3.1. Use of advanced secondary air (SA) system

Advanced SA systems gain their popularity in grate boilers. In modern grate boilers, the split ratio of SA/PA tends to be 60/40, instead of 20/80 in older units, facilitating the use of advanced SA systems.

Figure 2 shows some of the advanced SA systems that can optimize mixing, temperature, residence time, and local-stoichiometry in the freeboard and thus improve the performance of grate boilers [8,9], e.g., staged air jets on the front and rear walls in Fig. 2a, staggered over-fire air (OFA) jets in Fig. 2b, static mixing devices with air injections in Fig. 2c, and tangentially arranged air jets in Fig. 2d.

Figure 3 shows the CFD (computational fluid dynamics) predicted flow and combustion pattern in a grate boiler which fires 150,000 tons wheat straw per year and produces 35 MW_e and 50 MJ/s heat. In this boiler, the staggered OFA jets (sketched in Fig. 2b) are successfully used to optimize the combustion process.

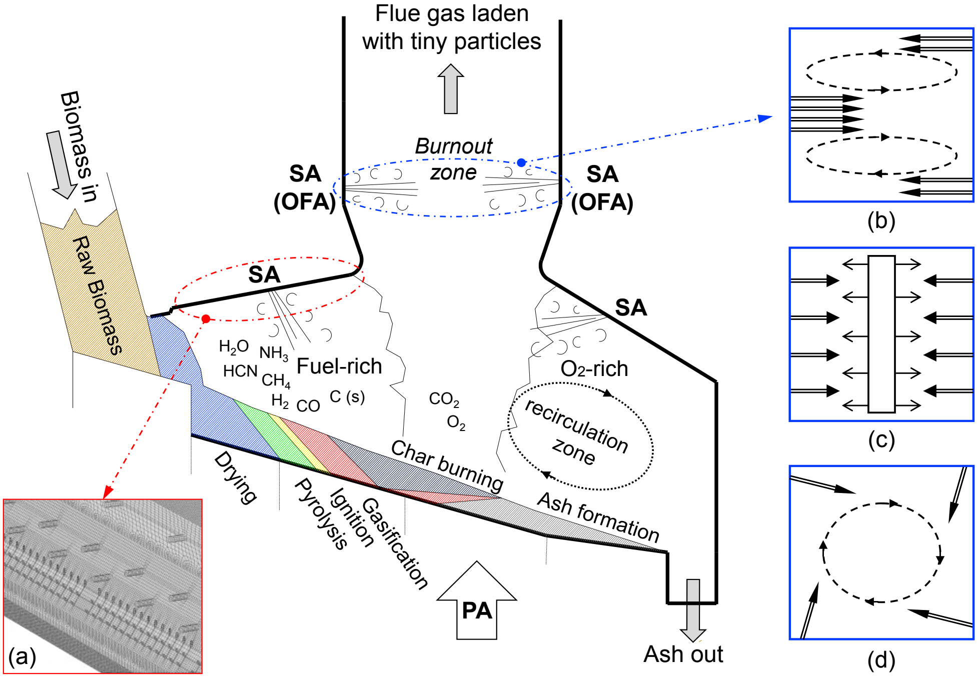

Fig. 2. Sketch of different zones in a grate-fired boiler and various advanced secondary air (SA) supply schemes.

