# Combustion Technology
## (Lecture - 4)

⇒ <u>Combustion</u>

* combustion is a heterogeneous chemical reaction between substances, usually including oxygen and usually accompanied by generation of heat and light in the form of flame (Figure-1)

* the rate and speed at which the reactant combine is high
  - in part because of the nature of the chemical reaction itself, and
  - in part more energy is generated than can escape into the surrounding
  - the result is that the temperature of the reactant is raised to further accelerate and continue the reaction

* in simple word, it is a high temperature exothermic reaction rxn. between a fuel and atmosperic oxygen.

⇒ Bioresource Technology and Combusion

* the burning of biomass in the presence of air is used over a wide range of outputs to convert the chemical energy stored in biomass into heat, mechanical power and est electricity

* process equipments such as stoves, furnaces, boilers, steam turbines, turbogenerators, etc are used for this purpose

* hot gases (flue gases) at temperatures around $800-1000°C$ are produced

* biomass with moisture content $< 50\%$ is used

* in case of moisture content $> 50\%$, pre-drying is required

* combustion plants from very small scale $(100\ MW)$ to large scale $(3000\ MW)$ exist

* now a nowadays, due to higher conversion efficiency, co-combustion with coal in coal-fired power plants is an attractive option for utilization of biomass
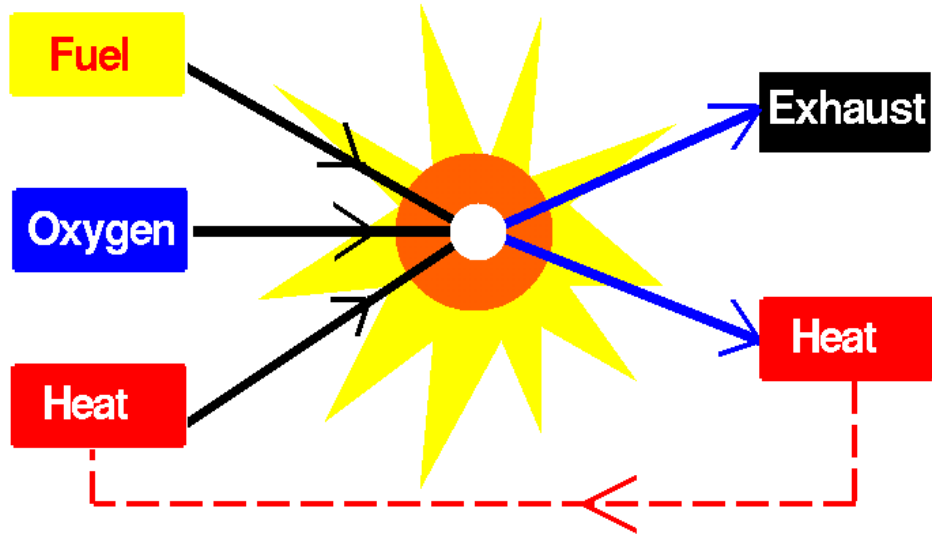
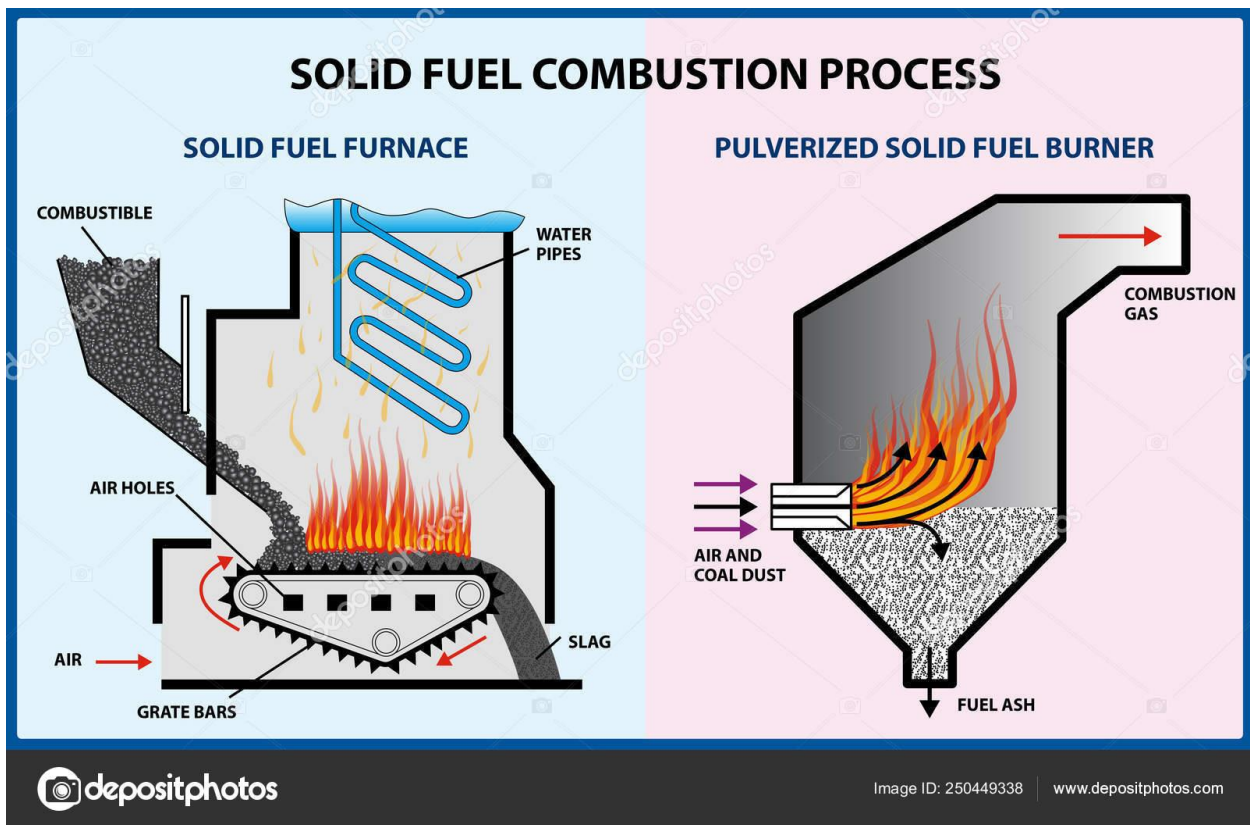**Figure-1A: Simple reperesentation of combustion**



**Figure-1B: Combustion of Biomass in a Furnace**

* biomass combustion is related to significant pollutant formation due to two reasons:
  - incomplete combustion which leads to high em emissions of unburnt pollutants, such as CO, soot and polyaromatic hydrocarbons (PAH).
  - pollutants such as $NO_x$ and particles are formed as a results of fuel constituents like N, K, Cl, Ca, Na, Mg, P and S.

* biomass furnaces exhibit relatively high emission of $NO_x$ and submicron particles

* primary majors such as air and fuel stagings have been developed to reduce NOx reduction from 50% to 80%.

* efforts are always required for optimized plant operation in order to guarantee low emissions and high conversion efficiency.

⇒ Motivation for Energy from Biomass

* globally, there is increasing interest in biomass utilization for production of energy

* in most cases the driving force is - the $CO_2$ neutrality of sustainable cultivated biomass or the utilization of biomass residues and wastes

* combustion is the most important and mature lech, technology available

* the availability of native and wastes biomass, ensures sustainable bioenergy utilization with the help of combustion technology

* improvements with respect to biomass conversion efficiency, reduction in pollutants emission and cost need to be further exploited.

⇒ Merits and Demerits of Combustion Technology.
  * Merits
    - combustion technology based on renewable feed stock, like biomass would not run out

- lower reliance on foreign energy sources is another benifit of this technology based on biomass, as biomass is available every where
- combustion technology is the mature and commercially viable technology
- saves money as the feed stock (biomass) is cheaply available
- the heat produced in the process can directly be used for power generation

* Demerits
  - due to emission of pollutants, it is not ecofriendly
  - there may be unpredictable weather condition leading to draught and acute shortage of biomass feedstock for the power plant.
  - No provision for storage of heat
  - due to emission of large volume of gases, bigger equipment is required for cleaning

Note: When it comes to the renewable energy, the positives outweigh the negatives.

⇒ Fundamentals of Biomass Combustion
  - a complex process which consists of consecutive heterogeneous and homogeneous chemical reactions (Figure-3).
  - energy is liberated with the breakdown of c-c, c-H, c-o and o-H bonds in biomass
  - chemical energy stored in biomass is converted into heat energy.
  - the main process steps in combustion are: drying, devolatilization, gasification, char combustion and gas-phase oxidation.
  - time used for each reaction depends on the fuel size and its properties, on temperature and on combustion conditions.

*[min]: TGA of beech wood, $m_0$ = 100 mg, dT/dt = 100°C/min (own)

**[s]: Particle combustion with $m_0$ = 1 mg (Baxter 2000)
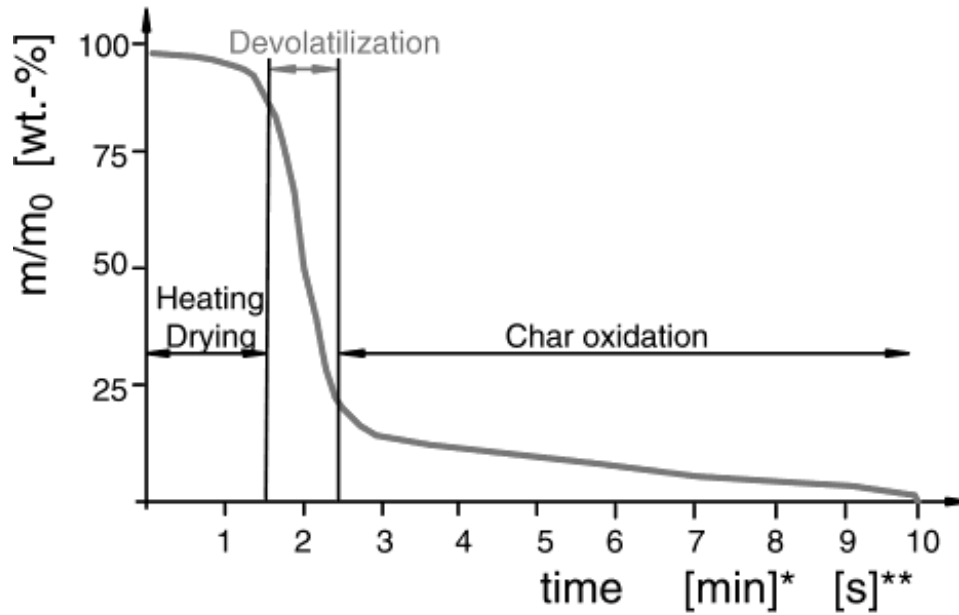


TGA of beech wood in air

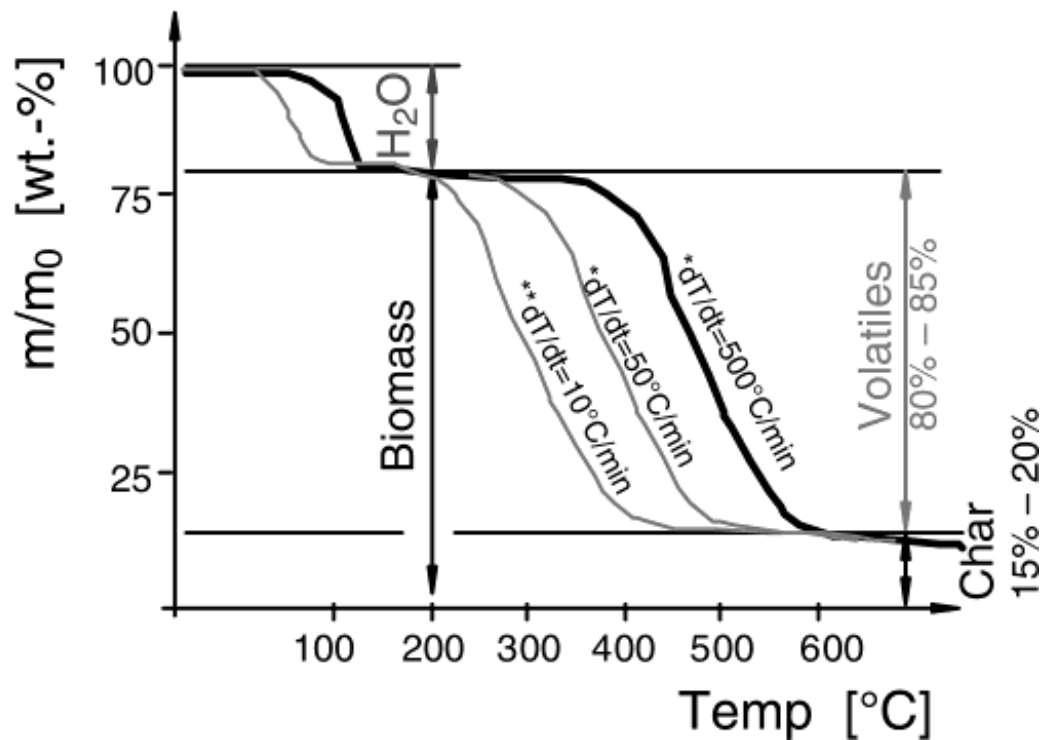*$m_0$ = 50 mg (own data), **$m_0$ = 5 mg (Skreiberg 1997)



**Figure-2: Mass loss as a function of time (above) and temperature (below) during combustion of wood in thermogravimetrical analysis (TGA). Source: Nussbaumer, 2003.**
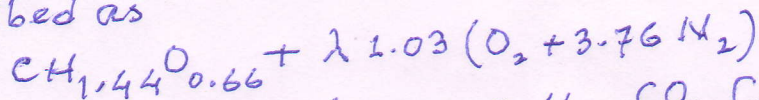
- batch combustion of small particles shows a distinct separation between volatile and char combustion phases with time (Figure 2)

- high contents of volatiles (80-85%) are respected for design of combustion appliances
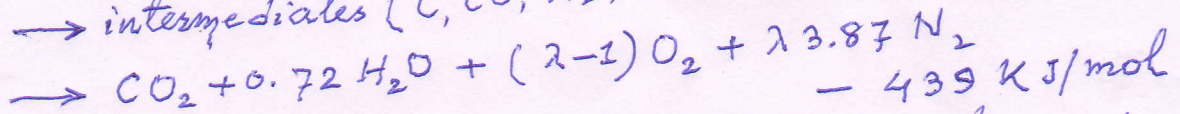
* <u>Excess Air Ratio</u>, $\lambda$

- it is the main parameter in design of the system carrying combustion

- $\lambda$ is defined as the ratio of available air (locally) to that of air required stoichiometrically

$$\lambda = \frac{locally\ available\ air}{stoichiometric\ amount\ of\ air}$$

- for typical biomass the combustion reaction may be described as

$$CH_{1.44}O_{0.66} + \lambda\, 1.03\,(O_2 + 3.76\,N_2)$$
$$\longrightarrow intermediates\ (C, CO, H_2, CO_2, C_mH_n, etc.)$$
$$\longrightarrow CO_2 + 0.72\,H_2O + (\lambda-1)\,O_2 + \lambda\,3.87\,N_2 \qquad - 439\ KJ/mol$$

where, $CH_{1.44}O_{0.66}$ represents the average composition of biomass, such as wood, straw, etc.

- in the above equation, biomass constituents, such as N, K, Cl, etc. have been neglected and the reactions have been shown in Figure - 3

* <u>Pollutants in Biomass Combustion</u> (Reference to Figure - 3)

① Unbusnt pollutants : $CO$, $C_xH_y$, PAH, tar, soot, unburnt carbon, $H_2$, HCN, $NH_3$, and $N_2O$

② Pollutant from complete combustion : $NO_x$ ( NO and $NO_2$) $CO_2$, and $H_2O$, and

③ Ash and contaminants : ash particles ($KCl$, etc.), $SO_2$, HCl, PCDD/F, Cu, Pb, Zn, Cd, etc.

