

Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction[†]

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Since biomass is the only carbon-based renewable fuel, its application becomes more and more important for climate protection. Among the thermochemical conversion technologies (i.e., combustion, gasification, and pyrolysis), combustion is the only proven technology for heat and power production. Biomass combustion systems are available in the size range from a few kW up to more than 100 MW. The efficiency for heat production is considerably high and heat from biomass is economically feasible. Commercial power production is based on steam cycles. The specific cost and efficiency of steam plants is interesting at large scale applications. Hence co-combustion of biomass with coal is promising, as it combines high efficiency with reasonable transport distances for the biomass. However, biomass combustion is related to significant pollutant formation and hence needs to be improved. To develop measures for emission reduction, the specific fuel properties need to be considered. It is shown that pollutant formation occurs due to two reasons: (1) Incomplete combustion can lead to high emissions of unburnt pollutants such as CO, soot, and PAH. Although improvements to reduce these emissions have been achieved by optimized furnace design including modeling, there is still a relevant potential of further optimization. (2) Pollutants such as NO_x and particles are formed as a result of fuel constituents such as N, K, Cl, Ca, Na, Mg, P, and S. Hence biomass furnaces exhibit relatively high emissions of NO_x and submicron particles. Air staging and fuel staging have been developed as primary measures for NO_x reduction that offer a potential of 50% to 80% reduction. Primary measures for particle reduction are not yet safely known. However, a new approach with extensively reduced primary air is presented that may lead to new furnace designs with reduced particle emissions. Furthermore, assisting efforts for optimized plant operation are needed to guarantee low emissions and high efficiency under real-world conditions.

1. Introduction

1.1. Motivation for Energy from Biomass. There is an increasing interest in biomass utilization for energy production worldwide.¹ The driving force for biomass combustion is in most cases either the CO₂ neutrality of sustainable cultivated biomass or the utilization of biomass residues and wastes. Large potentials of both—native biomass as well as biomass wastes—are still available and enable a relevant increase of sustainable bio energy utilization in the future.^{2,3} Combustion is the most important and mature technology available nowadays for biomass utilization.

Improvements with respect to efficiency, emissions, and cost are needed for further exploitation. Beside this, alternatives such as gasification also need to be considered and also combinations of different processes are of interest such as gasification as fuel pretreatment for co-combustion.¹

1.2. Feedstock for Biomass Combustion. Combustion can be applied for biomass feedstocks with water contents up to maximum 60%. Fuel constituents beside C, H, and O are undesired since they are related to pollutant and deposit formation, corrosion, and ash. The most relevant constituents in native biomass are nitrogen as a source of NO_x, and ash components (e.g., K and Cl as a source of KCl) that lead to particulate emissions. Native wood is usually the most favorable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass such as straw, miscanthus, switch grass, etc., have higher contents of N, S, K, Cl, etc., that lead to higher emissions of NO_x and particulates, increased ash, corrosion, and deposits. While wood is as well suited for household heating as for larger plants, herbaceous biomass is dedicated for larger plants. The same is true for urban waste wood and demolition wood. The combustion of such contaminated biomass should be strictly limited to combustion

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(3) Kaltschmitt, M., Hartmann, H., Eds. *Energie aus Biomasse*; Springer: Berlin, 2001; ISBN 3-540-64853-42001.

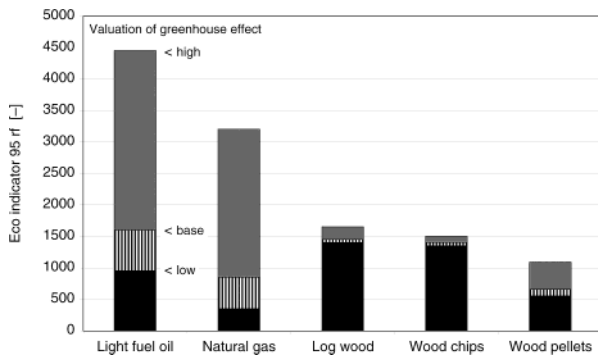


Figure 1. Environmental impact points (EIP) for different valuations of the greenhouse effect.⁷

Table 1. Environmental Impact Points (EIP) According to the Ecological Scarcity Method for Heating with Wood Chips (base case for greenhouse effect)^a

	[EIP/GJ]	[%]
NO _x	13 030	38.6%
PM 10	12 600	36.5%
CO ₂	670	2.0%
SO _x , NH ₃ , CH ₄ , NMVOC, primary energy, residues, and others	8 200	22.9%
Total	34 500	100%

^a Ref 7.

plants with efficient flue gas cleaning for the abatement of toxic pollutants such as heavy metals and chlorine compounds.

1.3. Environmental Impact of Biomass Combustion. Biomass furnaces exhibit relatively high emissions of NO_x and particulates in comparison to furnaces with natural gas or light fuel oil.^{4–6} Hence, they contribute significantly to particulate matter (PM), ozone, and NO₂ in the ambient air. For wood combustion, a life cycle assessment (LCA) indicates that 38.6% of the environmental impact of a modern automatic wood furnace is attributed to NO_x, 36.5% to PM 10, only 2% to CO₂, and 22.9% to all other pollutants (Table 1).⁷ The LCA for wood, light fuel oil, and natural gas also shows that the environmental impact of wood is higher than that for natural gas for a standard valuation of the greenhouse effect (Figure 1). Hence, improvements in the wood chain are necessary. However, it is also evident that the conclusions of the LCA strongly depend on the valuation of the greenhouse effect since the ranking changes significantly as a result of the different CO₂ impacts of the three fuels.

2. Fundamentals

Biomass combustion is a complex process that consists of consecutive heterogeneous and homogeneous reactions. The main process steps are drying, devolatilization, gasification, char combustion, and gas-phase oxi-

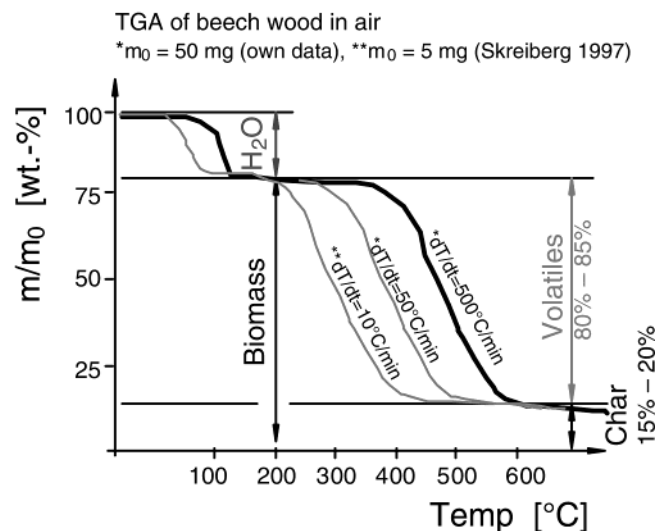
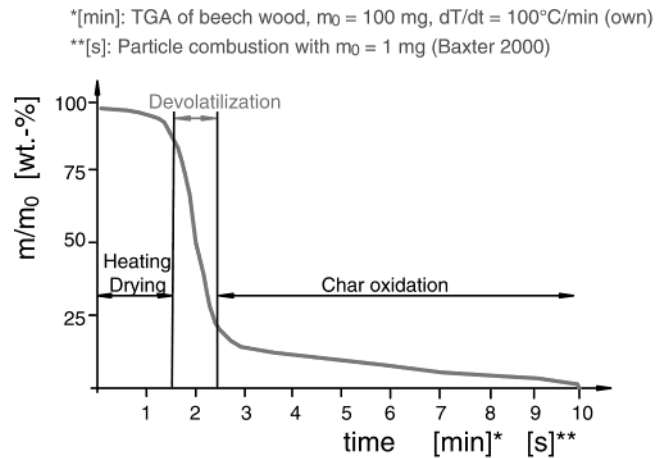


Figure 2. Mass loss as a function of time (above) and temperature (below) during combustion of wood. Our own results from thermogravimetical analysis (TGA) supplemented with data from Baxter⁸ and Skreiberg.⁹

ation. The time used for each reaction depends on the fuel size and properties, on temperature, and on combustion conditions. Batch combustion of a small particle shows a distinct separation between a volatile and a char combustion phase with time (Figure 2). For the design of combustion appliances, the high content of volatiles (80% to 85%) needs to be respected. For large particles, the phases overlap to a certain extent. Nevertheless, even for log wood furnaces, a certain separation of distinct combustion regimes with time can be found.