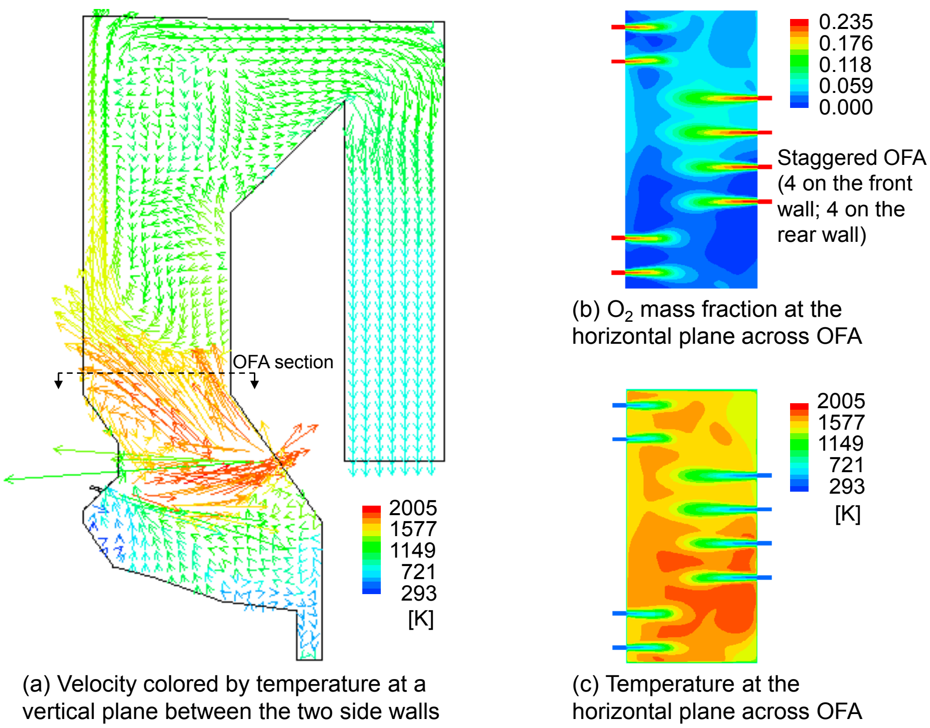

Fig. 3. A 108 MW wheat straw-fired grate boiler, in which staggered OFA jets are used to improve mixing and burnout: the flow, temperature and oxygen profiles.

Figure 4 shows a 50MW grate-fired furnace burning wet wood chip (1-5cm, 30-45 wt% moisture), in which the Ecotube air system is used to improve the performance of the boiler. The numerical simulation shows that the Ecotube sir system improves the mixing and air distribution in the furnace and reduces NOx emissions by 30% [10]. A similar Ecotube air system is used in a municipal solid waste-fired grate boiler and its performance is evaluated. The simulation results show that such an air system allows a far more uniform heat release, lower CO and NOx emissions, and a more uniform temperature distribution, due to the largely improved mixing in the furnace [11]. For both the grate boilers in which the Ecotube air system is used, no side impacts of the erosive and corrosive environments on the air system are reported.