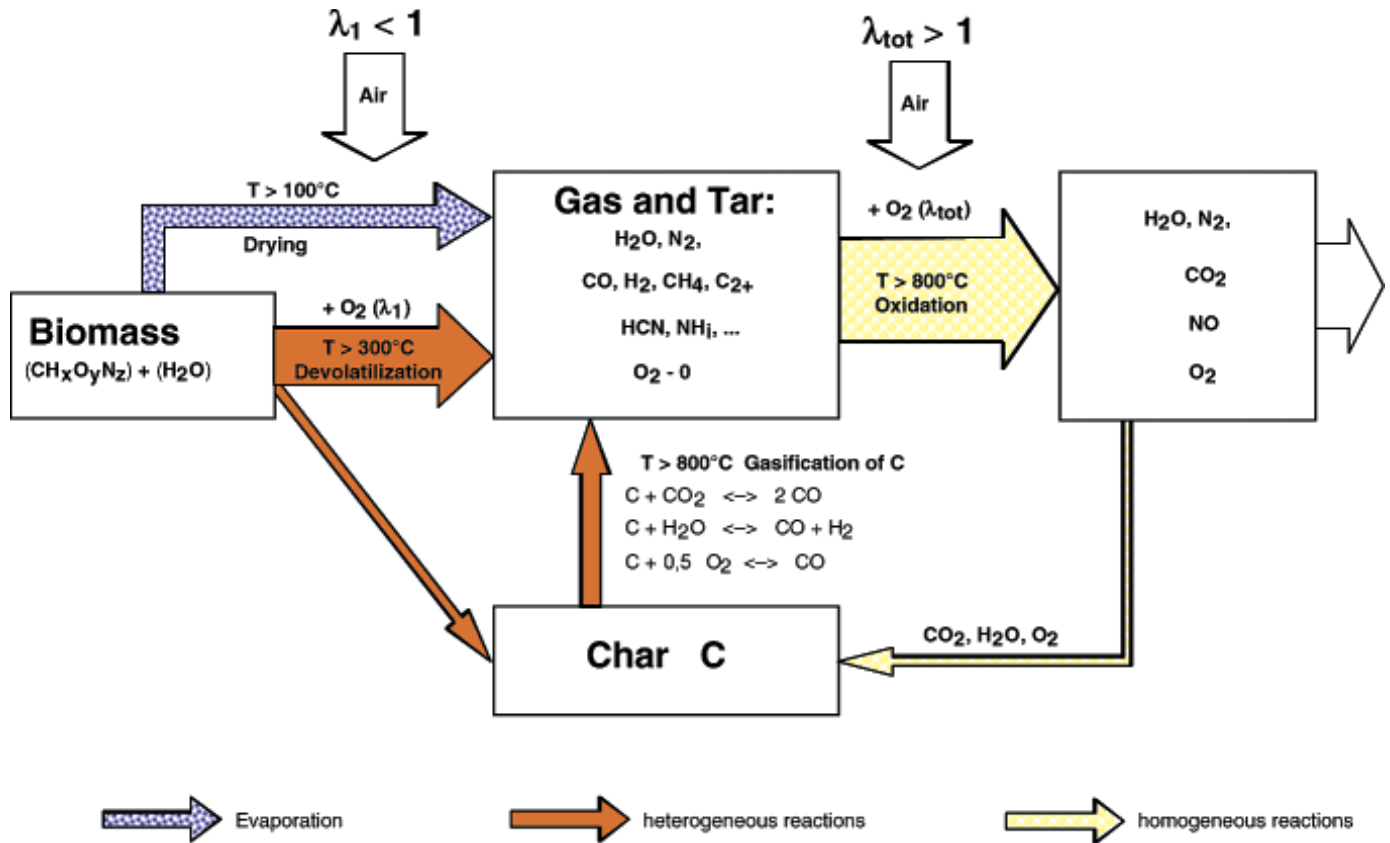Note: the conversion of fuel nitrogen to $NO_x$ has been reflected in Figure - 4

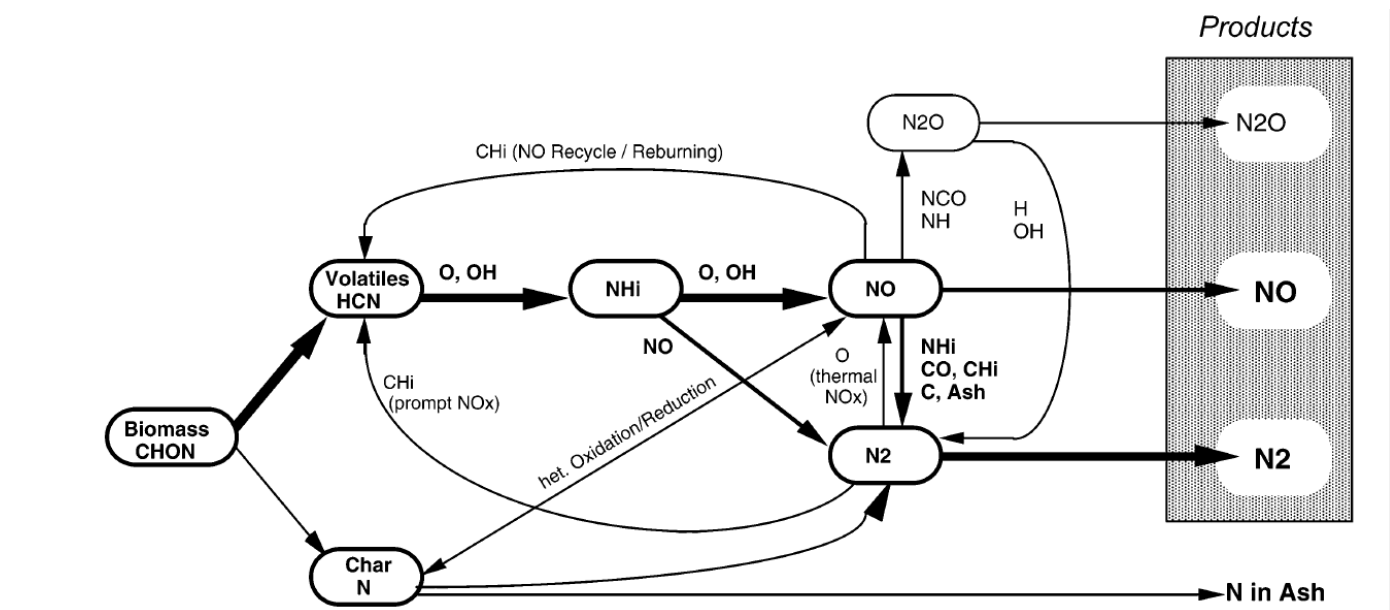**Figure-3: Main reactions during two-stage combustion of biomass with primary air and secondary air**



**Figutre-4 : Conversion of fuel nitrogen in biomass combustion.**

**\* Thermochemical Converters used in Biomass Combustion Technologies**

- the application of biomass is believed to play significant role in future in order to reduce GHG emissions

- three thermal conversion technologies, i.e. pyrolysis, gasification and combustion may be applied for the purpose

- combustion, being the most advanced and market-proven technology may play major role

- therefore, the application of biomass for energy production is primarily based on combustion

- combustion would be the dominant technology in future

- a broad spectrum of biomass combustion technologies using various types of biomass feedstocks, such as woody, herbaceous, agricultural and forestry wastes and residues are available

- the following three types of combustion technologies can be used for generation of energy from solid biomass (native, wastes and resides) as shown by figures 5 4 , 5 0 may :
  - fixed bed combustion ✓
  - fluidised bed combustion ✓
  - pulverised fuel combustion ✓

- fixed bed combustion includes ✓
  - grate furnaces and underfeed stokers
  - primary air passes through a fixed bed where drying, gasification and oxidation of charcoal take place
  - the combustible gases are burnt by secondary air
  - combustion zone is separated from the fuel bed
  - it large flexibility with respect to moisture contents (10 – 60% by weight w.b.) and particle size (5 mm – >10 cm)
  - mixing of wood fuels is possible but limited for herbaceous fuels
  - nominal boiler capacity ranges from 10 kW to 50 kW.

⇒ <u>fluidized bed combustion</u>

- biomass fuel is burnt in suspension of gas and solid bed material where the primary air enters from the bottom
- based on the fluidization velocity, bubbling fluidised bed and circulating fluidised bed may be differentiated
- in bubbling fluidised bed, the bed material is located in the bottom part of the furnace where the fluidisation velocity varies from 1.0 to 2.5 m/s.
- the circulating fluidised bed system is achieved by ~~increas~~ increasing the velocity to 5 to 10 m/s by using smaller biomass fuel and sand particles
- the sand particles are carried with flue gas, separated in a hot cyclone or a U-beam separator, and fed back into the combustion chamber
- fluidized bed furnaces offers a large flexibility for moisture content from 10-50 wt% w.b. and fuel mixing
- low flexibility with respect to particle size
  - ✓ in BFB particle size < 80 mm
  - ✓ in CFB " " < 40 mm
- ~~low~~ low excess air ratios are possible with higher efficiency compensating the higher investment costs due to homogeneous combustion conditions
- boiler capacity may range from 20 MW to several 100 MW.

⇒ <u>pulverized fuel combustion</u>

- suitable for fuel with small particle size
- primary combustion air and fuel mixture are injected in the combustion chamber
- combustion takes place while the biomass particles are in suspension, and gas is burnt out after addition of secondary air
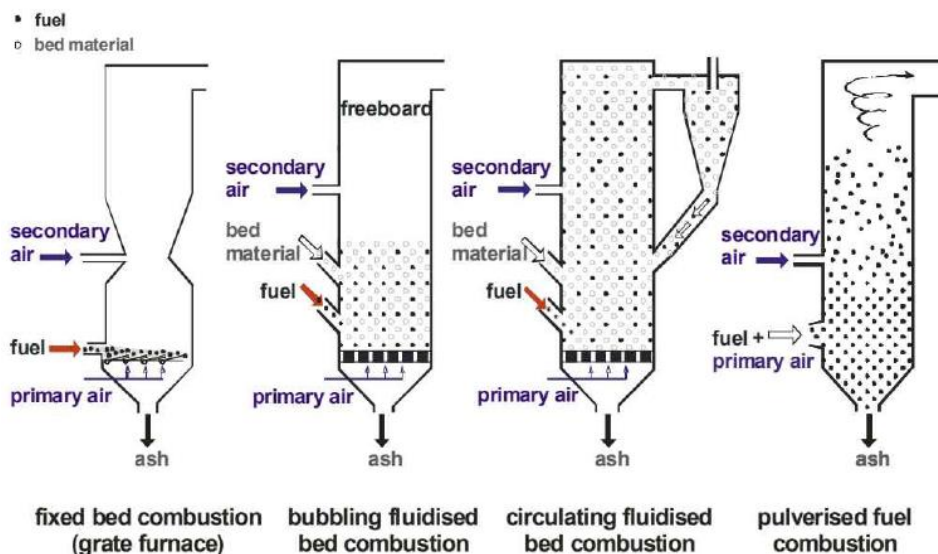- examples are: dust injection burners, muffle furnaces and cyclone burners.

※ - moisture content usually below 20 wt% w.b.
- particle size limited up to 20 mm
- a combination with grate and fluidised bed is possible
- most common for biomass co-firing, capacity of boiler varies from 500 kW to several 100 for co-firing systems

**Figure-5: Different combustion technologies for biomass conversion to energy.**

An overview of advantages, disadvantages, fields of application and capacity ranges of various combustion technologies have been reflected in Table-1.

**Table-1: Overview of Advantages, Disadvantages and Fields of Applications of Various Combustion Technologies**

| Advantages | Disadvantages |
|---|---|
| **Fixed bed combustion** - capacity range: 100 kW – 50 MW | |
| large flexibility concerning moisture content (10 – 60 wt% w.b.) and particle size (5 - >100 mm)<br>mixing of different wood fuels possible<br>low investment costs for plants < 20 $MW_{th}$<br>low operating costs<br>less sensitive to slagging than fluidised bed furnaces | mixing of wood fuels and herbaceous fuels limited<br>high excess oxygen (5 - 8 Vol%) decreases efficiency<br>combustion conditions not as homogeneous as in fluidised bed furnaces |
| **Fluidized bed combustion -** capacity range: 20 MW – several 100 MW | |
| high flexibility concerning moisture content (10 – 55 wt% w.b.) and kind of biomass fuels used<br>no moving parts in the hot combustion chamber<br>high specific heat transfer capacity due to high turbulence<br>low excess oxygen (1 - 4 vol%) raises efficiency and decreases flue gas flow | high investment costs, interesting only for plants > 20 $MW_{th}$<br>high operating costs<br>low flexibility with regard to particle size (< 80 mm for BFB, 40 mm for CFB)<br>high dust load in the flue gas<br>partial-load operation requires special technology<br>high sensitivity concerning ash slagging |
| **Pulverised fuel combustion -** capacity range: 500 kW – several 100 MW (co-firing) | |
| Medium excess oxygen (4 - 6 Vol%) increases efficiency<br>very good load control and fast alternation of load possible | water content usually < 20 wt% w.b.<br>particle size of biofuel is limited (< 10-20 mm)<br>high wear out of the insulation brickwork if cyclone or vortex burners are used<br>an extra start-up burner is necessary |

**Samall Scale. Medium Scale and Large Size Biomass Combustion Plants**

Concerning plant size, the different applications of biomass combustion can be divided into the following main fields:

- Small-scale biomass combustion systems: (capacity range: <100 $kW_{th}$)
- Medium-scale combustion systems (capacity: range: 100 $kW_{th}$ to 20 $MW_{th}$)
- Large-scale combustion systems (capacity: range: >20 $MW_{th}$)
- Co-firing of biomass in coal fired power stations (capacity range: some 100 $MW_{th}$)

**Small-scale biomass combustion units** are mainly applied for residential heating systems. Here, different types of pellet burners, wood stoves and fire-place inserts as well as log wood, wood chips and pellets boilers are commonly used. These systems are only suitable for high quality wood fuels.

The **medium capacity range** covers biomass district and process heating and biomass combined heat and power (CHP) plants. Underfeed stokers, grate-fired furnaces and pulverised fuel burners are the main technologies applied in this capacity range. In Figures 6 examples for underfeed stokers and grate-fired furnaces are shown. Heat transfer is most commonly based on hot water boilers, but also steam boilers and thermal

oil boilers. These systems usually burn woody biomass fuels such as wood chips, sawdust, bark, forest residues and waste wood but also straw and other agricultural residues (e.g. sunflower husks). In addition to heat production for process and district heat supply, combined heat and power (CHP) systems are of increasing importance. A number of CHP technologies such as Stirling engines, the ORC process, steam engines and steam turbines can be combined with such plants.