Since automatic combustion systems are operated continuously, the consecutive reactions occur simultaneously at different places in the furnace (e.g., in different sections on and above a grate). Hence the zones for different process steps during combustion can be optimized by furnace design. A distinct separation of different process steps can be advantageous with respect to pollutant formation.

The main combustion parameter is the excess air ratio (λ) that describes the ratio between the locally available and the stoichiometric amount of combustion air. For typical biomass, the combustion reaction can then be

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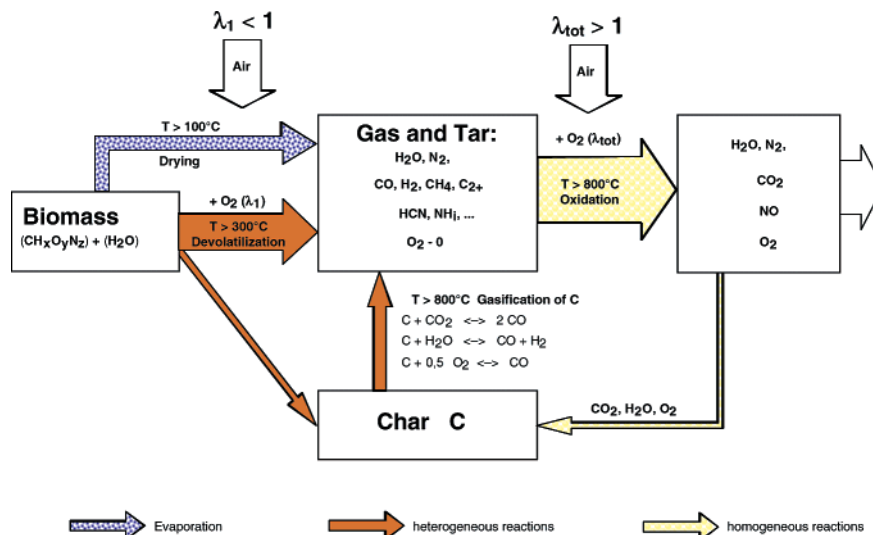
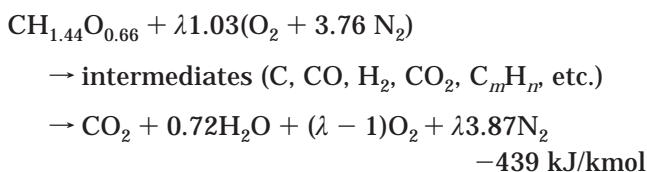


Figure 3. Main reactions during two-stage combustion of biomass with primary air and secondary air.¹⁰

described by the following equation if fuel constituents such as N, K, Cl, etc., are neglected:



where CH_{1.44}O_{0.66} describes the average composition of typical biomass used for combustion, i.e., wood, straw, or similar material.

As a result of the combustion process, different types of pollutants can be distinguished:

1. unburnt pollutants such as CO, C_xH_y, PAH, tar, soot, unburnt carbon, H₂, HCN, NH₃, and N₂O;
2. pollutants from complete combustion such as NO_x (NO and NO₂), CO₂, and H₂O; and
3. ash and contaminants such as ash particles (KCl, etc.), SO₂, HCl, PCDD/F, Cu, Pb, Zn, Cd, etc.

3. Emission Reduction

3.1. Staged Combustion. If staged combustion is applied, the excess air can vary in different sections.

Two-stage combustion is applied with primary air injection in the fuel bed and consecutive secondary air injection in the combustion chamber (Figure 3).¹⁰ This enables good mixing of combustion air with the combustible gases formed by devolatilization and gasification in the fuel bed. If good mixing is ascertained, an operation at low excess air is possible (i.e., excess air $\lambda < 1.5$) thus enabling high efficiency on one hand and high temperature (Figure 4) with complete burnout on the other hand (Figure 5). If good mixing is achieved, the concentrations of unburnt pollutants can be reduced to levels close to zero (e.g., CO < 50 mg/m³ and C_xH_y < 5 mg/m³ at 11 vol % O₂). However, an accurate process

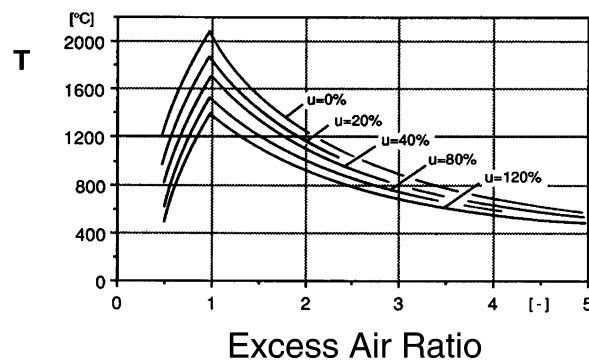


Figure 4. Adiabatic flame temperature for the combustion of wood with different humidity u (u is based on dry fuel, hence $u = 100\%$ corresponds to a moisture content $w = 50\%$).⁴

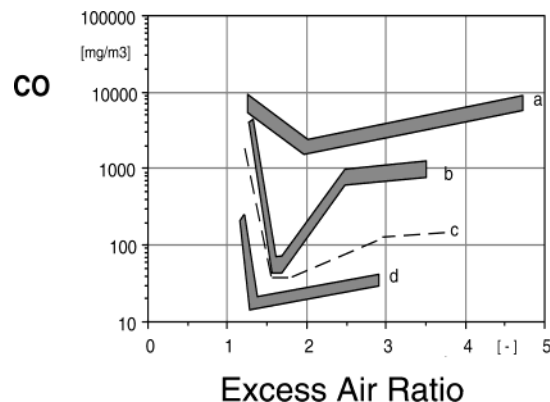


Figure 5. Carbon monoxide emissions as function of excess air ratio for different furnace types.^{4,10} (a) Wood stove, (b) downdraft boiler, (c) automatic wood furnace, (d) advanced automatic wood furnace.

control is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and λ (CO/ λ -controller)¹¹ or of CO and temperature¹² have been developed.

Air staging applies air injection at two levels as well. In addition to conventional two-stage combustion, pri-

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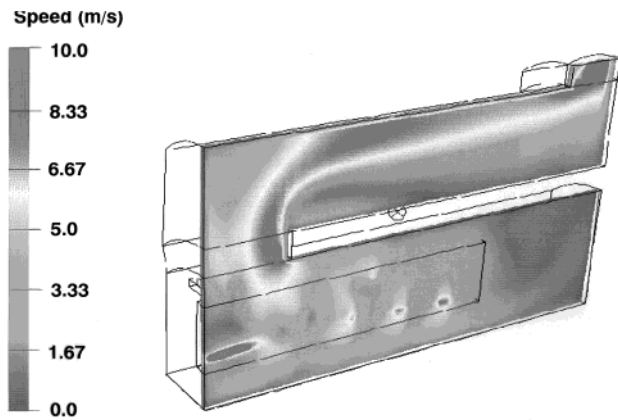


Figure 6. CFD modeling for optimization of furnace design. The example shows the velocity distribution in the combustion chamber over a grate with secondary air nozzles and post combustion chamber.¹³

mary air needs to be understoichiometric (λ primary < 1). Further, a relevant residence time (and hence a reduction zone in the furnace thus leading to an enlarged furnace volume) is needed between the fuel bed and the secondary air inlet.

In fuel staging, fuel is fed into the furnace at two different levels. The primary fuel is combusted with excess air > 1. A consecutive reduction zone is achieved by feeding secondary fuel and late inlet of final combustion air for the secondary fuel. Both air staging and fuel staging have been developed as primary measures for in-situ reduction of fuel NO_x in biomass combustion and are described below.