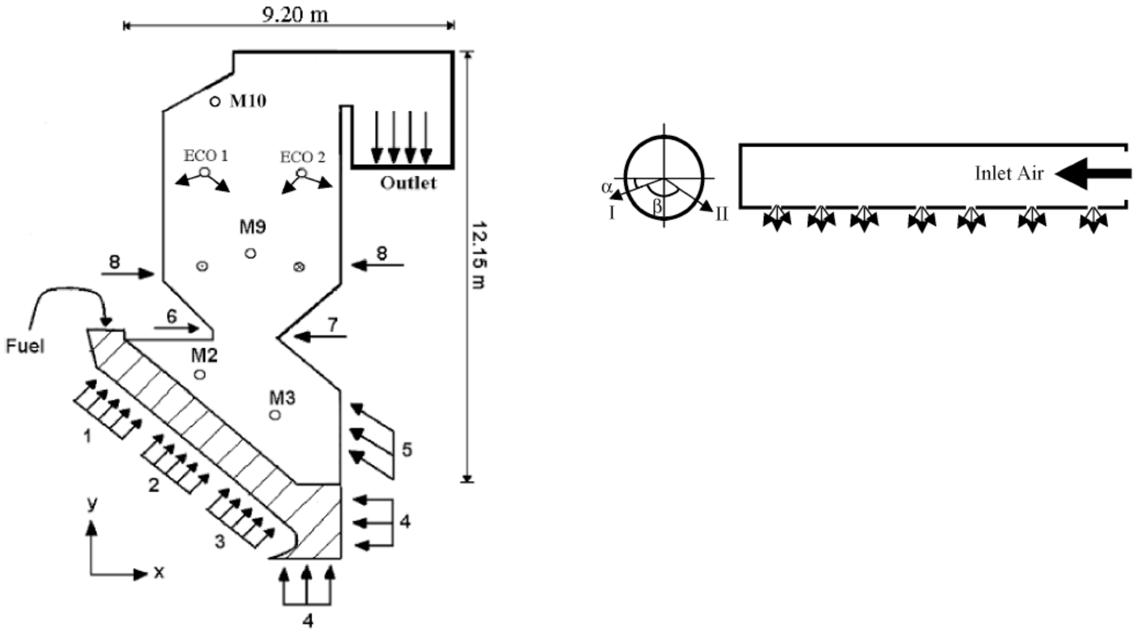

Fig. 4. A 50 MW wet wood chip-fired grate boiler, in which the Ecotube air system ECO1-2 are sketched on the right (Row-I: facing the boiler wall; α, β: the angles of air jets) [10].

The tangentially arranged air jets, as shown in Fig. 2d, which have been successfully used in suspension-fired boilers and may be integrated into grate boilers for improving mixing and combustion. The tangential arrangement of air jets can not only help to achieve a good burnout but also mitigate the deposit formation and corrosion on furnace walls by creating locally oxidative conditions and forming an air curtain on the walls. However, such an arrangement is not yet found in grate-fired boilers.

3.2. Use of flue gas recycling

In grate-fired boilers, the excess air is relatively high, which compromises the boiler efficiency. Proper use of recycled flue gas (RFG) can reduce the excess air and is also expected to have other benefits, e.g., enhancing mixing for homogeneous combustion conditions, better temperature control, suppression of NO_x and dioxins emissions, efficient waste heat recovery, and reduction in slagging tendency and flue gas emissions. However, RFG is rarely used in grate-fired boilers so far due to various practical difficulties.

A high-temperature low air-ratio technology is developed for MSW-fired grate boilers, by first mixing the air and exhaust gas and adjusting the O_2 concentration in the mixed gas, then heating the mixed gas to a high temperature, and finally blowing the heated gas mixture into the furnace at high speed from the two side walls. The use of this technology in a 105 ton/day MSW incinerator shows that a stable combustion operation can be attained at an overall excess O_2 of 4.8%. It yields a 17% decrease in flue gas flow, 10% improvement in energy efficiency and 50% reduction in NO_x emissions, compared to the normal operation without the use of RFG at an excess O_2 of 8.1% [12].

As seen in Fig. 5, RFG is also successfully used in a 13MW$_{th}$ waste wood-fired grate boiler to improve the boiler performance [13]. Part of the hot RFG (1kg/s) is recycled into the boiler from beneath the grate, mainly via the sections on which biomass drying and pyrolysis occur. Part of the RFG (1.56 kg/s) is introduced into the furnace via nozzles on the two side walls, in order to optimize temperature control, reduce slagging risk, and enhance mixing of the combustibles and oxidizer in the primary combustion zone. Figure 6 shows the CFD-predicted temperature and oxygen distribution in this grate boiler.

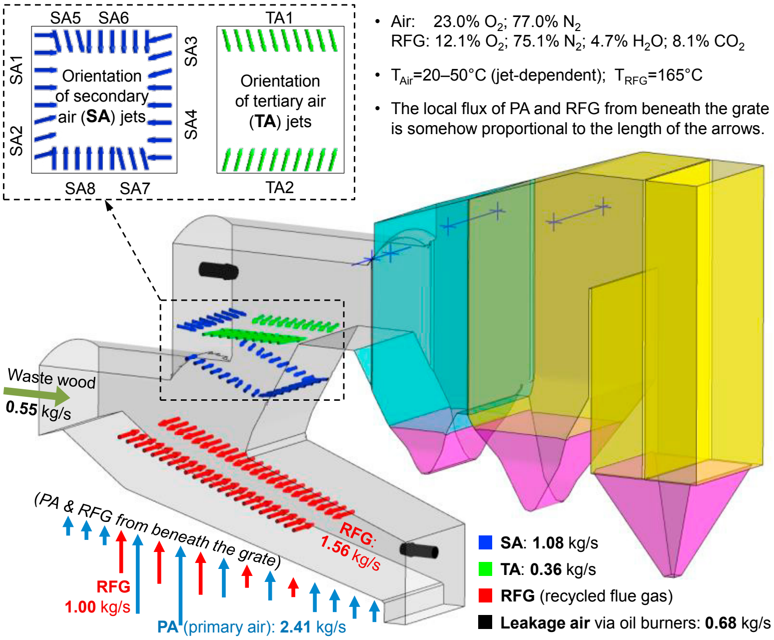

Fig. 5. A 13MW$_{th}$ waste wood-fired grate boiler with advanced SA system and RFG from beneath and above the grate.