The **large-scale range** (>20 MW$_{th}$) mainly comprises CHP plants and power plants with thermal capacities up to some 100 MW based on grate-fired and fluidised bed combustion systems     (Figures -7 a, b)       are usually fired with woody biomass fuels (wood chips, sawdust, bark, forest residues and waste wood) and straw but also with residues and wastes from the agricultural industry such as fruit stones, kernels, husks and shells. Usually steam boilers combined with steam turbines are applied.
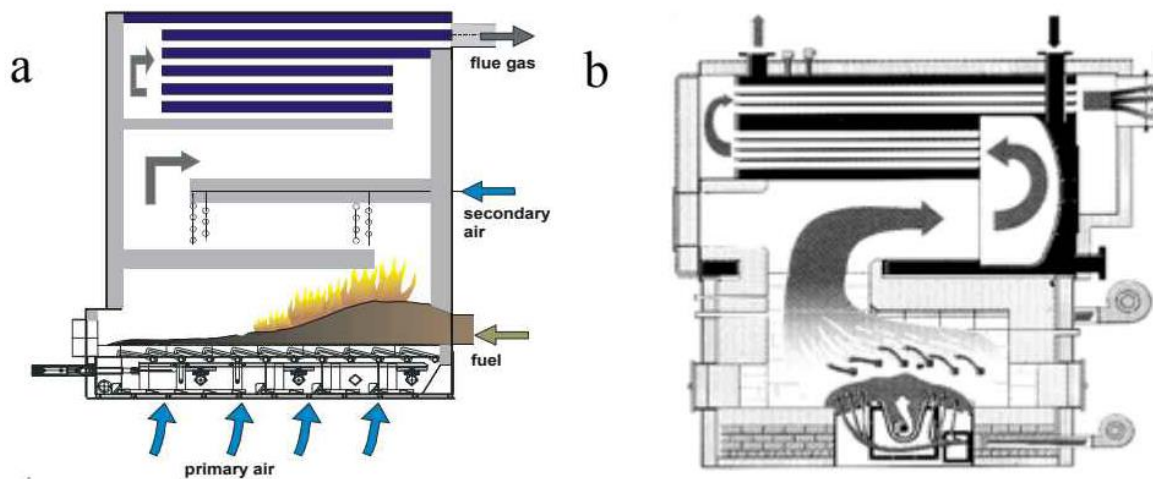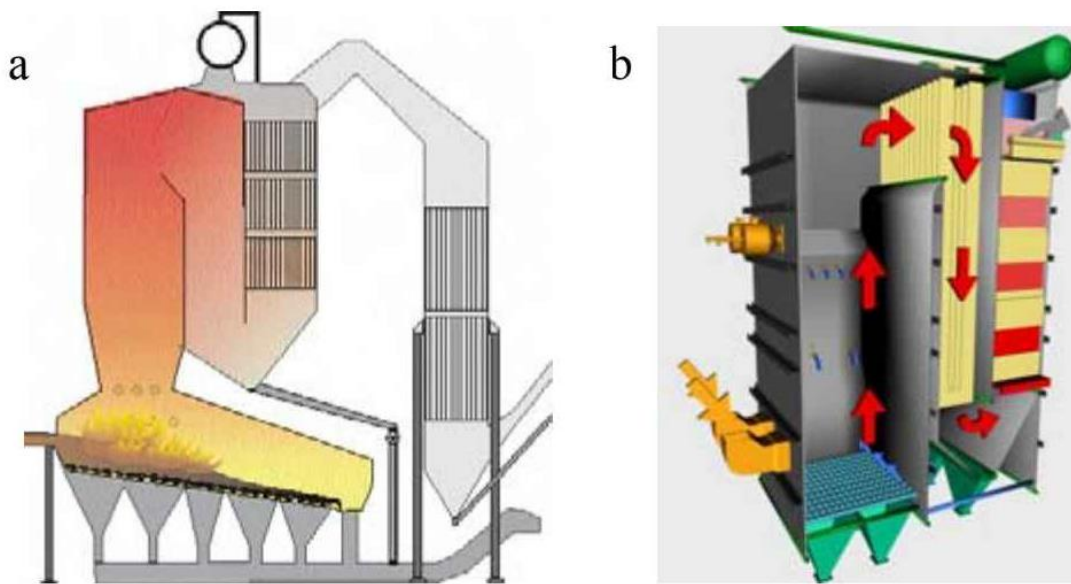


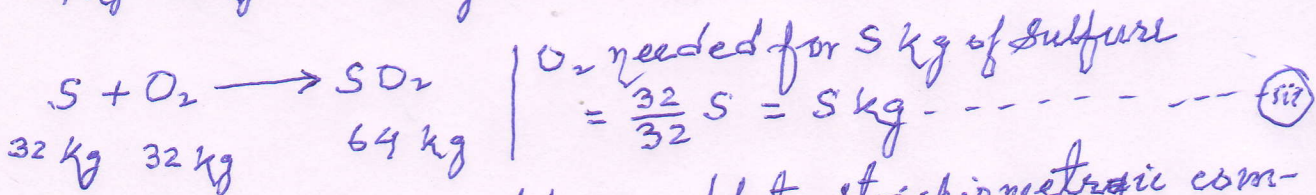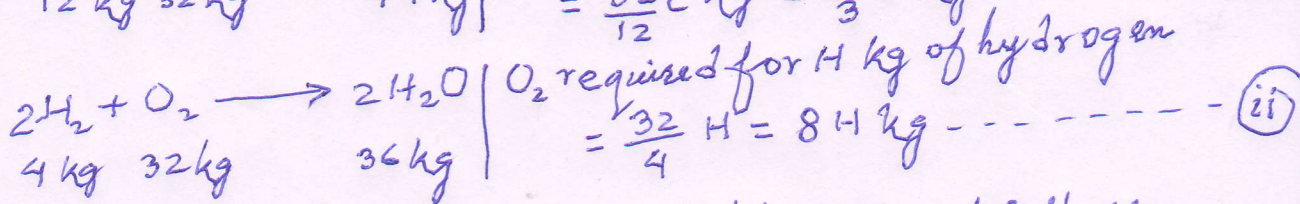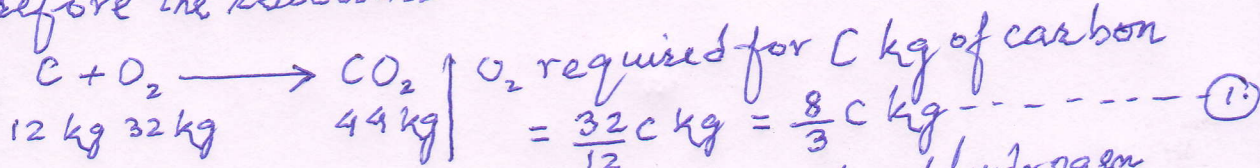Figure-6: Medium scale biomass combustion plants (a: Grate-fired furnace, b:Underfeed stoker)



Figures-7: Large scale biomass combustion plants (a:grate-fired furnace, b:fluidized-bed)

# Calculation of Minimum Quantity of Air Required for complete combustion of unit amount of Biomass fuel.

**Basis:** 1 kg of bioresource (biomass)

— by weight in air, oxygen is 23% and nitrogen 77%.

— by volume in air, oxygen is 21% where as nitrogen 79%.

— it is assumed that the elemental components of biomass which take part in combustion process are : $C, N, H, O, S$

— other elements including nitrogen don't disturb the process of combustion *(note: in practice they do influence)*

— let us also assume that 1 kg of biomass contains $C$ kg carbon, $H$ kg hydrogen, $N$ kg nitrogen, $S$ kg sulfur and $O$ kg Oxygen

— only the combustible elements carbon, hydrogen and sulfur react with oxygen during combustion

— therefore the reactions

$$C + O_2 \longrightarrow CO_2$$
$$12\,kg \quad 32\,kg \qquad 44\,kg$$

$O_2$ required for $C$ kg of carbon
$$= \frac{32}{12}C\,kg = \frac{8}{3}C\,kg \quad \text{————} \quad ①$$

$$2H_2 + O_2 \longrightarrow 2H_2O$$
$$4\,kg \quad 32\,kg \qquad 36\,kg$$

$O_2$ required for $H$ kg of hydrogen
$$= \frac{32}{4}H = 8H\,kg \quad \text{————} \quad ②$$

$$S + O_2 \longrightarrow SO_2$$
$$32\,kg \quad 32\,kg \qquad 64\,kg$$

$O_2$ needed for $S$ kg of Sulfur
$$= \frac{32}{32}S = S\,kg \quad \text{————} \quad ③$$

Therefore, oxygen required for complete stoichiometric combustion of 1 kg of biomass is ① + ② + ③

$$= \left(\frac{8}{3}C + 8H + S\right)kg \quad \text{————} \quad ④$$

— Since $O$ kg oxygen is already present in the biomass, therefore, oxygen required for 1 kg of biomass

$$= \left(\frac{8}{3}C + 8H + S - O\right)kg \quad \text{————} \quad ⑤$$

— Since oxygen is 23% (by wt.) in air

The amount of air required $= \dfrac{100}{23}\left[\dfrac{8}{3}C + 8H + S - O\right]kg$ ⑥

1. The ultimate analysis of biomass fuel shows 83% carbon, 5% hydrogen 2% oxygen, 0.2% sulfur and remainder being incombustible. Determine the total amount of theoretical air required for complete combustion of 1 kg of the bioresource.

Basis: 1 kg of bioresource (biomass)

In 1 kg, the amount of carbon, hydrogen, oxygen, and sulfur would be 0.83, 0.05, 0.02 and 0.002 kg, respectively

Minimum quantity of air required for complete combustion

$$= \frac{100}{23}\left[\frac{8}{3}C + 8H + S - O\right] = \frac{100}{23}\left[\frac{8}{3} \times 0.83 + 8 \times 0.05 + 0.002 - 0.02\right]$$

$$= 11.28 \text{ kg}$$

2. If air is supplied 20% in excess in the above question, determine the composition of flue gas.

Since air is supplied 20% excess

Actual amount of air supplied $= 11.28 \times 1.20 = 13.54$ kg.

Excess Air $= 13.54 - 11.28 = 2.26$ kg.

Amount of oxygen present in excess air which goes with flue gas

$$= \frac{23}{100} \times 2.26 = 0.52 \text{ kg}$$

Nitrogen in flue gas = nitrogen in biomass + nitrogen coming with air

Nitrogen in biomass = 0 (non combustible assumed to be ash)

Nitrogen coming with 20% excess air $= \frac{77}{100} \times 13.54 = 10.43$ kg.

$CO_2$ in the flue gas $= \frac{44}{12} \times 0.83 = 3.04$ kg

$H_2O$ in " " $= (36/4) \times 0.05 = 0.45$ kg

$SO_2$ " " " $= (64/32) \times 0.002 = 0.004$ kg.

| S.No | Analysis of Flue gas by Weight | | | | Analysis by Volume. | | |
|------|-----------|-------------|---------|----------|--------|-----------------|----------|
| | Constituent | Weight (kg) | Weight % | Mol. wt. | wt.% | Relative Volume | % Volume |
| 1. | $CO_2$ | 3.04 | 21.83 | 44 | 21.83 | 21.83/44=0.5 | 14.97 |
| 2. | $N_2$ | 10.43 | 74.91 | 28 | 74.91 | 74.91/28=2.68 | 80.22 |
| 3. | $H_2O$ | 0.45 | 3.23 | 18 | 3.23 | $\frac{3.23}{18}=0.18$ | 5.38 |
| 4. | $SO_2$ | 0.004 | 0.03 | 64 | 0.03 | $\frac{.03}{64}=0.00047$ | 0.02 |
| | | 13.924 | 100.00 | | | 3.3405 | 101.09 |

# 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 $CO_2$ 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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[†] Revised version of the invited plenary oral presentation at the *12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, 17-21 June 2002, Amsterdam.[1]

(1) Palz, W.; Spitzer, J.; Maniatis, K.; Kwent, K.; Helm, P.; Grassi, A., Eds. *12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, 17–21 June 2002, Amsterdam, Vol. I&II, ETA Florence and WIP Munich, ISBN 88-900442-5-X and ISBN 3-936338-10-8, pp 31–37.

(2) van Loo, S.; Koppejan, J. *Handbook of Biomass Combustion and Co-Firing*; Twente University Press: Twente, 2002; ISBN 9036517737.

(3) Kaltschmitt. M., Hartmann, H., Eds. *Energie aus Biomasse*; Springer: Berlin, 2001; ISBN 3-540-64853-42001.
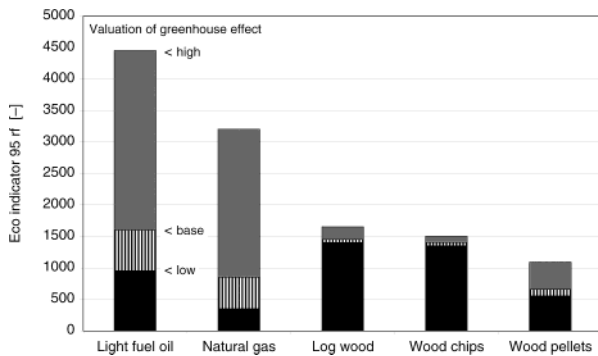
**Figure 1.** Environmental impact points (EIP) for different valuations of the greenhouse effect.[7]

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

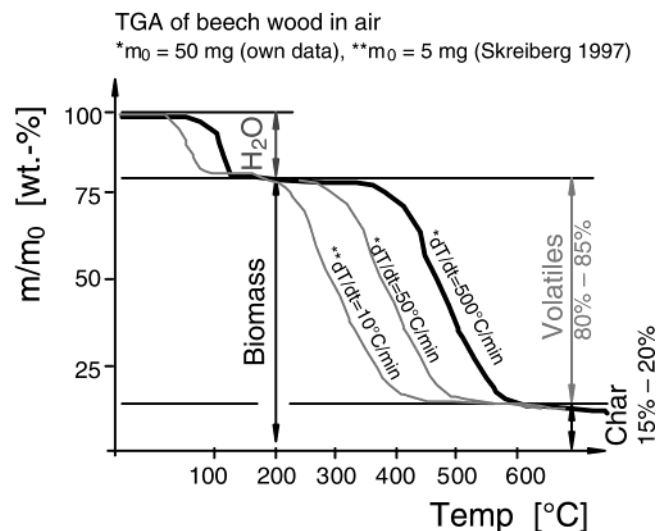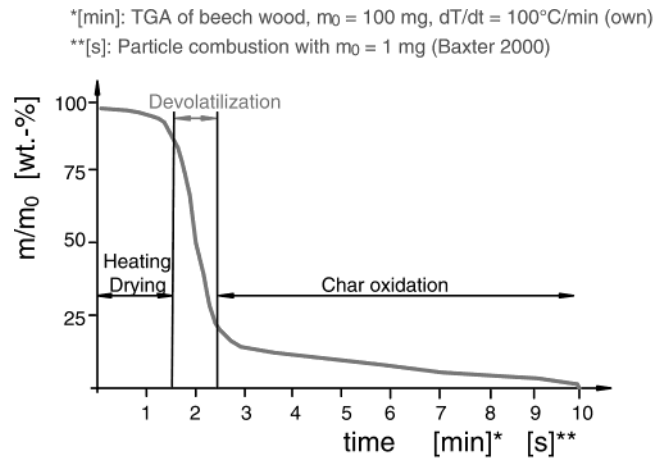| | [EIP/GJ] | [%] |
|---|---|---|
| $NO_X$ | 13 030 | 38.6% |
| PM 10 | 12 600 | 36.5% |
| $CO_2$ | 670 | 2.0% |
| $SO_X$, $NH_3$, $CH_4$, NMVOC, primary energy, residues, and others | 8 200 | 22.9% |
| Total | 34 500 | 100% |

[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 $NO_2$ 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 $CO_2$, 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 $CO_2$ 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-

(4) Nussbaumer, T. Schadstoffbildung bei der Verbrennung von Holz, Ph.D. Thesis 8838, ETH Zürich, 1989.

(5) Marutzky, R. Erkenntnisse zur Schadstoffbildung bei der Verbrennung von Holz und Spanplatten, WKI-Bericht Nr. 26, Braunschweig, 1991.

(6) Baumbach, G.; Zuberbühler, U.; Siegle, V.; Hein, K. *Luftverunreinigungen aus gewerblichen und industriellen Biomasse- und Holzfeuerungen*; Ecomed-Verlag: Landsberg, 1997.

(7) Kessler, F.; Knechtle, N.; Frischknecht, R. *Heizenergie aus Heizöl, Erdgas oder Holz*; Swiss Federal Office of Environment (BUWAL), Umwelt Schrift Nr. 315, Berne, 2000.