3.2. Unburnt Pollutants. The main needs for complete burnout are temperature, time, and turbulence (TTT). The mixing between combustible gases and air can be identified as the factor that is mostly limiting the burnout quality, while the demands for temperature (around 850 °C) and residence time (around 0.5 s) can easily be achieved.⁴ Sufficient mixing quality can be achieved in fixed bed combustion by the above-described two-stage combustion. In fluidized bed, good mixing is achieved in the bed and the freeboard and also dust combustion enables good mixing.

For future improvements in furnace design, computational fluid dynamics (CFD) can be applied as a standard tool to calculate flow distributions in furnaces, as shown by an example in Figure 6.¹³ Furthermore, the reaction chemistry in the gas phase can be implemented in CFD codes.^{14,15} However, the heterogeneous reactions during drying, transport, devolatilization, and gasification of solid biomass before entering the gas-phase combustion need to be considered as well and needs further improvement to enable the application of whole furnace modeling (Figure 7).^{15–17}

3.3. NO_x Emissions. In combustion processes, NO and NO_2 (summarized as NO_x) Can be formed in three

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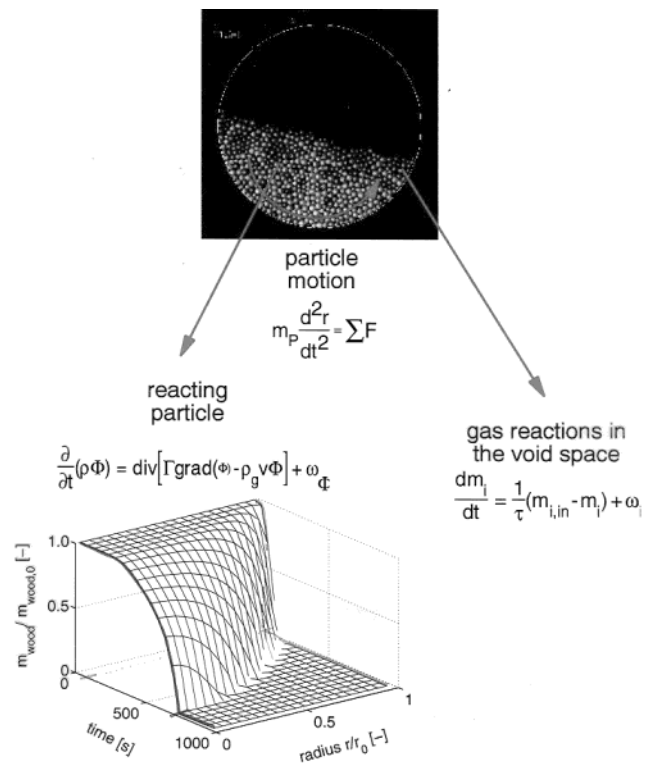


Figure 7. Basic approach for modeling the solid fuel conversion during combustion of large particles in motion: particle motion, reacting particle, and gas reactions in the void space.¹⁷

different reactions. Thermal NO_x and prompt NO_x are formed from nitrogen in the air at high temperatures and in the case of prompt NO_x in the presence of hydrocarbons. Further, fuel NO_x can be formed from nitrogen-containing fuels. For biomass combustion, fuel-bound nitrogen is the main source of NO_x emissions, while thermal and prompt NO_x are not relevant due to relatively low temperatures as has been shown by theoretical and experimental investigations.^{4,18}

Fuel nitrogen is converted to intermediate components such as HCN and NH_i with $i = 0, 1, 2, 3$. These can be oxidized to NO_x if oxygen is available, which is the case in conventional combustion. If no oxygen is present, intermediates can interact in the reduction zone and form N_2 in reactions such as $\text{NO} + \text{NH}_2 = \text{N}_2 + \text{H}_2\text{O}$ (Figure 8). During the past 10 years, staged combustion technologies have been developed as a primary measure for process internal NO_x reduction based on this concept, thus leading to the above-described techniques of air staging and fuel staging (Figure 9).^{19,20} Both measures enable a NO_x reduction on the order of up to 50% for wood with low and up to

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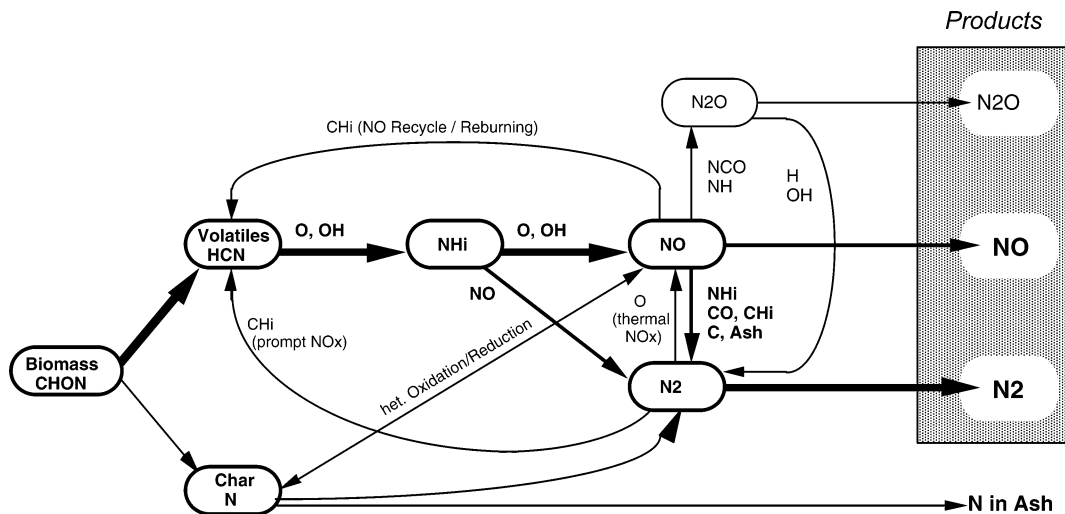


Figure 8. Conversion of fuel nitrogen in biomass combustion.¹⁹

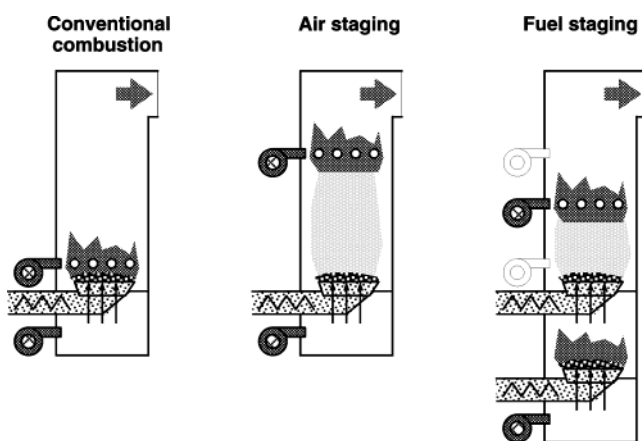


Figure 9. Principle of conventional two-stage combustion, air staging with reduction zone, and fuel staging with reduction zone.¹⁰

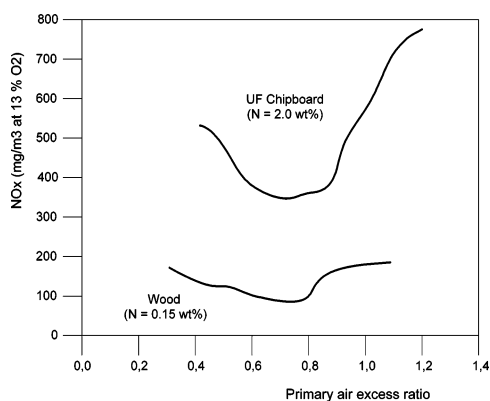


Figure 10. NO_x emissions as a function of primary excess air ratio with air staging.²¹

80% for bio fuels with high nitrogen content. However, different specific conditions have to be met accurately to exhaust this reduction potential.