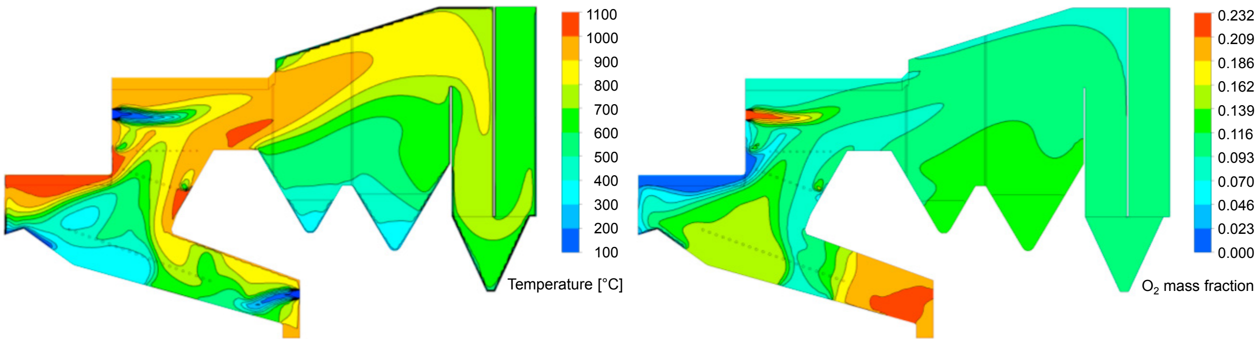

Fig. 6. Temperature and oxygen on the middle plane between the two side walls in the 13 MW$_{th}$ grate boiler.

3.3. Optimization of grate system

The grates may be air- or water-cooled. The choice needs to be made by properly accounting for the feedstock properties. For difficult fuels (e.g., high-moisture silage, MSW), air-cooled grates can be used to keep the grates under relatively high temperatures. For good fuels, water-cooled grates can be used so that the PA is only confined to combustion requirement, giving more flexibility to advanced SA systems.

The grates can also be classified according to their movement patterns. Figure 7 shows a reciprocating grate which tumbles and transports fuels by reciprocating (forward or reverse) movements of the grate rods, and a vibrating grate which spreads and transports fuels via shaking movement. Both the grates greatly improve fuel mixing in the fuel bed and reduce the unburnt char in the ash. Their movement frequency and amplitude need to be adjusted based on the feedstock properties and firing conditions. The grate assembly also needs to be optimized by, e.g., allowing a better under-grate PA distribution, and improving fabric seal of the system to lower air leakage.

(a) A reciprocating grate and its basic movement pattern (b) A vibrating grate

Fig. 7. Two kinds of commonly used mordern grate systems: (a) a reciprocating grate; (b) a vibrating grate.

CFD, which integrates the understandings and achievements in combustion fundamentals in the best possible way, plays an important role in advancing combustion technologies. For instance, new combustion systems are often conceptually developed using CFD, followed by lab and site testing and adjustment [14]. Among the various measures to advance grate-firing technology, CFD is also expected to play a vital role, as demonstrated above in developing advanced SA [9] and RFG [13] in grate-fired boilers.

4. Conclusions

Grate-firing is well suited for decentralized biomass and municipal/industrial wastes combustion in CHP plants. Integration of advanced secondary air systems such as staged air supply, staggered over-fire jets and static mixing device with air-jets, and use of flue gas recycling witness the improvement in the performance of grate-fired boilers. To further improve grate-firing technology, the secondary air supply system and grate assembly can be further optimized, in which CFD can play the central role.

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