**Figure 2.** Mass loss as a function of time (above) and temperature (below) during combustion of wood. Our own results from thermogravimetrical analysis (TGA) supplemented with data from Baxter[8] and Skreiberg.[9]

dation. 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 ($\lambda$) that describes the ratio between the locally available and the stoichiometric amount of combustion air. For typical biomass, the combustion reaction can then be
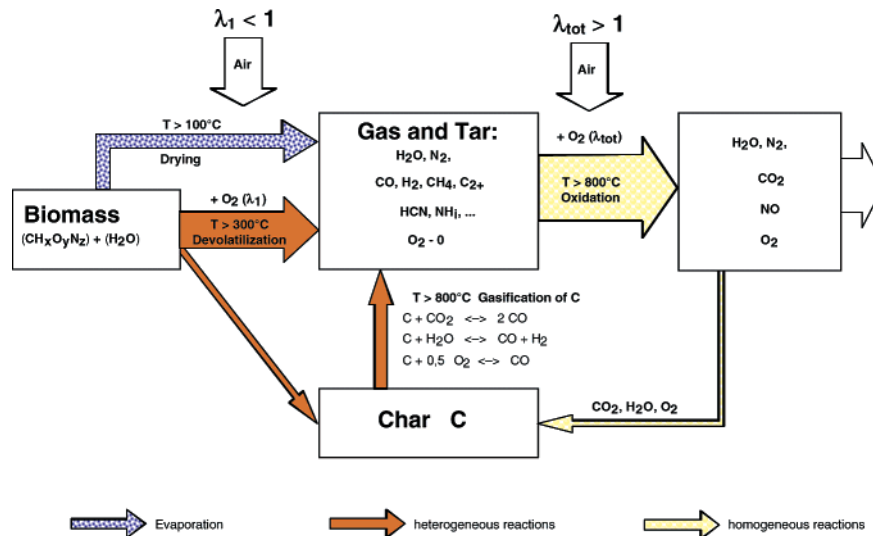
**Figure 3.** Main reactions during two-stage combustion of biomass with primary air and secondary air.[10]

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

$$CH_{1.44}O_{0.66} + \lambda 1.03(O_2 + 3.76\ N_2)$$

$$\rightarrow \text{intermediates (C, CO, H}_2\text{, CO}_2\text{, C}_mH_n\text{, etc.)}$$

$$\rightarrow CO_2 + 0.72H_2O + (\lambda - 1)O_2 + \lambda 3.87N_2$$
$$-439\ kJ/kmol$$
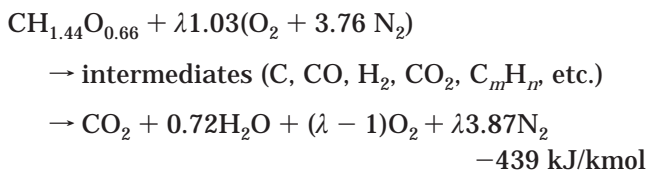
where $CH_{1.44}O_{0.66}$ describes the average composition of typical biomass used for combustion, i.e., wood, straw, or similar material.

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, $H_2$, HCN, $NH_3$, and $N_2O$;

2. pollutants from complete combustion such as $NO_X$ (NO and $NO_2$), $CO_2$, and $H_2O$; and

3. ash and contaminants such as ash particles (KCl, etc.), $SO_2$, 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/m$^3$ and $C_XH_Y$ < 5 mg/m$^3$ at 11 vol % $O_2$). However, an accurate process
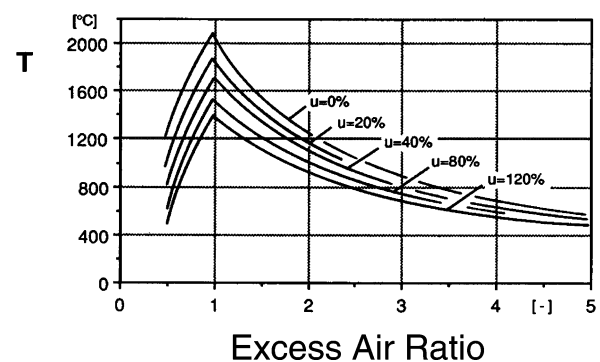


**Figure 4.** Adiabatic flame temperature for the combustion of wood with different humidity $u$ ($u$ a is based on dry fuel, hence $u = 100\%$ corresponds to a moisture content $w = 50\%$).[4]
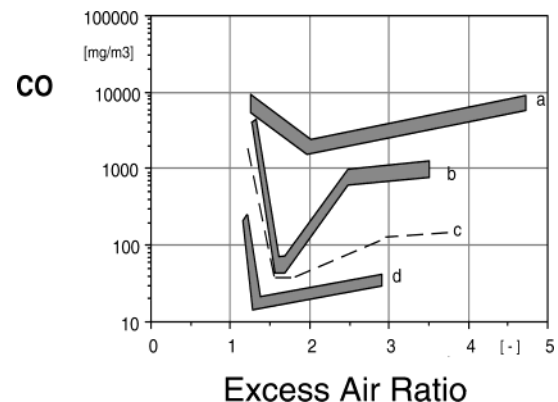


**Figure 5.** Carbon monoxide emissions as function of excess air ratio for different furnace types.[4,10] (a) Wood stove, (b) downdraft boiler, (c) automatic wood furnace, d) advanced automatic wood furnace.

control is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and $\lambda$ (CO/$\lambda$-controller)[11] or of CO and temperature[12] have been developed.

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

(8) Baxter, L. L. Figure 2.2. In *Handbook of Biomass Combustion and Co−Firing*; Twente University Press: Twente 2002; ISBN 9036517737, p 26.

(9) Skreiberg, Ø. *Theoretical and Experimental Studies on Emissions from Wood Combustion*. Ph.D. Thesis, Norwegian University, Trondheim, 1997.

(10) Nussbaumer, T. In *Energie aus Biomasse*; Springer: Berlin 2001; ISBN 3-540-64853-42001, pp 288−389.

(11) Good, J. Verbrennungsregelung bei automatischen Holzfeuerungen, Ph.D. Thesis, ETH 9771, ETH Zürich, 1992.

(12) Padinger, R. *Regelungstechnik für die Hausheizung der Zukunft*. Berichte aus Energie- und Umweltforschung 5/2002, Bundesministerium für Verkehr, Innovation und Technologie, Wien, 2002.
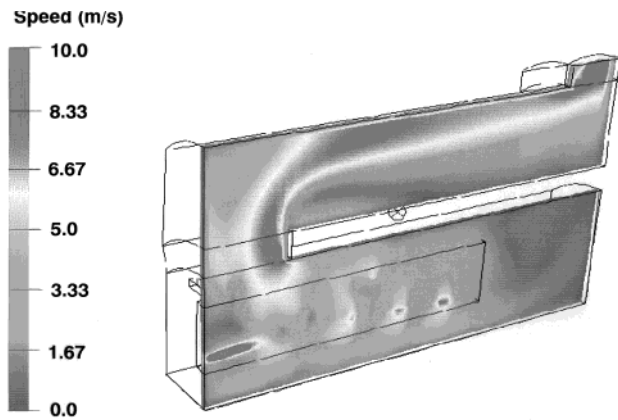
**Figure 6.** CFD modeling for optimization of furnace design. The example shows the velocity distribution in the combustion chamber over a grate with secondary air nozzles and post combustion chamber.[13]

mary air needs to be understoichiometric ($\lambda$ 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.
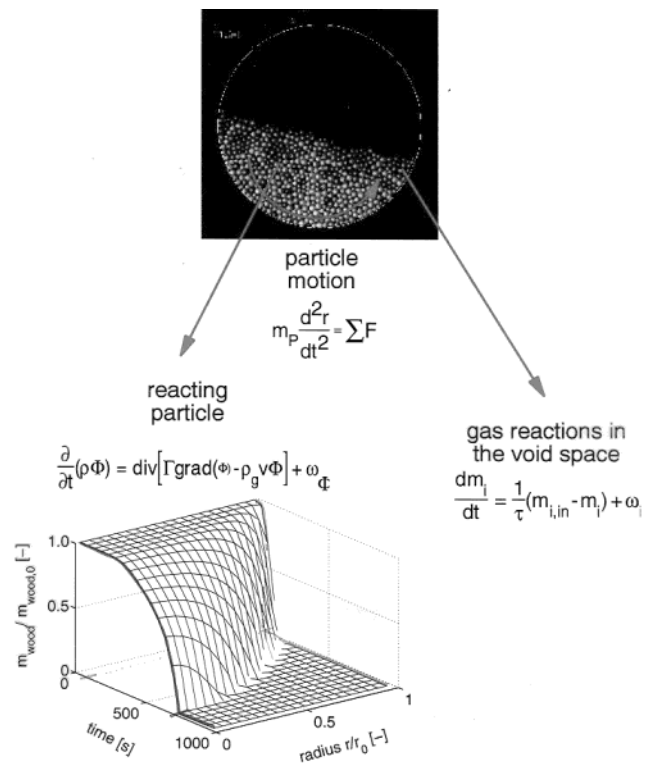
For future improvements in furnace design, computational fluid dynamics (CFD) can be applied as a standard tool to calculate flow distributions in furnaces, as shown by an example in Figure 6.[13] Furthermore, the reaction chemistry in the gas phase can be implemented in CFD codes.[14,15] However, the 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



**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 $NO + NH_2 = N_2 + H_2O$ (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

(13) Bruch, C.; Nussbaumer, T. Verbrennungsmodellierung mit CFD zur optimierten Gestaltung von Holzfeuerungen. In *5. Holzenergie-Symposium*, 16. Oktober 1998, Zürich, Swiss Federal Office of Energy (BFE) and ENET, Bern, 1998; pp 189−202.

(14) Schnell, U. Numerical modelling of solid fuel combustion processes using advanced CFD-based simulation tools. *Int. J. Prog. Comput. Fluid Dyn.* **2001**, *1* (4), 208−218.

(15) Peters, B. Numerical Simulation of Packed Bed Combustion. In *4th Eur. Conf. Ind. Furnaces Boilers,* 1-4 April 1997, Porto (Portugal) **1997**, 1−23.

(16) Bruch, C.; Peters, B.; Nussbaumer, T. Modelling wood combustion under fixed bed conditions. *Fuel* **2003**, *82*, 729−738.

(17) Bruch, C. Beitrag zur Modellierung der Festbettverbrennung in automatischen Holzfeuerungen, Ph.D. Thesis 14040, ETH Zürich, 2001.

(18) Nussbaumer, T.: Wood Combustion. In *Advances in Thermo-chemical Biomass Conversion*, Blackie Academic & Professional: London, 1994; ISBN 0 7514 0171 4, pp 575−589.

(19) Nussbaumer, T. Primär- und Sekundärmassnahmen zur Stick-oxidminderung bei Holzfeuerungen. In *Moderne Feuerungstechnik zur energetischen Verwertung von Holz und Holzabfällen*, Springer-VDI: Düsseldorf, 1997; ISBN 3-18-990028-0, pp 279−308.

(20) Siegle, V.; Kicherer, A.; Spliethoff, H.; Hein, K. Verbrennung von Biomasse in Staubbrennern, In *3. Holznergie-Symposium*, 21. Oktober 2001, Zürich, Swiss Federal Office of Energy (BFE) and ENET, Bern, 1994; pp 57−74.
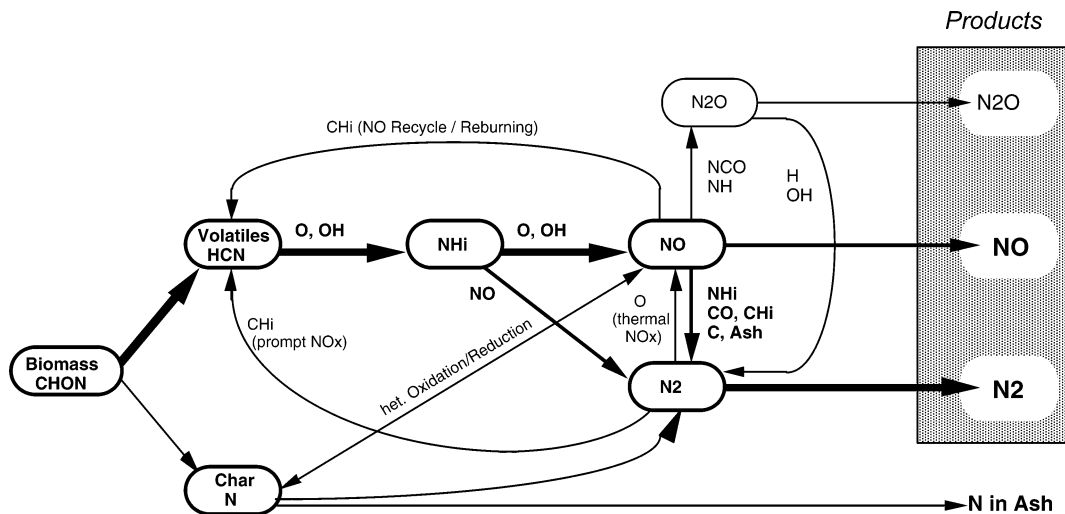
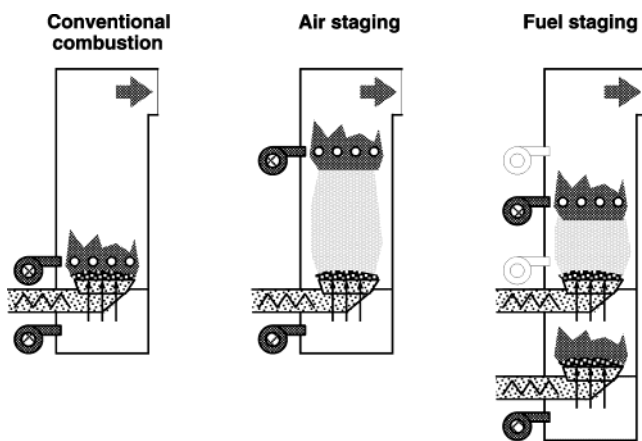**Figure 8.** Conversion of fuel nitrogen in biomass combustion.[19]



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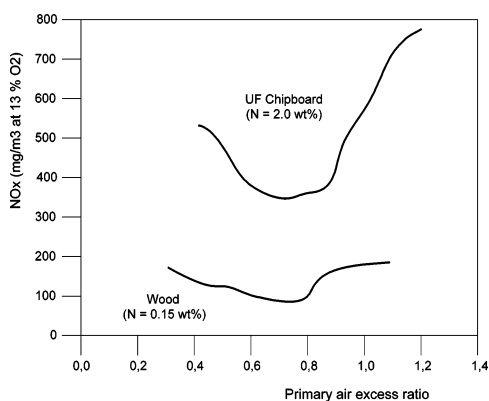


**Figure 10.** $NO_X$ emissions as a function of primary excess air ratio with air staging.[21]

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., $NO + NH_2 = N_2 + H_2O$. 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/m³ at 11 vol % $O_2$.[4,25] The majority of the particulates are smaller than 10 $\mu$m (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]

(21) Keller, R. *Primärmassnahmen zur NOX-Minderung bei der Holzverbrennung mit dem Schwerpunkt der Luftstufung*, Ph.D. Thesis 10514, ETH Zürich, 1994.

(22) Salzmann, R.; Nussbaumer, T. Fuel Staging for NOX Reduction in Biomass Combustion: Experiments and Modeling. *Energy Fuels* **2001**, *15*, 575–582.

(23) Fastenaekels, H.; Nussbaumer, T. Entwicklung einer kombinierten Unterschub- und Einblasfeuerung zur Luft- und Brennstoffstufung. In *7. Holzenergie-Symposium, 18. Oktober 2002*, Zürich; ISBN 3-908705-01-0, pp 89–102.