In the case of air staging, a primary air excess around 0.7, a temperature in the reduction zone of 1150 °C and a residence time of 0.5 s are needed (Figure 10).²¹ The relatively high temperature can limit the application in

practice due to undesired ash softening and deposit formation. For fuel staging, similar results are achieved at lower temperature, i.e., already at temperatures as low as 850 °C.²² However, the furnace concept and operation is more complex due to the need of two independent fuel feeding systems. Nevertheless, a pilot plant based on this concept has been successfully realized with a combination of understoker furnace and entrained flow reactor (Figure 11).²³ For both types of staged combustion, accurate process control is needed to ensure an operation at the excess air ratio needed in the different zones.

Besides primary measures, secondary measures are available for NO_x abatement. The most relevant techniques are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) using the same reaction as mentioned for staged combustion, i.e., $\text{NO} + \text{NH}_2 = \text{N}_2 + \text{H}_2\text{O}$. However, urea or ammonia is injected as reducing agent and as source of NH_2 . SNCR has to be applied in a narrow temperature window around 820 °C to 940 °C, thus enabling a NO_x reduction up to 90%.²⁴ SCR is typically applied in the flue gas in a temperature range around 250° to 450 °C and enables a NO_x reduction of more than 95%.²⁴ However, relevant concentrations of undesired side products such as HNCO , N_2O , NH_3 , HCN , and others can be formed in both types of secondary measures under unfavorable conditions. Hence, primary measures are preferable if they can achieve sufficient emission reduction.

3.4. Particulate Emissions. Biomass combustion leads to relatively high emissions of particulates, i.e., well above 50 mg/m^3 at 11 vol % O_2 .^{4,25} The majority of the particulates are smaller than 10 μm (i.e., particulate matter PM 10) with a high share of submicron particles (PM 1) as shown by an example from wood in Figure 12.^{25–29}

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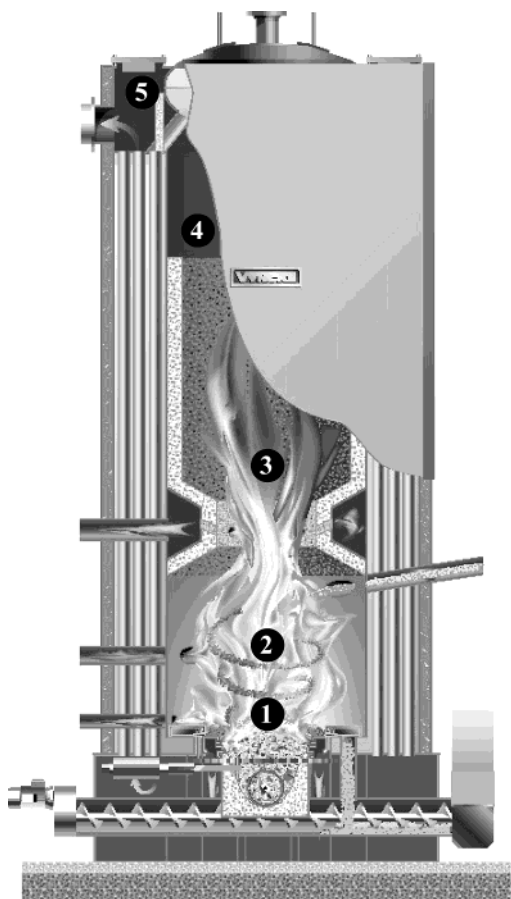


Figure 11. Combination of understoker furnace with entrained flow reactor for air and fuel staging.²³ Demonstration plant 1,5 MW. 1 = Feeding of primary fuel and primary air, 2 = Reduction zone, 3 = Injection of secondary fuel and consecutively tertiary air, 4 = End of post combustion chamber, flue gas exit to convection part and cyclone.

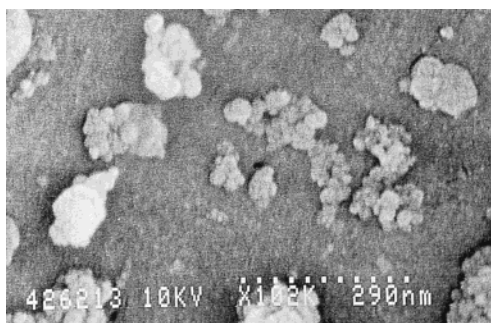


Figure 12. Fly ash from wood combustion.²⁶

The composition of submicron and supermicron particles in fluidized bed combustion is distinctive as the fine particles are composed mainly of K, Cl, S, Na, and Ca and the coarse particles of Ca, Si, K, S, Na, Al, P, and Fe.³⁰ In fixed bed combustion, increasing mass

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concentrations of particulate emissions are typically related to increasing mean diameter.³¹ Further, a dependency of the particle composition on size can also be found in fixed bed conditions, as K, S, Cl, and Zn are mainly found in the submicron fraction, while the content of Ca is increasing with increasing particle size.³² If almost complete burnout is achieved by appropriate furnace design, the particulates result almost exclusively from ash components in the fuel with salts such as KCl as main components.³³ The main fuel constituents with respect to aerosol formation are typically K, Cl, S, Ca, Na, Si, P, Fe, and Al. Primary measures which can safely meet a high reduction potential, i.e., by at least a factor of 10, of this category of aerosols are not known so far.

However, a new approach for primary particle reduction has been presented recently.³⁴ It was shown, that particles from wood combustion are mainly formed by nucleation, coagulation, and condensation during temperature decrease in the boiler. Further, these particles are mainly salts and consist mainly of K. K in the fuel is present as a salt with high melting point and devolatilization temperature. If oxygen is available at high temperature, a high share of K can be oxidized. As K oxides have significantly lower devolatilization temperatures than the K salts, they are almost completely vaporized into the gas phase and lead then to particle formation from the gas phase. If no oxygen is present in the fuel bed, the conversion of K to volatiles may be reduced since the majority of K salts can be converted into the grate ash. Since a similar behavior for other ash components in the fuel is assumed, the oxygen content during the solid fuel conversion is regarded as a key parameter for aerosol formation.

According to this hypothesis, an experimental setup was realized based on an understoker furnace that enables a wood combustion with extremely low primary air in the fuel bed (or glow bed) on the grate. At such operation conditions, the glow bed height increases significantly and hence the furnace design must be adapted. Furthermore, combustion becomes unstable below a certain primary air excess and hence an

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Table 2. Types of Biomass Furnaces with Typical Applications and Fuels

application	type	typical size range	fuels	ash	water content	
manual	wood stoves	2 kW–10 kW	dry wood logs	<2%	5%–20%	
	log wood boilers	5 kW–50 kW	log wood, sticky wood residues	<2%	5%–30%	
pellets	pellet stoves and boilers	2 kW–25 kW	wood pellets	<2%	8%–10%	
	understoker furnaces	20 kW–2.5 MW	wood chips, wood residues	<2%	5%–50%	
automatic	moving grate furnaces	150 kW–15 MW	all wood fuels and most biomass	<50%	5%–60%	
	pre-oven with grate	20 kW–1.5 MW	dry wood (residues)	<5%	5%–35%	
	understoker with rotating grate	2 MW–5 MW	wood chips, high water content	<50%	40%–65%	
	cigar burner	3 MW–5 MW	straw bales	<5%	20%	
	whole bale furnaces	3 MW–5 MW	whole bales	<5%	20%	
	straw furnaces	100 kW–5 MW	straw bales with bale cutter	<5%	20%	
	stationary fluidized bed	5 MW–15 MW	various biomass, $d < 10$ mm	<50%	5%–60%	
	circulating fluidized bed	15 MW–100 MW	various biomass, $d < 10$ mm	<50%	5%–60%	
	dust combustor, entrained flow	5 MW–10 MW	various biomass, $d < 5$ mm	<5%	<20%	
	co-firing ^a	stationary fluidized bed	total 50 MW–150 MW	various biomass, $d < 10$ mm	<50%	5%–60%
		circulating fluidized bed	total 100–300 MW	various biomass, $d < 10$ mm	<50%	5%–60%
		cigar burner	straw 5 MW–20 MW	straw bales	<5%	20%
		dust combustor in coal boilers	total 100 MW–1 GW	various biomass, $d < 2$ –5 mm	<5%	<20%

^a Biomass covers typically less than 10% of the total fuel input.