(24) Nussbaumer, T. Selective Catalytic Reduction and Selective Non-Catalytic Reduction of Nitric Oxides for Wood Firings. In *Advances in Thermochemical Biomass Conversion*; Blackie Academic & Professional: London, 1994; ISBN 0 7514 0171 4, pp 708–720.

**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.
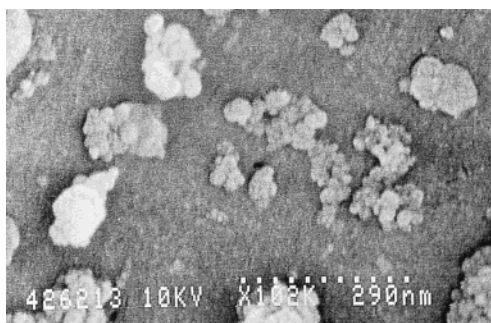


**Figure 12.** Fly ash from wood combustion.[26]

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 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

(25) Nussbaumer, T.; Hasler, P. Bildung und Eigenschaften von Aerosolen aus Holzfeuerungen. *Holz als Roh- Werkstoff* **1999**, *57*, 13−22.

(26) Kaufmann, H.; Nussbaumer, T.; Baxter, L.; Yang, N. Deposit formation on a single cylinder during combustion of herbaceous biomass. *Fuel* **2000**, *79*, 141−151.

(27) Nussbaumer, T.; van Loo, S. Aerosols from biomass combustion − Overview on activites in IEA Bioenergy. *12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, 17−21 June 2002, Amsterdam, Volume II, ETA Florence (I) and WIP Munich (D); ISBN 88-900442-5-X and ISBN 3-936338-10-8, pp 917−921.

(28) Hüglin, C.; Gaegauf, C.; Kuenzel, S.; Burtscher, H. Characterization of Wood Combustion Particles. Morphology, Mobility and Photoelectric Activity. *Env. Sci. Techn.* **1997**, *31*, 3439−3447.

(29) Johansson, L. S. *Characterisation of Particle Emissions from Small-Scale Biomass Combustion*. Thesis, Chalmers University of Technology, Göteborg, 2002.

(30) Jokiniemi, J.; Lind, T.; Hokkinen, J.; Kurkela, J.; Kauppinen, E. Modelling and experimental results on aerosol formation, deposition and emissions in fluidized bed combustion of biomass. In *Aerosols from Biomass Combustion;* Verenum: Zurich, 2001; ISBN 3-908705-00-2, pp 31−40.

(31) Obernberger, I.; Brunner, T.; Jöller, M. Characterisation and formation of aerosols and fly ashes from fixed-bed biomass combustion. In *Aerosols from Biomass Combustion;* Verenum: Zurich 2001; ISBN 3-908705-00-2, pp 69−74.

(32) Brunner, T.; Obernberger, I.; Jöller, M.; Arich, A.; Pölt, P. Measurement and analyses of aerosols formed during fixed-bed biomass combustion. In *Aerosols from Biomass Combustion*; Verenum: Zurich, 2001; ISBN 3-908705-00-2, pp 75−80.

(33) Oser, M.; Nussbaumer, T.; Schweizer, B.; Mohr, M.; Figi, R. Influences on aerosol emissions in an automatic wood furnace. In *Aerosols from Biomass Combustion*; Verenum: Zurich, 2001; ISBN 3-908705-00-2, pp 59−64.

(34) Oser, M.; Nussbaumer, Th.; Müller, P.; Mohr, M.; Figi, R. *Grundlagen der Aerosolbildung in Holzfeuerungen: Beeinflussung der Partikelemissionen durch Primärmassnahmen und Konzept für eine partikelarme automatische Holzfeuerung (Low-Particle-Feuerung)*, Bundesamt für Energie (BFE), Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Schlussbericht Projekt 26688, Zürich und Bern, 2003, ISBN 3-908705-02-9.

**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% |
| automatic | understoker furnaces | 20 kW−2.5 MW | wood chips, wood residues | <2% | 5%−50% |
| | 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.
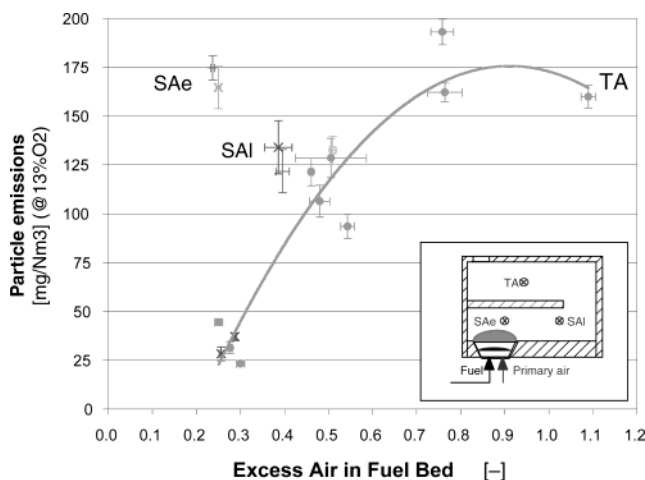


**Figure 13.** Particle emissions as a function of the excess air in the fuel bed at different air settings according to the location in the small graph: TA = tertiary air (curve), SAe = secondary air early, SAl = secondary air late.[34]

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
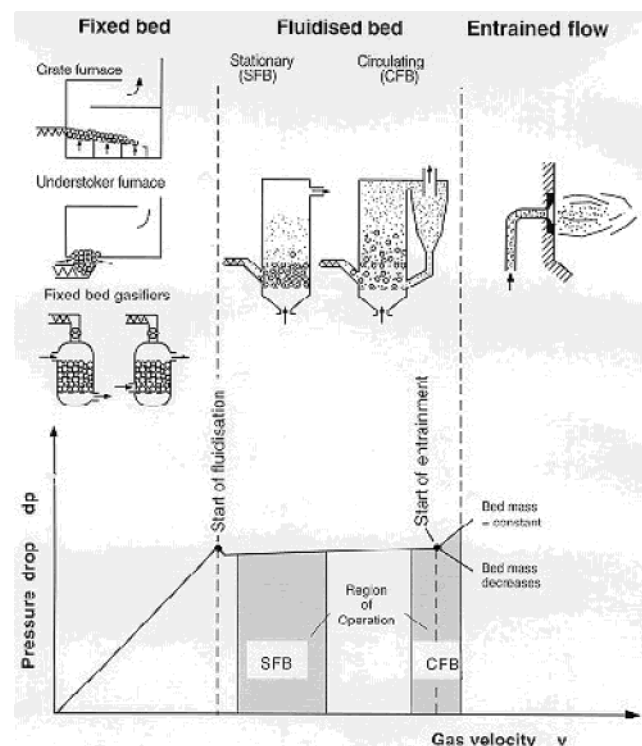


**Figure 14.** Furnace types and flow conditions: fixed bed, fluidized bed, and entrained flow reactor.[10]

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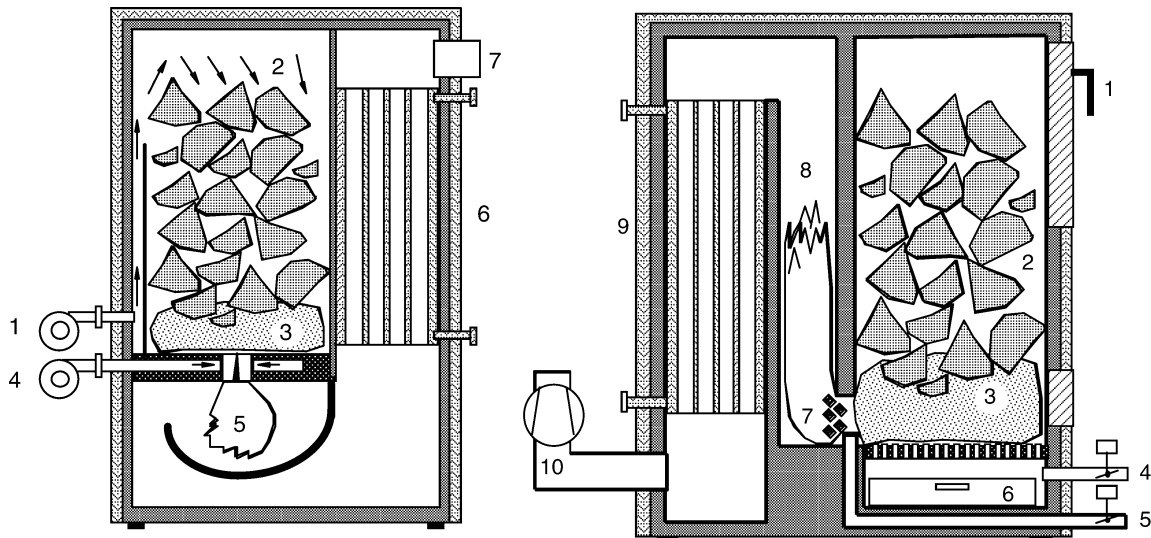
**Figure 15.** Downdraft boilers with inverse combustion of log wood and with enforced air flow and air supply with primary and secondary air. Left: 1 Primary air, 2 fuel hopper, 3 glow bed, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 chimney. Right: 1 Fuel inlet, 2 fuel hopper, 3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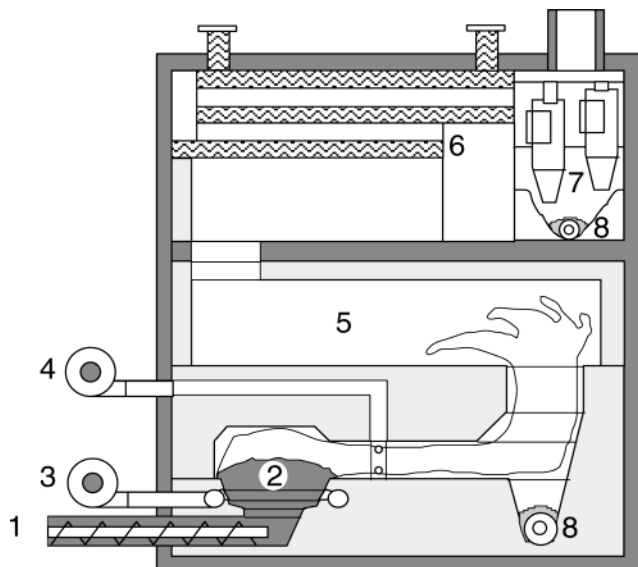


**Figure 16.** Understoker furnace with primary and secondary air, mixing zone, and post combustion chamber. 1 Screw feeder, 2 understoker zone with glow bed, 3 primary air, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal.



**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 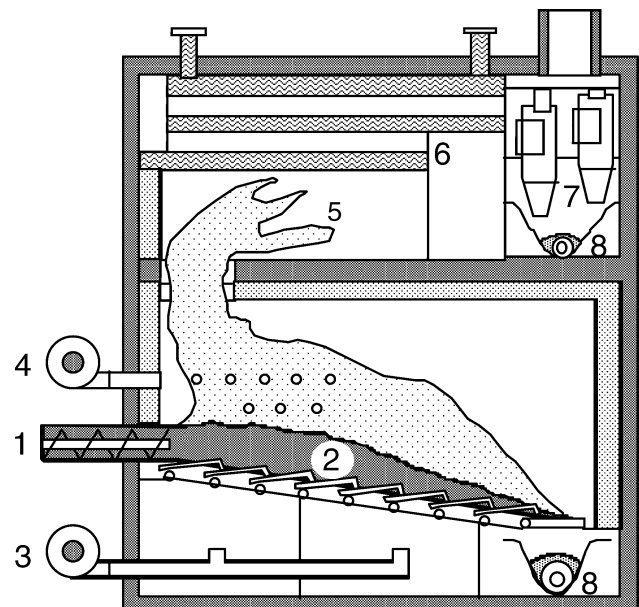(Figure 15). An operation of log wood furnaces at very low load should be avoided as it can lead to high emissions of unburnt pollutants. Hence, it is recommended to couple log wood boilers to a heat storage tank.

Since wood pellets are well suited for automatic heating at small heat outputs as needed for todays 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
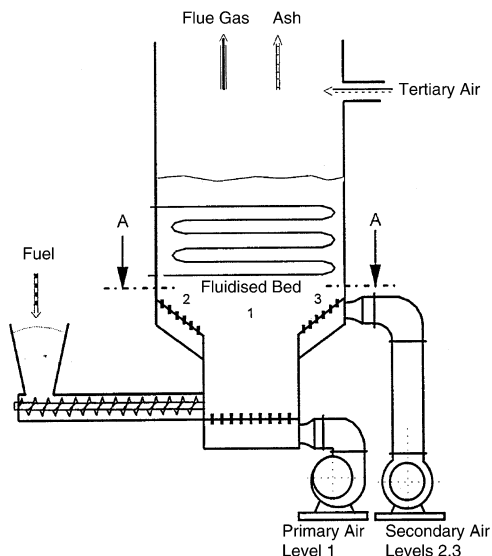
**Figure 18.** Stationary fluidized bed combustor with staged combustion (Lurgi).

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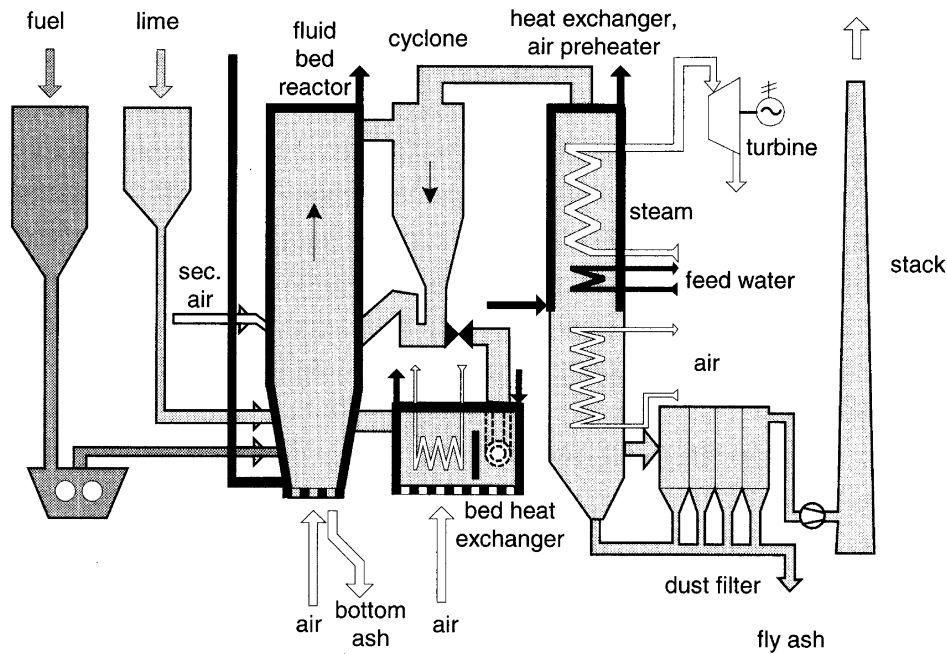
**Figure 19.** CFB plant with steam boiler for coal and biomass (Lurgi).
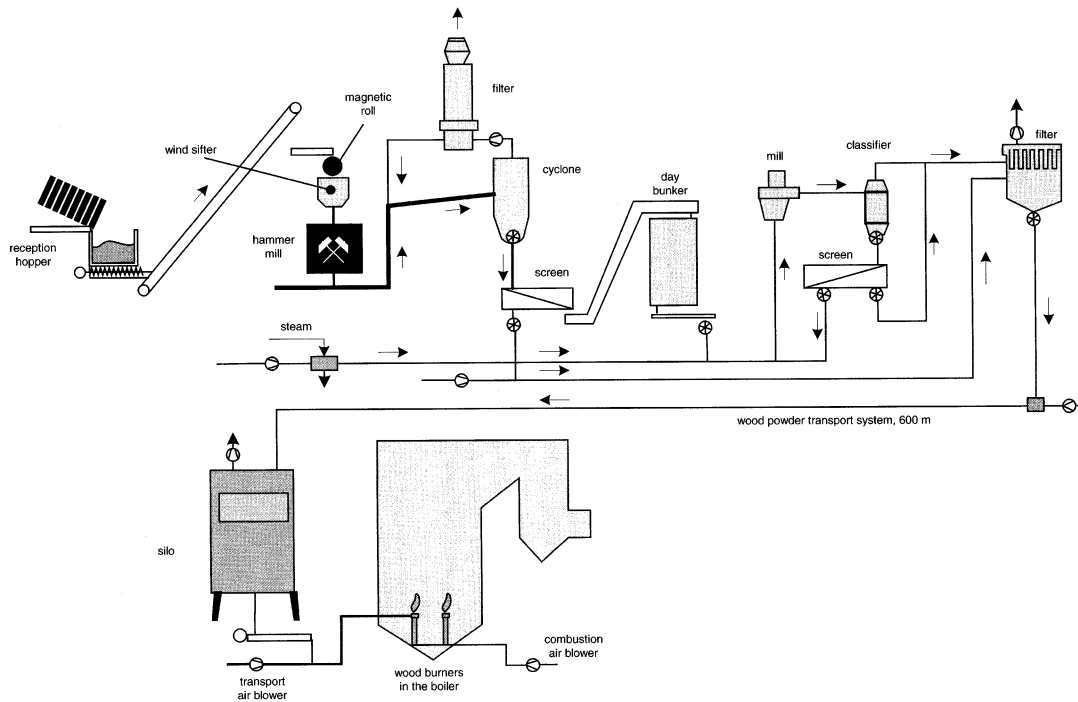


**Figure 20.** Power plant in Gelderland (NL) with direct co-firing of waste wood in pulverized coal boiler after drying, magnetic separation, and grinding of the wood (moisture < 8%, size < 1 mm). With 635 MW$_e$ in total, 60'000 t/a waste wood used in 4 × 20 MW$_{th}$ wood burners cover 3%–4% of the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

Coal burners

Biomass feeding

Biomass feeding

Wet slag remover
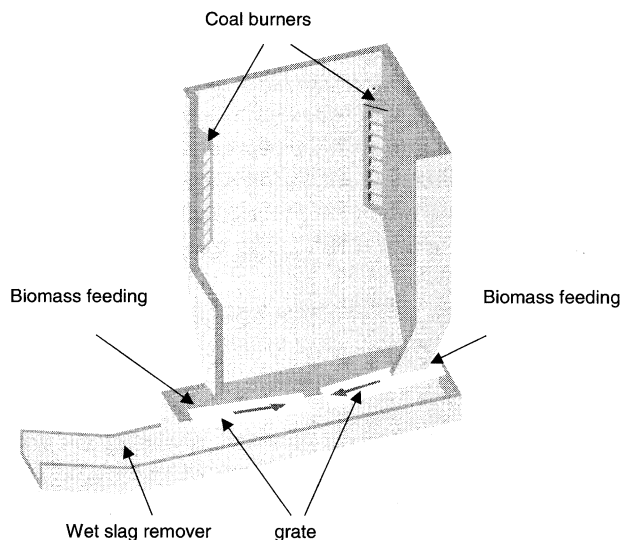
grate

**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.
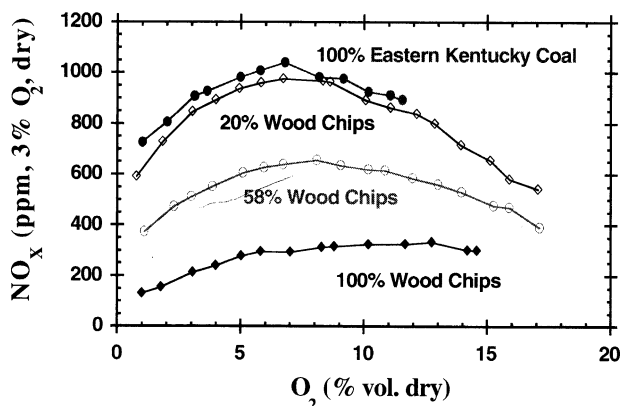
**Figure 22.** Effect of co-firing on NO$_X$ emissions.[39]
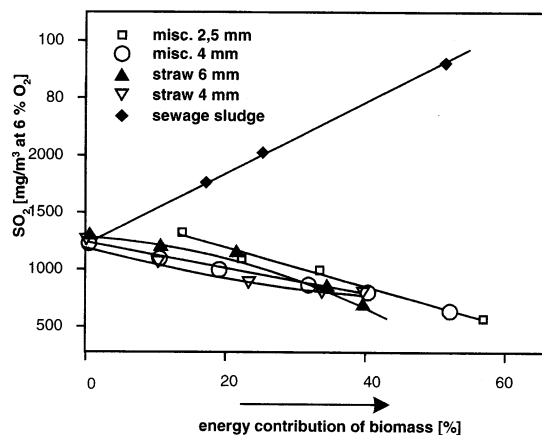
**Figure 23.** Influence of co-firing bio fuels on SO$_2$ emissions (increase: sewage sludge).[40]

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-
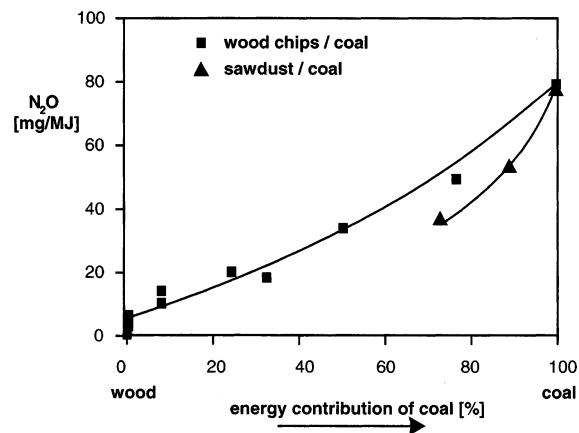
**Figure 24.** Influence of co-firing on N$_2$O emissions in a circulating fluidized bed boiler.[41]

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 CO$_2$ 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 $\lambda$, 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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# THE PRESENT STATE AND FUTURE DEVELOPMENT OF INDUSTRIAL BIOMASS COMBUSTION FOR HEAT AND POWER GENERATION

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## ABSTRACT

The energetic utilisation of solid biomass is expected to play a major role in future concepts for the reduction of greenhouse gas emissions. Within the field of energetic biomass utilisation combustion is the most advanced and market-proven application. A broad spectrum of biomass combustion technologies for heat and electricity production and for different types of biomass fuels (woody and herbaceous biomass fuels, biodegradable wastes and residues) covering a wide range of plant capacities (from a few kW to several hundred MW) is currently available. Concerning plant design chemical and physical properties of biomass fuels are of great importance. In this paper, these properties are discussed with a special focus on relevant guiding parameters and on ash related problems, like aerosol formation, slagging, deposit formation and corrosion. Furthermore, the present state-of-science concerning the design of biomass combustion system by means of CFD simulations, gaseous emissions under special consideration of $NO_x$ and new control concepts for biomass combustion plants are presented. Future developments mainly focus on the utilisation of new biomass fuels, the further development of combustion technology towards "zero emissions" systems, on efficiency improvements and increased availability (e.g. reduction of deposit formation and fouling).

## INTRODUCTION

In recent years the thermal utilisation of solid biomass for heat and electricity production has gained great importance. Within the European Union in particular, biomass is seen as the most relevant renewable energy source besides hydropower and is thus expected to substantially contribute to the $CO_2$ emission reduction targets defined in the Kyoto protocol. There is a broad international consensus that the utilisation of renewable energy sources should be further enforced in order to reduce greenhouse gas emissions. The increase of fossil fuel prices due to increasing energy demand and limited resources is a major driving force towards renewable energy.

In the EU, several political measures have been initiated with the aim of supporting the utilisation of renewable energies including the Res-e Directive (2001), the EU Biomass action plan (2005), Energy & Climate Change Package (March 2007), and the Renewable Energy Directive (June 2009). Within the scope of the Energy & climate change package the following targets have been defined:

- 20% renewables by 2020
- 20% reduction of greenhouse gas emissions by 2020
- 20% increase of energy efficiency
- 10% increase in biofuels by 2020

According to the renewable energy directive the target of 20% renewables by 2020 is now binding. Furthermore, targets for the EU member states will be defined which will be binding as well.
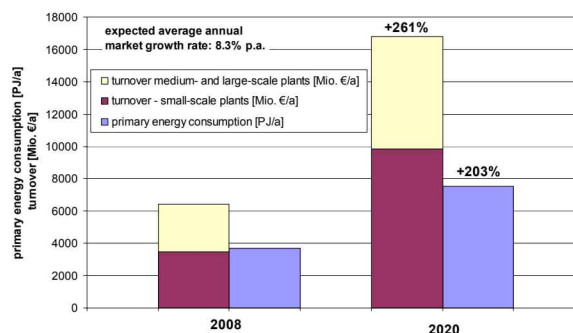


**Figure 1:** Estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 and outlook 2020
Explanations: small-, medium-, and large-scale plants considered; small-scale plants: nominal boiler capacity < 100 $kW_{th}$; calculations based on present market and achievement of EU 2020 targets [1,2,3,4,5]

Figure 1 shows the estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 as well as the outlook for 2020. The calculations are based on the present market [1,2,3,4] and the assumption that the EU 2020 targets will be achieved [5]. The results show that an average market growth rate of approx. 8.3% p.a. is expected, the market volume should grow up to 260% and the primary energy consumption from biomass should be more than doubled until 2020.

## BIOMASS COMBUSTION TECHNOLOGIES

As already mentioned the energetic utilisation of solid

biomass is expected to play a major role in future concepts for the reduction of greenhouse gas emissions from heat and electricity production. In general, three different technologies for thermal biomass conversion can be applied, namely pyrolysis, gasification and combustion. Combustion is the most advanced and market-proven application, while pyrolysis and gasification are still in the development or demonstration stages. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at present and will be the dominant conversion technology in future.

A broad spectrum of biomass combustion technologies for different types of biomass fuels (woody biomass fuels, herbaceous biomass fuels, biodegradable wastes and residues) covering a wide range of plant capacities is currently available. In principle, the following combustion technologies can be distinguished (see Figure 2) [6]:

- fixed-bed combustion,
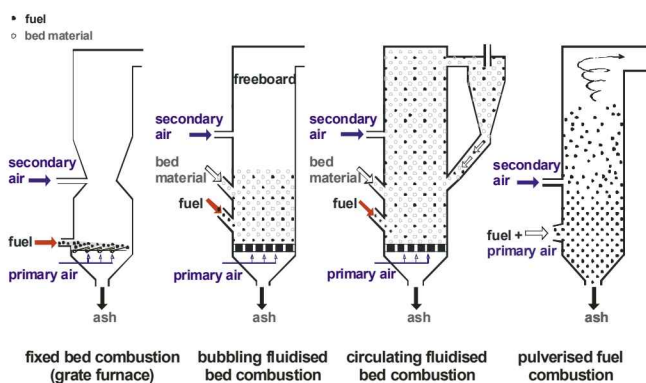- fluidised bed combustion,
- pulverised fuel combustion.



**Figure 2:** Overview of different biomass combustion technologies

**Table 1:** Overview of advantages, disadvantages and fields of application of different biomass combustion technologies

| Advantages | Disadvantages |
|---|---|
| **Fixed bed combustion** - capacity range: 100 kW – 50 MW | |
| large flexibility concerning moisture content (10 – 60 wt% w.b.) and particle size (5 - >100 mm) mixing of different wood fuels possible low investment costs for plants < 20 MW$_{th}$ low operating costs less sensitive to slagging than fluidised bed furnaces | mixing of wood fuels and herbaceous fuels limited high excess oxygen (5 - 8 Vol%) decreases efficiency combustion conditions not as homogeneous as in fluidised bed furnaces |
| **Fluidized bed combustion** - capacity range: 20 MW – several 100 MW | |
| high flexibility concerning moisture content (10 – 55 wt% w.b.) and kind of biomass fuels used no moving parts in the hot combustion chamber high specific heat transfer capacity due to high turbulence low excess oxygen (1 - 4 vol%) raises efficiency and decreases flue gas flow | high investment costs, interesting only for plants > 20 MW$_{th}$ high operating costs low flexibility with regard to particle size (< 80 mm for BFB, 40 mm for CFB) high dust load in the flue gas partial-load operation requires special technology high sensitivity concerning ash slagging |
| **Pulverised fuel combustion** - capacity range: 500 kW – several 100 MW (co-firing) | |
| Medium excess oxygen (4 - 6 Vol%) increases efficiency very good load control and fast alternation of load possible | water content usually < 20 wt% w.b. particle size of biofuel is limited (< 10-20 mm) high wear out of the insulation brickwork if cyclone or vortex burners are used an extra start-up burner is necessary |

In Table 1 an overview of advantages, disadvantages, fields of application and capacity ranges of different biomass combustion technologies is given.

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The combustible gases produced are burnt after secondary air addition has taken place, usually in a combustion zone separated from the fuel bed. Fixed-bed combustion systems have a large flexibility concerning moisture content (10 – 60 wt% w.b.) and particle size (5 mm - >10 cm). Furthermore, the mixing of wood fuels is possible but limited for herbaceous fuels. The nominal boiler capacities range between 10 kW to 50 MW (see also Table 1).

Within a fluidised bed furnace, biomass fuel is burnt in suspension of gas and solid-bed material into which primary combustion air enters from below. Depending on the fluidisation velocity, bubbling fluidised bed and circulating fluidised bed combustion can be distinguished. In BFB furnaces, the bed material is located in the bottom part of the furnace with a fluidisation velocity between 1.0 and 2.5 m/s. By increasing the fluidising velocity to 5 to 10 m/s and using smaller biomass fuel and sand particles a CFB system is achieved. The sand particles are carried with the flue gas, separated in a hot cyclone or a U-beam separator, and fed back into the combustion chamber. Fluidised bed furnaces offer a large flexibility concerning moisture content (10 – 55 wt% w.b.) and fuel mixing but a low flexibility concerning particle size (< 80 mm for BFB and <40 mm for CFB systems). Due to the homogeneous combustion conditions given in fluidised bed systems, low excess air ratios are possible which raise the efficiency und thus compensate the higher investment costs with increasing capacity. The boiler capacity range covers 20 MW to several hundred MW (see Table 1).

Pulverised fuel combustion is suitable for fuels with small particle size. A mixture of fuel and primary combustion air is injected into the combustion chamber. Combustion takes place while the fuel is in suspension, and gas burnout is achieved after secondary air addition. Examples are dust injection burners, muffle furnaces and cyclone burners. The moisture content of the fuel is usually below 20 wt% w.b. and the particle size is limited up to 20 mm (see Table 1). Stand-alone applications as well as a combination with grate and fluidised bed combustion are possible (fuel staging). Moreover, this technology is the most common application for biomass co-firing. The boiler capacity of pulverised fuel combustion systems ranges from 500 kW to several hundred MW (for co-firing systems).

Concerning plant size, the different applications of biomass combustion can be divided into the following main fields:

- Small-scale biomass combustion systems: (capacity range: <100 kW$_{th}$)
- Medium-scale combustion systems (capacity: range: 100 kW$_{th}$ to 20 MW$_{th}$)
- Large-scale combustion systems (capacity: range: >20 MW$_{th}$)
- Co-firing of biomass in coal fired power stations (capacity range: some 100 MW$_{th}$)

**Small-scale biomass combustion units** are mainly applied for residential heating systems. Here, different types of pellet burners, wood stoves and fire-place inserts as well as log wood, wood chips and pellets boilers are commonly used. These systems are only suitable for high quality wood fuels.