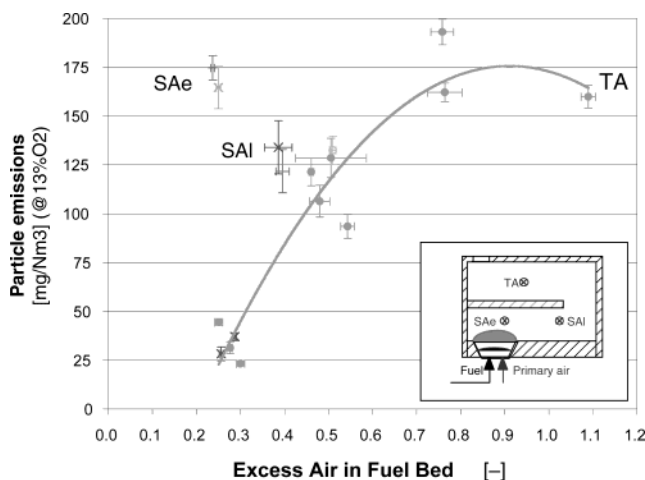


Figure 13. Particle emissions as a function of the excess air in the fuel bed at different air settings according to the location in the small graph: TA = tertiary air (curve), SAE = secondary air early, SAI = secondary air late.³⁴

accurate process control is needed. As the results from the laboratory furnace show, a reduction of particle emissions in the order of a factor of 5 is achievable, i.e., from 160–195 mg/m³ to 20–45 mg/m³ (13% O₂) (Figure 13). With most of the investigated fuels, particle emissions below 50 mg/m³ (13% O₂) were achieved. Hence the results are in accordance to the theory, although other effects beside the described one may also influence the particle formation.

Nevertheless, since fuel composition is the main parameter for aerosol formation, secondary measures are necessary as well for further reduction in the future. Among those, fabric filters are regarded as most promising. However further developments and adaptations are necessary for particle removal technologies appropriate for the needs and size for typical biomass combustion at reasonable cost.

4. Combustion Technologies

Biomass combustion is mainly used for heat production in small and medium scale units such as wood stoves, log wood boilers, pellet burners, automatic wood chip furnaces, and straw-fired furnaces. District heating systems are often in the size range from 0.5 MW_{th} to 5 MW_{th} with some applications up to 50 MW_{th}. Combined

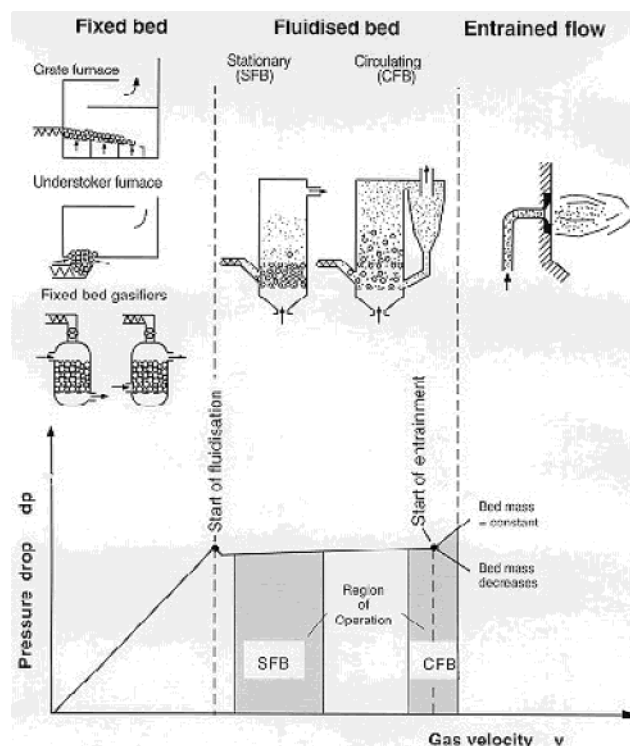


Figure 14. Furnace types and flow conditions: fixed bed, fluidized bed, and entrained flow reactor.¹⁰

heat and power production (CHP) with biomass is applied by steam cycles (Rankine cycle) with steam turbines and steam engines and organic Rankine cycles (ORC) with typical power outputs between 0.5 MW_e and 10 MW_e.³⁵ Stirling engines (10 kW_e to 100 kW_e) and closed gas turbines are in development or demonstration mode. Co-firing in fossil-fired power stations enables the advantages of large size plants (>100 MW_e), which are not applicable for dedicated biomass combustion due to limited local biomass availability.

Table 2 gives an overview of the most frequently used furnace types for biomass combustion. The systems can be distinguished by the flow conditions in the furnace, thus describing fixed bed combustion, fluidized bed, and entrained flow or dust combustion (Figure 14). To

(35) Nussbaumer, T. Stromerzeugung aus biogenen Brennstoffen. *Brennstoff Wärme Kraft* 51 1999, 7/8, 51–55.

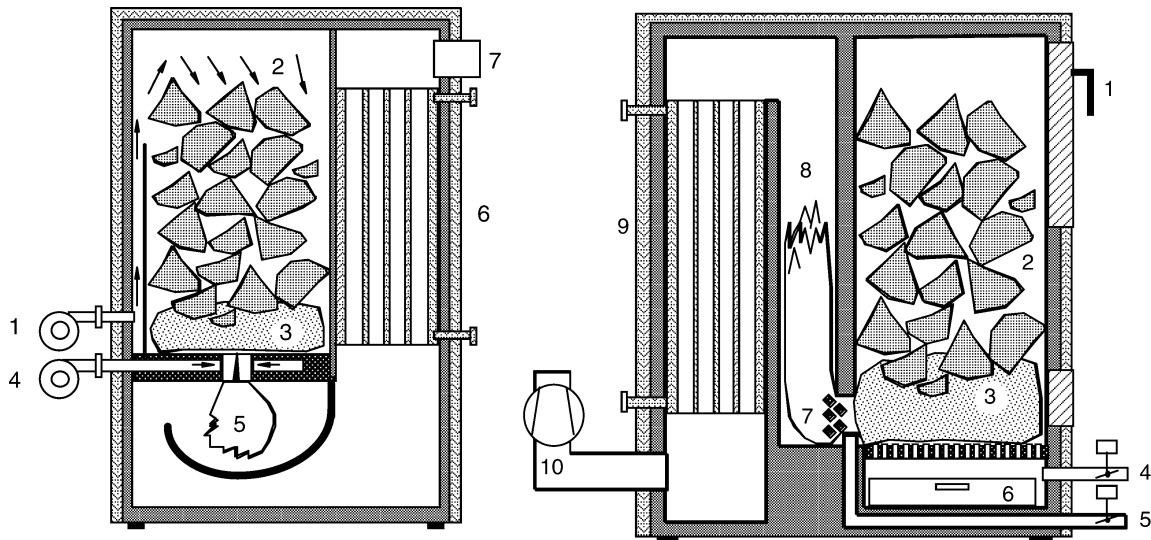


Figure 15. Downdraft boilers with inverse combustion of log wood and with enforced air flow and air supply with primary and secondary air. Left: 1 Primary air, 2 fuel hopper, 3 glow bed, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 chimney. Right: 1 Fuel inlet, 2 fuel hopper, 3 glow bed, 4 primary air, 5 secondary air, 6 ash bin, 7 mixing zone, 8 post combustion chamber, 9 heat exchanger, 10 chimney.

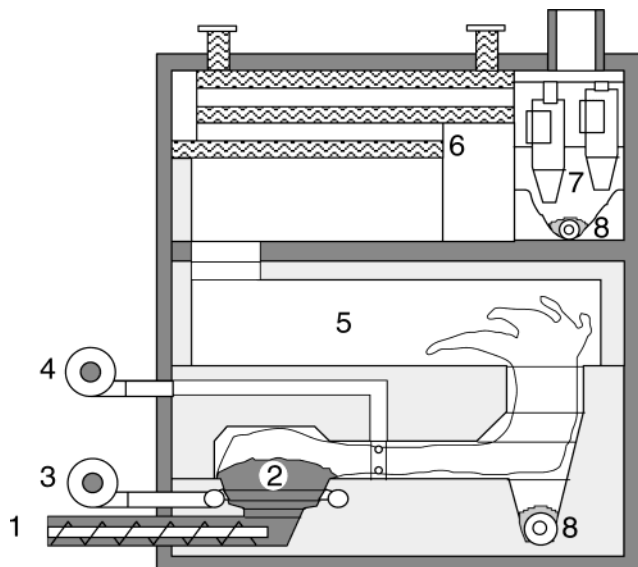


Figure 16. Understoker furnace with primary and secondary air, mixing zone, and post combustion chamber. 1 Screw feeder, 2 understoker zone with glow bed, 3 primary air, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal.

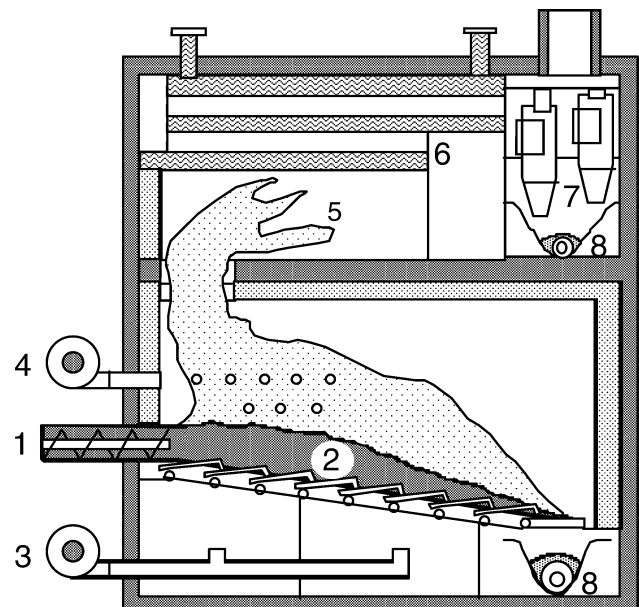


Figure 17. Moving grate furnace with primary air in two stages in the grate and secondary air. 1 Screw feeder, 2 moving grate, 3 primary air, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal.

achieve complete burnout and high efficiencies in small-scale combustion, downdraft boilers with inverse flow have been introduced, which apply the two-stage combustion principle described above (Figure 15). An operation of log wood furnaces at very low load should be avoided as it can lead to high emissions of unburnt pollutants. Hence, it is recommended to couple log wood boilers to a heat storage tank.

Since wood pellets are well suited for automatic heating at small heat outputs as needed for today's buildings, pellet furnaces are an interesting application with growing propagation. Thanks to the well-defined fuel at low water content, pellet furnaces can easily achieve high combustion quality. They are applied both as stoves and as boilers.

Understoker furnaces are mostly used for wood chips and similar fuel with relatively low ash content (Figure

16), while grate furnaces can also be applied for high ash and water content (Figure 17). Special types of furnaces have been developed for straw that has very low density and is usually stored in bales. Beside conventional grate furnaces operated with whole bales, cigar burners and other specific furnaces are in operation.

Stationary or bubbling fluidized bed (SFB) as well as circulating fluidized bed (CFB) boilers are applied for large-scale applications and often used for waste wood or mixtures of wood and industrial wastes, e.g., from the pulp and paper industry (Figures 18 and 19). In CFB boilers, nearly homogeneous conditions of temperature and concentrations can be achieved, thus enabling high burnout quality at low excess air. The choice of different bed materials in CFB offers additional opportunities of

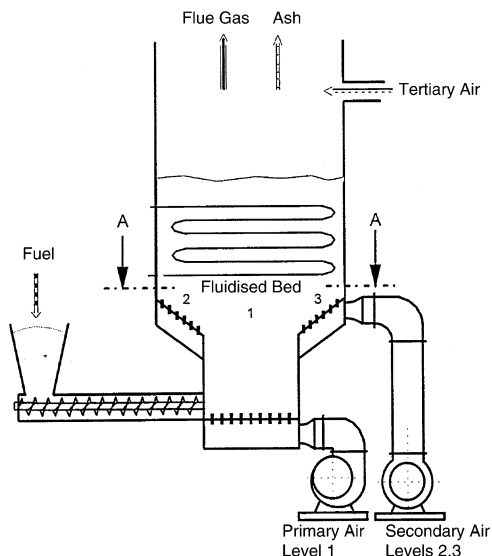


Figure 18. Stationary fluidized bed combustor with staged combustion (Lurgi).

catalytic effects. Further, the option of heat removal from the bed allows controlling the combustion temperature and hence enables an operation at low excess air without excessive ash sintering. Since similar conditions for nitrogen conversion as by air and fuel staging are attained, relatively low NO_x emissions are achieved.

5. Co-combustion

5.1. Overview on Co-utilization. A co-utilization of biomass with other fuels can be advantageous with regard to cost, efficiency, and emissions. Lower specific cost and higher efficiencies of large plants can be utilized for biomass and emissions of SO_x and NO_x can be reduced by co-firing. However, attention must be paid to increased deposit formation in the boiler and limitations in ash utilization due to constituents in biomass, especially alkali metals, that may disable the use of ash in building materials. Due to undesired changes of ash compositions, the share of biomass is usually limited to approximately 10% of the fuel input. Hence, other opportunities are also of interest and the following three options for co-utilization of biomass with coal are applied:²

(a) *Co-combustion or direct co-firing:* The biomass is directly fed to the boiler furnace (fluidized bed, grate, or pulverized combustion), if needed after physical preprocessing of the biomass such as drying, grinding, or metal removal.

(b) *Indirect co-firing:* The biomass is gasified and the product gas is fed to a boiler furnace (thus a combination of gasification and combustion).

(c) *Parallel combustion:* The biomass is burnt in a separate boiler for steam generation. The steam is used in a power plant together with the main fuel.

Co-combustion of biomass leads to a substitution of fossil fuels and to a net reduction of CO_2 emissions. In many countries co-firing is the most economic technology to achieve the target of CO_2 reduction and biomass co-firing can therefore be motivated by savings of CO_2 taxes.

5.2. Co-combustion or Direct Co-firing with Coal. The main application nowadays is direct co-firing

in coal-fired power stations. The typical size range is from 50 MW_e to 700 MW_e with a few units between 5 and 50 MW_e .² The majority of the plants are equipped with pulverized coal boilers in which co-combustion can be applied in different ways.

(a) The biomass can be burnt in separate wood burners in the boiler. Due to the requirements of pulverized combustion, drying, metal separation, and grinding of the biomass is needed as pretreatment. An example is shown in a 635 MW_e power plant in The Netherlands that burns the majority of the local urban waste wood and demolition wood (Figure 20). Wood replaces 3%–4% of the coal in this plant. Thanks to the scale and the flue gas cleaning, the urban waste wood is used with high efficiency and low environmental impact. At an electric efficiency of the plant of 43%, the net efficiency for wood with regard to fuel pretreatment is estimated at 36%–38%. As comparison: a modern 25 MW_e wood-based fired plant reaches ~30% efficiency.³⁶

(b) As an alternative, the biomass can also be burnt on a separate grate at the bottom of a pulverized coal boiler (Figure 21). The advantage is that costly and energy-consuming fuel pretreatment is not needed, since biomass with high water content and large in size can be burnt.

(c) Further applications of co-combustion with coal are related to BFB, CFB, cyclone, and stoker boilers, which accept a much wider range of fuel size, composition, and moisture content than burners in pulverized coal boilers.

5.3. Effects of Co-combustion on Plant Operation and Emissions.^{37,38} Co-firing can have several effects on the emissions and the plant operation: positive effects are that SO_x and NO_x emissions usually decrease due to the lower sulfur and nitrogen content in biomass than in coal (Figures 22 and 23). Furthermore, alkali components in biomass ash can have an effect of SO_x removal. Since biomass has a high volatile content, it can also be used as reburn fuel for NO_x reduction from the coal combustion, which gives a further potential for significant decrease of the NO_x emissions. Besides NO and NO_2 , also N_2O can be significantly reduced by co-firing of biomass in coal-fired fluidized bed boilers (Figure 24).