The **medium capacity range** covers biomass district and process heating and biomass combined heat and power (CHP) plants. Underfeed stokers, grate-fired furnaces and pulverised fuel burners are the main technologies applied in this capacity range. In Figure 3 examples for underfeed stokers and grate-fired furnaces are shown. Heat transfer is most commonly based on hot water boilers, but also steam boilers and thermal

oil boilers. These systems usually burn woody biomass fuels such as wood chips, sawdust, bark, forest residues and waste wood but also straw and other agricultural residues (e.g. sunflower husks). In addition to heat production for process and district heat supply, combined heat and power (CHP) systems are of increasing importance. A number of CHP technologies such as Stirling engines, the ORC process, steam engines and steam turbines can be combined with such plants.
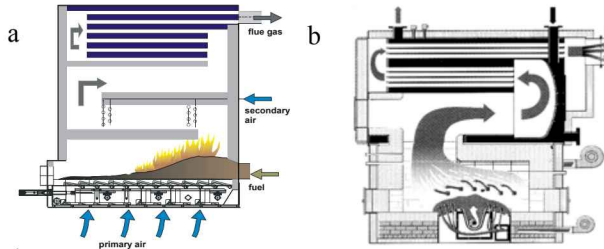


**Figure 3:** Medium-scale biomass combustion systems
Explanations: a) grate-fired furnace (source: MAWERA Holzfeuerungsanlagen GmbH); b) underfeed stoker (source: MAWERA Holzfeuerungsanlagen GmbH)

The **large-scale range** (>20 MW$_{th}$) mainly comprises CHP plants and power plants with thermal capacities up to some 100 MW based on grate-fired and fluidised bed combustion systems (see Figure 4). These are usually fired with woody biomass fuels (wood chips, sawdust, bark, forest residues and waste wood) and straw but also with residues and wastes from the agricultural industry such as fruit stones, kernels, husks and shells. Usually steam boilers combined with steam turbines are applied.



**Figure 4:** Large-scale biomass combustion systems
Explanations: a) grate-fired furnace (source: Josef Bertsch GmbH & Co); b) fluidised bed combustion (source: AE&E Austria GmbH & Co KG)
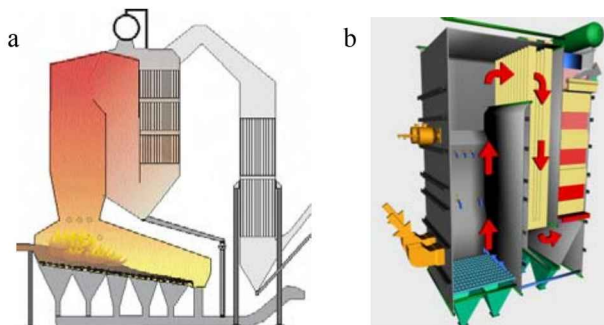
**Co-firing of biomass** fuels in large-scale coal fired power stations also represents an interesting option for biomass utilisation. Due to the large plant sizes co-firing offers great potential for $CO_2$ reduction in the short term if applied in existing power plants. The biomass co-firing options can be categorised as follows [6]:
- Biomass co-firing in existing pulverised coal combustion (PCC) systems
  - Co-firing of biomass on a separate grate directly under the coal boiler
  - Co-firing of finely milled biomass mingled with coal
  - Co-firing of finely milled biomass by separate injection
- Biomass co-firing in fluidised bed combustion (CFB and BFB) systems
- Biomass co-firing by using separate combustion units and junction of steam

- Biomass gasification and utilisation of the product gas as fuel in a coal combustion system

Dust injection burners or fluidised bed systems are mainly used. Figure 5 shows an example of a co-firing plant utilising milled straw in dust injection burners. The biomass input in co-firing units is usually restricted to about 10-20% (by mass) of the whole fuel input if existing coal-fired power stations are used.
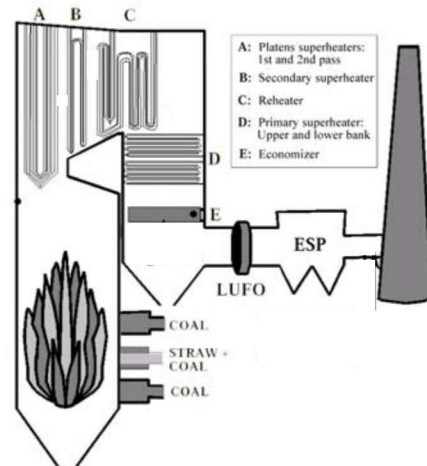


**Figure 5:** Co-firing of straw in a pulverised fuel boiler
Explanations: source: [7]

## RELEVANT CHARACTERISTICS OF BIOMASS FUELS

The chemical composition of biomass fuels can vary concerning both, the concentrations of the main elements (C, H, O, N) as well as the ash content respectively the concentrations of ash forming elements. The ash content can be seen as a guiding parameter indicating increased ash related problems with raising ash content. However, more detailed information about the single ash forming elements is needed in order to evaluate a biomass fuel with respect to different ash related problems that can occur. Thereby also interactions between these elements have to be considered. In the following some specific characteristic parameters of biomass fuels, which can be taken as a basis for the evaluation of a fuel are summarised. It may also in many cases be helpful to calculate the fuel ash composition from the biomass fuel composition. The fuel ash represents the composition of the total ash formed during combustion. Its composition is calculated by dividing the concentrations of the single ash forming elements by the ash content of the fuel.

Table 2 shows important physical properties of solid biomass fuels and their effects on the combustion process and the plant design. The moisture content of the fuel provides information concerning the general applicability of a certain fuel in a combustion process and its storability.

The ash content has to be considered concerning the de-ashing system, ash storage, ash utilisation, the grate design as well as the fact that high ash contents lead to higher entrainment of ash particles from the fuel bed with the flue gas and consequently to increased deposit formation, erosion, and dust emissions. Therefore, it is an important parameter to be considered during plant design.

The ash melting behaviour of ash mixtures is characterised by the contents and by the melting temperatures of the single ash forming elements respectively their compounds. Si, Ca and Mg increase the ash melting temperature, while K, Na, and P as well as Cl decrease the

ash melting temperature. The ash melting behaviour affects the combustion technology and the process control system and is an important factor concerning deposit formation and operational safety.

The bulk density of the fuel has also to be considered concerning fuel transport, storage, and feeding systems.

The amount of fines is relevant concerning the appropriate selection of the combustion technology and the process control. Regarding small-scale systems the amount of fines is also of big relevance concerning the fuel feeding system (special quality parameter for pellets). In medium and large-scale plants the amount of fines is an important factor regarding particle entrainment (can cause strain formation and incomplete burnout).

**Table 2:** Combustion relevant characteristics of solid biomass fuels – physical properties

| Properties | Effects |
| --- | --- |
| Moisture content | Storability, dry matter losses, NCV, self-ignition, plant design |
| NCV, GCV | Fuel utilisation, plant design |
| Volatiles | Thermal decomposition behaviour |
| Ash content | Dust emissions, ash manipulation, ash utilisation / disposal, combustion technology |
| Ash melting behaviour | Operational safety, combustion technology, process control system, hard deposit formation |
| Fungi | Health risks |
| Bulk density | Fuel logistics (storage, transport, handling) |
| Particle density | Thermal conductance, thermal decomposition |
| Physical dimension, form, size distribution | Hoisting and conveying, combustion technology, bridging, operational safety, drying, formation of dust |
| Amount of fines | Fuel feeding, particle entrainment |
| Abrasion resistance (wood pressings) | Quality changes, segregation, fine parts |

In Table 3 combustion relevant chemical properties of solid biomass fuels are listed. For a complete characterisation of a biomass fuel contents of C, H, O and N as well as the gross calorific value (GCV) should be determined since they provide basic information concerning the general applicability of a certain fuel in a combustion process and regarding the energy content of a fuel. The N content is of special relevance concerning $NO_x$ emissions.

**Table 3:** Combustion relevant characteristics of solid biomass fuels – chemical properties

| Properties | Effects |
| --- | --- |
| Carbon (C) | GCV |
| Hydrogen (H) | GCV, NCV |
| Oxygen (O) | GCV |
| Chlorine (Cl) | HCl-, PCDD/F emissions, corrosion |
| Nitrogen (N) | $NO_x$-, $N_2O$ emissions |
| Sulphur (S) | $SO_x$ emissions, corrosion |
| Fluor (F) | HF emissions, corrosion |
| Potassium (K) | Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilisation (plant nutrient) |
| Sodium (Na) | Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols |
| Magnesium (Mg) | Increase of ash melting temperature, ash utilisation (plant nutrient) |
| Calcium (Ca) | Increase of ash melting temperature, ash utilisation (plant nutrient) |
| Phosphor (P) | Ash utilisation (plant nutrient), ash melting, aerosol formation |
| Heavy metals | Emissions, ash utilisation, formation of aerosols |

Moreover, ash forming elements have to be divided into non-volatile elements such as Si, Ca, Mg, Al and Fe, semi-volatile elements such as P and Mn and rather volatile elements such as K and Na. During combustion semi-volatile and especially volatile elements are partly released from the fuel to the flue gas and react with other elements such as S, Cl or $CO_2$ in the flue gas. Major ash forming elements originate either from the biomass (plant) itself or from impurities such as soil, stones and residues from the pre-processing of the

fuels. Elements such as P, K and Na for example are part of the cell matrix of plants and elements such as Ca and Si are embedded in the plant fibres. In wood fuels usually Ca is the dominating major ash forming element while in herbaceous biomass fuels significantly higher Si-contents prevail.

Subsequently, the resulting sulphate, chloride and also carbonate compounds may form fine particles by nucleation (formation of aerosols) or condense on already formed aerosols and coarse fly ash particles as well as on heat exchanger surfaces (ash deposit formation). In most fuels mainly K and Na are involved in these processes. In P rich fuels also a part of the organically bound P is released to the flue gas and is involved in aerosol and deposit formation mainly via the formation of $KPO_3$, $P_2O_5$ and $P_4O_{10}$ [8].

Minor ash forming elements (Zn, Pb, Cd, Cu, Cr, Co, Ni, Mo, As, Sb, Hg, Tl) are mainly of interest concerning problems with too high gaseous and particle bound heavy metal emissions as well as regarding the ash utilisation. Moreover, the presence of heavy metal chlorides in ash deposits can significantly reduce the melting temperatures of the deposits thus leading to increased deposit formation and corrosion rates.
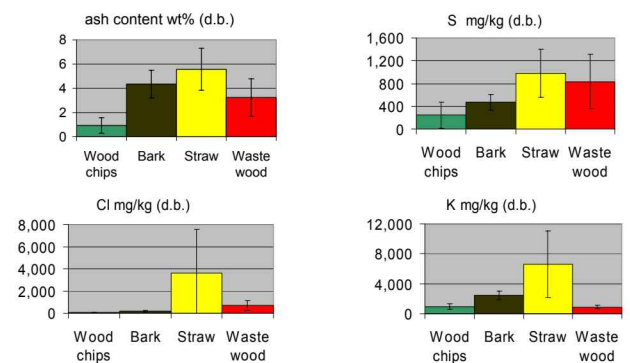


**Figure 6:** Chemical compositions of different solid biomass fuels - ash, S, Cl, K

S and Cl are relevant elements concerning gaseous emissions ($SO_x$, HCl), fine particle (aerosol) formation as well as ash deposit formation on boiler tube surfaces. Ash deposits are mainly formed by alkali metal salts such as $K_2SO_4$ and KCl. High Cl-contents of the fuel therefore also increase corrosion related problems especially due to ash deposits with high Cl-contents. Moreover, Cl reduces the ash melting temperature of deposits. Due to these deposit formation and corrosion related issues an impact of the S- and Cl-contents of the fuel on the superheater surface temperatures (steam temperatures) in steam boilers is given. Furthermore, it has to be taken into account, that increasing S and Cl concentrations in the flue gas result in a change of the dew point of the flue gas, which has to be considered concerning possible condensation in the heat exchangers and the flue gas cleaning systems.

Figure 6 exemplary shows how the chemical composition and the ash content of different solid biomass fuels can vary. The ash contents for bark and waste wood are high and even higher for straw while the ash content of pure wood fuels is comparably low. The sulphur content is high in straw and waste wood. The lowest sulphur contents are found in wood chips. The chlorine and potassium content of herbaceous fuels is considerably higher than of woody biomass fuels, which directly affects aerosol formation and ash melting. The big deviations between different biomass fuels concerning their contents of ash forming elements clearly underlines the

relevance of considering the fuel specific properties during plant design.

Figure 7 shows relevant guiding parameters which can be derived from the chemical compositions of different solid biomass fuels. An important guiding parameter is the molar ratio $(K+Na) / (2S+Cl)$. During combustion S and Cl preferably form alkaline (K and Na) sulphates and chlorides (S also forms Ca and Mg sulphate). Cl and S, which are not bound by these elements, form gaseous emissions, namely HCl and $SO_x$. A molar ratio of $(K+Na)/(2S+Cl) > 1$ indicates a surplus of alkaline metals. Therefore, for high molar ratios of $(K+Na)/(2S+Cl)$ lower HCl and $SO_x$ emissions have to be expected, since most of the S and Cl is expected to be bound in the ash.
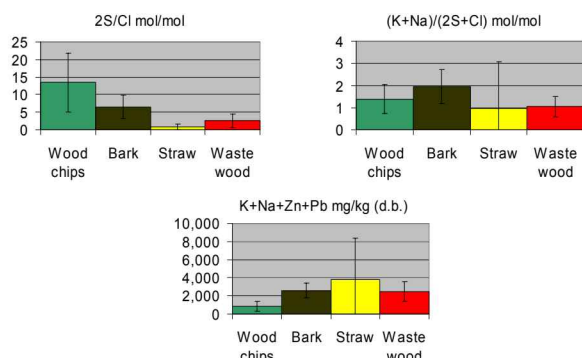


**Figure 7:** Chemical compositions of different solid biomass fuels – relevant guiding parameters

A molar ratio of $2S/Cl > 1$ indicates an increased formation of alkaline sulphates, whereas a molar ratio of $2S/Cl < 1$ indicates the preferred formation of alkaline chlorides. As corrosion related problems on heat exchanger surfaces are depending on the Cl content of the ash deposits, a low molar ratio of $2S/Cl$ increases the risk of corrosion.

The elements K, Na, Zn and Pb are the most relevant aerosol forming elements in biomass fuels. With increasing concentration of these elements in a biomass fuel the probability of the release of ash forming elements during combustion rise and therefore aerosol formation as well as deposit formation increase as well. However, the formation of ash vapours during combustion is not proportional to the concentration of these elements in the fuel since chemical reactions with other elements (e.g. Si) as well as the gaseous atmosphere and the combustion temperature significantly influence the release behaviour.

## ASH FORMATION AND ASH RELATED PROBLEMS

As already mentioned, ash related problems in biomass combustion processes are always strongly associated with the fuel chemistry, in detail with the concentration and speciation of inorganic compounds in the fuel. Therefore, if an ash related problem has to be evaluated always comprehensive knowledge about the fuel is needed. Solid biomass fuels, which are presently utilised in combustion processes can be categorised as follows:

- Chemically untreated wood fuels (wood chips, sawdust, wood pellets, bark etc.)
- Waste wood
- Wood from short rotation forestry
- Straw

- Biogenic agricultural and industrial residues (e.g. kernels, shells, olive residues, residues from liquid biofuel production etc.)