Negative effects of co-firing are additional investment cost for biomass pretreatment and boiler retrofitting, higher operation cost due to increased fouling and corrosion, and a possible decrease of the electric efficiency (if the superheater temperature has to be decreased due to high temperature corrosion). Besides potential poisoning of SCR catalyst also the efficiency of electrostatic precipitators may be reduced. Furthermore, the utilization of the ash and the residues from the flue gas cleaning system (especially the De- SO_x installation) has to be considered when co-firing biomass. The ash quality can be negatively influenced

(36) Remmers, R. 25 MW Holzkraftwerk mit stationärer Wirbelschichtfeuerung in Cuijk (NL). In *6. Holzenergie-Symposium*, October 20 2000, Zürich, Swiss Federal Office of Energy (BFE) and ENET, Bern 2000; pp 187–196.

(37) Baxter, L. L.; Robinson, A. Key Issues when Co-firing biomass with Coal. In *Proceedings of the Sixteenth Annual International Pittsburgh Coal Conference*, October 11–15, 1999.

(38) Hein, K.; Spliethoff, H. Co-combustion of Coal and Biomass in Pulverised Fuel and Fluidised Bed. In *Proceedings of the Sixteenth Annual International Pittsburgh Coal Conference*, October 11–15, 1999.

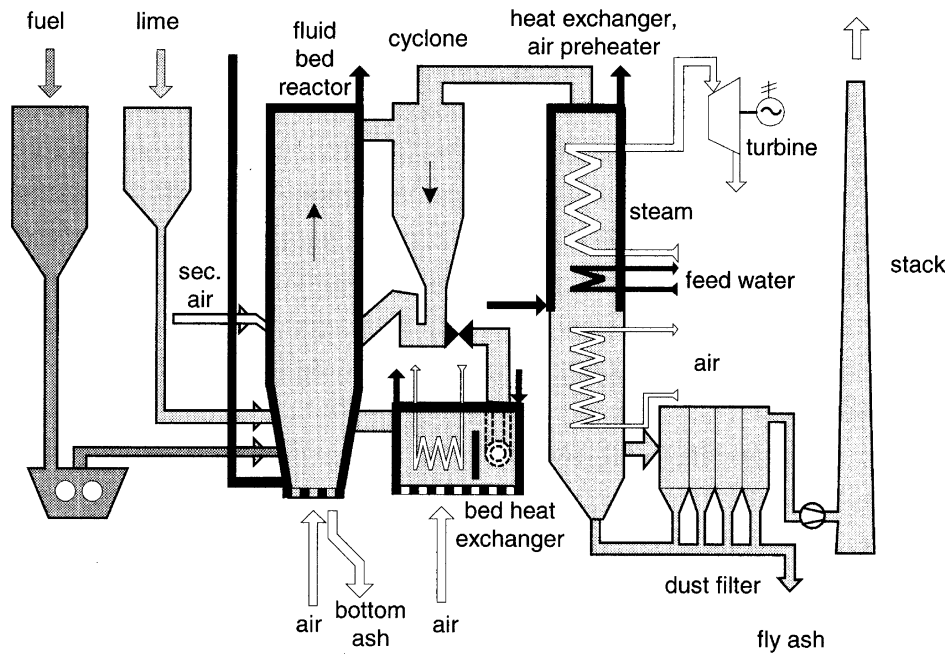


Figure 19. CFB plant with steam boiler for coal and biomass (Lurgi).

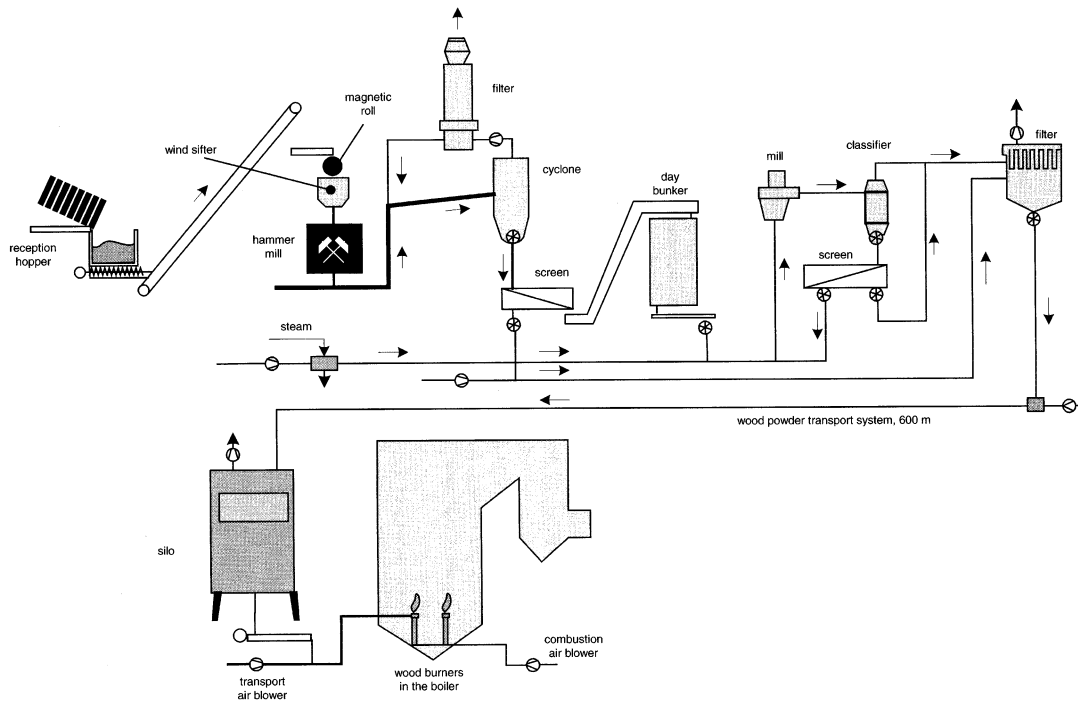


Figure 20. Power plant in Gelderland (NL) with direct co-firing of waste wood in pulverized coal boiler after drying, magnetic separation, and grinding of the wood (moisture < 8%, size < 1 mm). With 635 MW_e in total, 60'000 t/a waste wood used in 4 × 20 MW_{th} wood burners cover 3%–4% of the total energy demand.²

mainly by alkali metals and chlorine contained in biomass. Furthermore, also the content of unburnt carbon can increase. Usually a biomass input in the range of 5% to 10% according to the energy input is acceptable without major influence on the residues.

5.4. Other Applications of Co-combustion. Co-firing of biomass can also be applied in cement kilns, which is of special interest for contaminated waste wood. Additionally, biomass fuels can be co-fired in municipal solid waste (MSW) incinerators. This can be advantageous with respect to logistics and efficiency, since biomass can easily be stored while municipal waste needs to be burnt immediately. Further, the combina-

tion of biomass with oil or natural gas also offers specific advantages. Especially the topping with natural gas enables a significant increase of the plant efficiency, since steam from a biomass boiler can be superheated to higher temperatures with natural gas.

5.5. Indirect Co-firing and Parallel Combustion. Parallel combustion enables a complete separation of the ashes and flue gases from different fuels such as biomass and coal. Hence, no disadvantages or limitations result from undesired alkali metals or contaminants in the ash. Further, the flue gas cleaning equipment can be optimized for each fuel. Indirect co-firing of producer gas from biomass gasification also enables

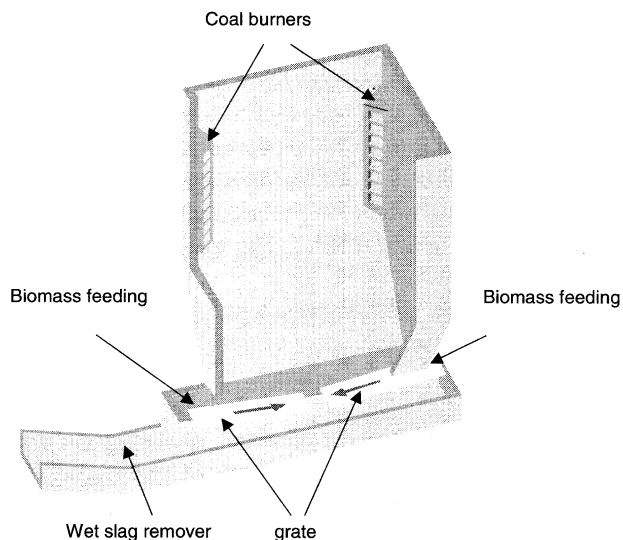


Figure 21. Biomass co-firing plant at St. Andrea (A).² Wood fuel with high moisture (10–55%) and size up to 0.5 m is burnt on a separate grate at the bottom of the boiler.² With 124 MW_e, 10 MW_{th} of wood cover 3% of the total energy input.

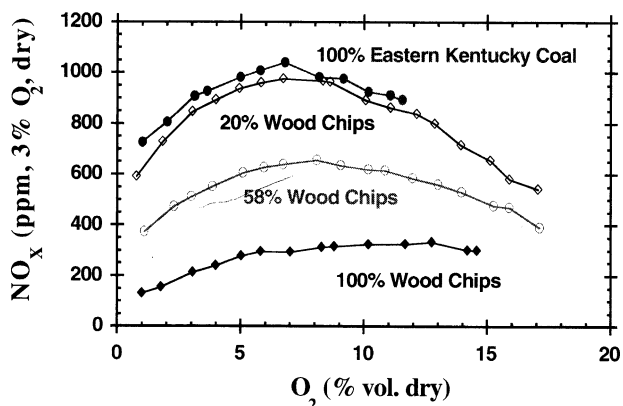


Figure 22. Effect of co-firing on NO_x emissions.³⁹

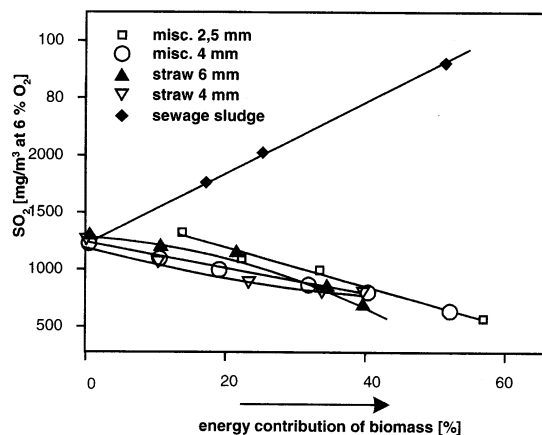


Figure 23. Influence of co-firing bio fuels on SO₂ emissions (increase: sewage sludge).⁴⁰

the separation of the ashes to a certain extent, while the flue gases cannot be separated. In comparison to parallel combustion, investment cost can be reduced because only one boiler and flue gas cleaning are needed.

6. Conclusions

Biomass combustion contributes significantly to the global energy supply nowadays. It is a proven technol-

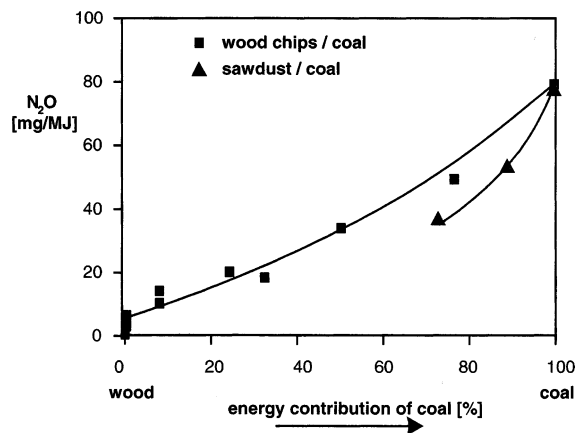


Figure 24. Influence of co-firing on N₂O emissions in a circulating fluidized bed boiler.⁴¹

ogy and widely applied in the size range from a few kW for household heating to several MW for district heating and up to more than one hundred MW for power stations based on steam cycles. Co-combustion of biomass is applied in coal-fired power stations or cement kilns and has reached a relevant propagation in the past decade. The driving forces are in both cases the CO₂ neutrality of sustainable cultivated biomass or the utilization of residues and wastes.

However, there are strong needs to improve biomass combustion in terms of environmental impact. Although the measures for complete combustion are well-known in principle, future efforts for improvement are needed to implement sufficient gas mixing in commercial furnaces and to guarantee correct operation in practice. Combustion modeling including CFD can be applied for further optimization of furnace design in future. Further, conversion efficiencies from biomass combustion to heat still have a potential for improvement. On one hand, applications in practice have a high potential of improvement by system optimization, improved maintenance, correct adjustment of fuel-to-air ratio, and optimized management of heat distribution. On the other hand quality assurance for the new realization of complex heating plants is recommended.⁴²

However, the key parameter for high combustion efficiency is the excess air ratio, which in most applications is far higher than theoretically and practically needed (i.e., often >2 while 1.2 to 1.5 is possible). To enable operation at optimum excess air and guarantee maximum efficiency in practice, advanced process control (e.g., with application of sensors for λ , temperature, and unburnt substances) should be adapted for the large variety of applications and widely implemented in the

(39) Baxter, L. L. Figure 7.16. In *Handbook of Biomass Combustion and Co-Firing*; Twente University Press: Twente, 2002; ISBN 9036517737, p 26.

(40) Spliethoff, H.; Siegle, V.; Hein, K. Zufeuerung von Biomasse in Kohlekraftwerken. In *4. Holzenergie-Symposium*, October 18 1996, Zürich, Swiss Federal Office of Energy (BFE) and ENET, Bern, 1996; pp 155–176.

(41) Leckner, B.; Karlsson, M. *Emissions from combustion of wood in a circulating fluidized bed boiler*; Chalmers University, Göteborg, 1992.

(42) Bühler, R.; Gabathuler, H.; Good, J.; Jenni, A. Quality assurance for planning and construction of biomass district heating plants. *12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, 17–21 June 2002, Amsterdam, Volume I, ETA Florence and WIP Munich; ISBN 88-900442-5-X and ISBN 3-936338-10-8, pp 952–955.

future. For the combustion of biomass with high water content, process economy can be improved either by flue gas condensation (without heat-consuming vapor abatement) and/or process integrated fuel drying with waste heat.

The remaining issues after implementation of these techniques are the reduction of NO_x emissions and the reduction of particles that are mainly in the submicron size range. The most promising technology for further emission reduction is certainly staged combustion including air staging, fuel staging and advanced staged combustion at extremely low primary air. However, since both pollutants result predominantly from fuel constituents, i.e., fuel nitrogen and ash components respectively, there are physical limitations to reducing NO_x and particles by primary measures, since high temperatures as well as the presence of oxygen are system immanent in combustion. Following, there are two options, which have to be considered for the future as well. On one hand, secondary measures need to be developed for the specific requirements of biomass combustion. Although certain technologies for NO_x and particulate abatement exist, they are not yet properly implemented (e.g., air staging and fuel staging) or they do not fulfill the needs for biomass for reasonable cost in the most frequently used appliances up to 5 MW. On the other hand, alternatives to direct combustion, such as gasification, that have not yet reached commercial standard, need to be considered as well for future applications.

By following these needs for research and development and by introducing available knowledge in practice, biomass combustion can still significantly be improved and has a potential for better economy, reduced environmental impact, and increased propagation. Besides woody fuels widely used nowadays, further bio fuels such as herbaceous biomass and bio residues can significantly contribute to the future energy supply. Additional challenges related to fuel constituents such as increased emissions and corrosion need to be overcome for these types of fuels. Further, the potential of contaminated biomass waste such as urban or demolition wood can be utilized in plants that fulfill the specific requirements.

If the presented requirements are met, combustion will remain an important technology for biomass conversion in the future and enable an increased contribution to the world's energy supply.

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