## Ash and aerosol formation and their impact on combustion technology

During the combustion of solid biomass fuels, the behaviour of ash forming elements follows a general scheme, which is depicted in Figure 8. The following gives a brief description of the basic principles of ash formation during biomass combustion.
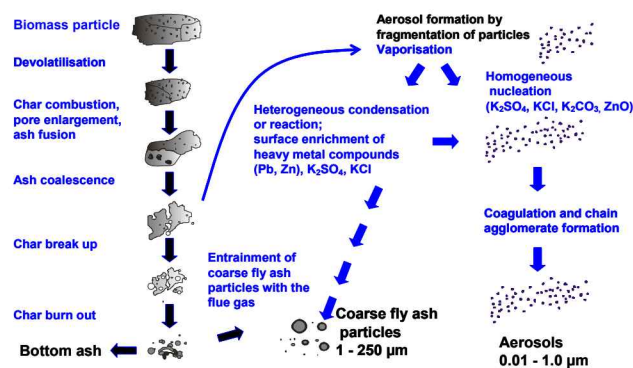


**Figure 8:** Ash formation during biomass combustion

Upon entering the combustion unit, the fuel is first dried, followed by devolatilisation of the volatile organic matter. Subsequently, the remaining fixed carbon is oxidised during heterogeneous gas-solid reactions, which is called charcoal combustion. During these steps the ash forming elements behave in two different ways depending on their volatility. Non-volatile compounds such as Si, Ca, Mg, Fe and Al are engaged in ash fusion as well as coagulation processes. Once the organic matter has been released or oxidised, these elements remain as coarse ash structures. Easily volatile species such as K, Na, S, Cl, Zn and Pb generally behave differently. A considerable proportion of these elements is released to the gas phase due to the high temperatures occurring during combustion. There they undergo homogeneous gas phase reactions and later, due to supersaturation in the gas phase, these ash forming vapours start to nucleate (formation of submicron aerosol particles) or condense on respectively react with the surfaces of existing particles or directly condense on heat exchanger surfaces. The submicron particles, so-called aerosols, form one important fraction of the fly ashes. The second fly ash fraction consists of small coarse ash particles entrained from the fuel bed with the flue gas. Depending on particle size, they are either precipitated from the flue gas in the furnace or boiler mainly by inertial impaction or gravitational settling, or are entrained with the flue gas, forming coarse fly ash emissions. Consequently, the most relevant difference between coarse fly ashes and aerosols is that coarse fly ashes always remain in the solid phase while aerosols undergo phase changes during their formation process (release to the gas phase and gas-to-particle conversion).

It is also important to mention that a share of the volatile ash forming elements is not released to the gas phase but undergoes secondary reactions with the non-volatile species (e.g. Ca, Si), thus being embedded in the coarse ash. The mechanisms of these secondary reactions and the parameters influencing the release of volatile species from the fuel are of great relevance for aerosol and deposit formation and are therefore a major issue in research projects [9].

Especially with respect to the utilisation of herbaceous biomass fuels as well as residues from agricultural, food and biofuel industry the special role of P has to be mentioned. In conventional wood fuels P is mainly inorganically bound and therefore, almost all P is embedded in the coarse ash fraction. In agricultural biomass as well as biogenic residues from industrial processes a share of the P may also be organically bound. Parts of this organically bound P can also be released to the gas phase and therefore participate in aerosol and deposit formation processes [8,10].

The *bottom ash* represents the ash fraction remaining in the furnace after combustion of the fuel and is then removed by the de-ashing system. *Coarse fly ash* particles which are entrained from the fuel bed with the flue gas are partly precipitated on their way through the furnace and the boiler by inertial impaction, gravitational and centrifugal forces and therefore form the so-called *furnace* or *boiler ash*. Particles which are small enough to follow the flue gas on its way through the furnace and the boiler finally form the *coarse fly ash emission* at boiler outlet. The major share of these particles is precipitated in cyclones or filters and forms the *cyclone fly ash* and parts of the *filter fly ash*.

**Table 4:** Typical shares of the different ash fractions on the total ashes produced

|  | bark combustion | wood chips combustion | sawdust combustion | straw combustion |
|---|---|---|---|---|
| bottom ash | 65 - 85 | 60 - 90 | 20 - 30 | 80 - 90 |
| cyclone fly ash | 10 - 25 | 10 - 30 | 50 - 70 | 2 - 5 |
| filter fly ash | 2 - 10 | 2 - 10 | 10 - 25 | 5 - 15 |

In Table 4 typical data concerning the fractionation of ashes into bottom ashes, cyclone fly ashes and filter fly ashes in modern fixed-bed biomass combustion plants are presented [11]. On the contrary, in fluidised bed and pulverised fuel combustion the amount of bottom ash is low while the fly ash fractions clearly dominate. It is recommended to use a two-stage fly ash precipitation (cyclone plus filter) in order to increase the overall dust precipitation efficiency.
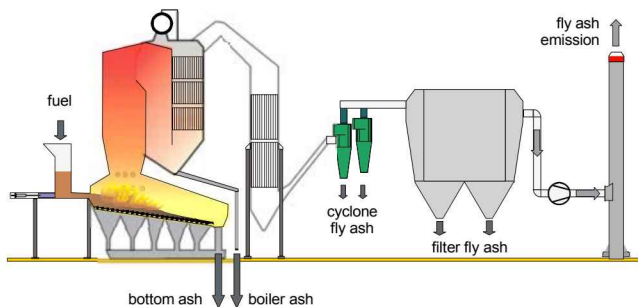


**Figure 9:** Ash fractions in a biomass combustion unit
Explanations: typical plant scheme of a large-scale grate-fired steam boiler

As already mentioned, *aerosols* are formed by gas-to-particle conversion processes in the furnace and in the boiler. Some of the aerosol particles coagulate with coarse fly ashes due to collisions. Moreover, a smaller part of aerosols is also precipitated in the boiler and therefore contributes to the boiler ash while the major part of this fraction is emitted with the flue gas at boiler outlet. Since aerosols are characterised by particle sizes significantly <1 µm (ae.d.), precipitation in a cyclone, which usually has a cut diameter of about 5 to 10 µm, is almost impossible. Aerosols can thus only be precipitated in more advanced filter systems such as baghouse filters and electrostatic precipitators (ESP). Consequently, aerosols do not contribute to the cyclone fly ashes but to the filter fly ashes as well as to the particulate emissions at the filter outlet.

In Figure 9 the scheme of a typical large-scale grate-fired steam boiler is presented to show where the different ash fractions occur.

A considerable number of tests has been carried out to investigate possible parameters which could influence the mass of aerosols formed during combustion. Therefore, the combustion air ratio, the furnaces temperature, the moisture content of the fuel as well as the influence of flue gas recirculation were considered. These parameters were varied during test runs in a range, which is typical for the operation of fixed-bed combustion units. From the evaluation of these tests no significant influences of the parameters mentioned on the mass of aerosols formed during combustion could be identified. This leads to the conclusion that as long as almost complete burnout prevails, the fuel composition, or in more detail, the release of aerosol forming species from the fuel during combustion, is the most relevant parameter which determines the mass of aerosols formed.
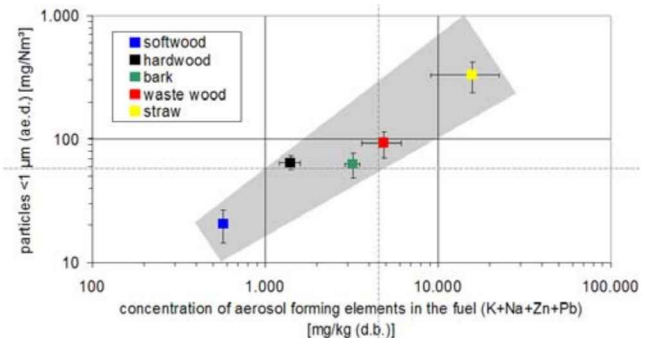


**Figure 10:** Influence of the fuel used on the mass of aerosols formed

This statement is confirmed by the data presented in Figure 10, where the concentrations of the most relevant aerosol forming elements K, Na, Zn, and Pb in the fuel are plotted against the average aerosol emissions measured at boiler outlet of medium and large-scale fixed-bed combustion plants [12].

Results from test runs including element balances over fixed-bed combustion plants performed with beech, bark and waste wood have shown that usually 10 - 90 wt% of K, more than 80% of S, more than 95% of Cl as well as more than 80% of Zn and Pb are released to the gas phase.

With decreasing burnout quality of the flue gas, aerosol emissions also contain differing amounts of carbonaceous species (organic carbon and soot). Organic carbon and soot emissions are of relevance in small-scale combustion units and older plants. In state-of-the-art medium and large-sale combustion systems almost complete burnout is achieved and aerosol emissions almost exclusively consist of inorganic compounds.

The basic mechanisms of aerosol formation in combustion processes are generally well known from previous research work [13,14]. As already mentioned, aerosols are formed by nucleation of ash forming vapours. The particles subsequently grow by condensation of vapours on their surfaces as well as by coagulation processes.

Figure 11 shows SEM images and results from EDX analyses of aerosols. It can be derived that aerosols consist of almost spherically shaped particles and agglomerates thereof,

which is typical for particles formed by nucleation and subsequent coagulation.

K, Na, S and Cl are the most relevant aerosol forming species in the specific case of chemically untreated wood combustion. Consequently, the formation of K and Na sulphates and K and Na chlorides followed by nucleation of these compounds are the most relevant processes leading to aerosol formation. The molar ration of S/Cl strongly influences sulphate and chloride formation. Aerosols from straw combustion are strongly dominated by KCl (see Figure 12). Carbonates are formed if there is not enough S and Cl available to bind all the K and Na released from the fuel.

Additionally, easily volatile heavy metals such as Zn and Pb may significantly contribute to aerosol formation, especially with increasing concentration of these elements in the fuel. Aerosols formed during the combustion of waste wood (which is very rich in heavy metals), for instance, may contain more heavy metal compounds than alkaline compounds [15,16,17]. Zn mainly forms oxides and chlorides and Pb chlorides. This behaviour is confirmed by the results of the EDX analyses presented in Figure 11.
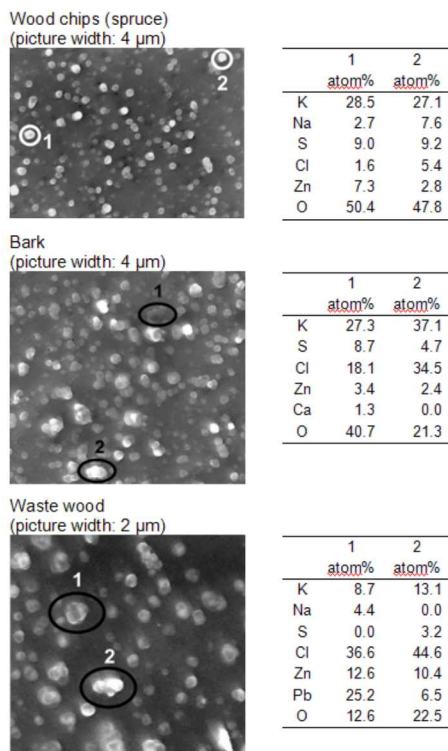


Wood chips (spruce) (picture width: 4 µm)

|  | 1 atom% | 2 atom% |
|---|---|---|
| K | 28.5 | 27.1 |
| Na | 2.7 | 7.6 |
| S | 9.0 | 9.2 |
| Cl | 1.6 | 5.4 |
| Zn | 7.3 | 2.8 |
| O | 50.4 | 47.8 |

Bark (picture width: 4 µm)

|  | 1 atom% | 2 atom% |
|---|---|---|
| K | 27.3 | 37.1 |
| S | 8.7 | 4.7 |
| Cl | 18.1 | 34.5 |
| Zn | 3.4 | 2.4 |
| Ca | 1.3 | 0.0 |
| O | 40.7 | 21.3 |

Waste wood (picture width: 2 µm)

|  | 1 atom% | 2 atom% |
|---|---|---|
| K | 8.7 | 13.1 |
| Na | 4.4 | 0.0 |
| S | 0.0 | 3.2 |
| Cl | 36.6 | 44.6 |
| Zn | 12.6 | 10.4 |
| Pb | 25.2 | 6.5 |
| O | 12.6 | 22.5 |

**Figure 11:** SEM images and results from EDX analyses of aerosols
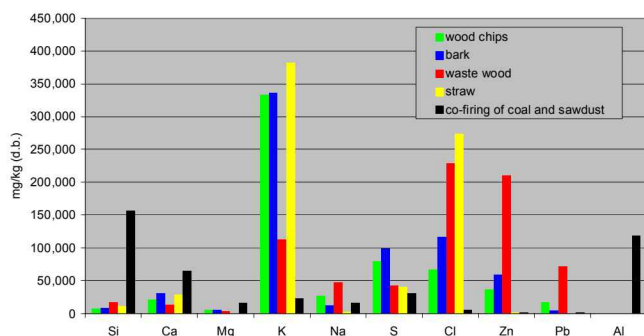


**Figure 12:** Typical compositions of aerosols from biomass combustion and co-firing of biomass (sawdust)
Explanations: Data related to dry flue gas and 13 vol.% O$_2$; results from real-scale test runs

Non-volatile elements like Ca and Si can also be found to a certain extent in aerosols due to defragmentation processes during combustion or direct release from the organic matrix (or the cell solution) during decomposition. When cofiring biomass with coal completely different chemical composition of aerosols dominated by alumosilicates and CaSO$_4$ occur (due to the different chemical composition of coal and the higher combustion temperatures in entrained coal flames, see Figure 12). The chemical composition of the fuel strongly dominates the amount and chemical composition of the aerosols formed which is relevant regarding their stickiness and corrosiveness (see next sections). Especially for new biomass fuels and fuel blends aerosol characterization and measurements are very important. To gain appropriate data regarding aerosol formation in biomass combustion systems, a unique high-temperature impactor that can operate at temperatures up to about 1,100°C is available [18,19].

### Slagging, deposit formation and corrosion and their impact on combustion technology

Ash melting, deposit formation and corrosion are the major internal plant operation related problems which are associated to ash forming elements. Ash melting can occur on the grate and on non-cooled furnace walls. Moreover, fly ash depositions formed on heat exchanger surfaces can also melt. As soon as ashes start partly to melt or fuse, the resulting ash pieces are usually called slag.

Deposit formation means the formation of ash layers on furnace and boiler surfaces (furnace walls, radiative and convective heat exchanger surfaces). Thereby it is often distinguished between slagging and fouling. Slagging is the formation of molten or partially fused deposits on furnace walls or convection surfaces exposed to radiant heat. Fouling is commonly defined as the formation of deposits on convective heat exchanger surfaces such as boiler tubes in hot water fire tube boilers and superheaters in water tube steam boilers.

Ash melting on the grate can result in problems with the combustion process since slag plates can hinder the primary air flow through the fuel bed. Moreover, larger slag pieces can lead to damages of the grate as well as to problems with blocking the de-ashing system. Slagging in the furnace can lead to increased pressure losses due to smaller flow areas in narrow parts of the furnace and slagging in the radiative sections of steam boilers can lead to reduced heat transfer. In Figure 13 typical examples for slagging on a grate and for slag formation in the radiative part of a steam boiler are presented.



**Figure 13:** Examples for slag formation
Explanations: left: slag formation in a moving grate furnace during combustion of industrial biogenic residues; right: slag formation in the radiative section of a steam boiler

Slag formation in biomass furnaces and boilers is always a result of ash melting. Not necessarily the whole ash has to melt. Usually, single phases which show low melting

temperatures start to melt and act as glue between ash particles with higher melting temperatures. Therefore, always different phases of molten and non-molten compounds can be found when analysing slag pieces or hard deposits. According to practical experiences and literature [20] the formation of slag pieces and hard deposits starts at temperatures where 15 wt% of the ash in a certain ash piece are molten ($T_{15}$). At the temperature where the share of molten phases exceeds 70 wt% ($T_{70}$), the slag/deposit starts to flow.

Thermodynamic equilibrium analyses have turned out to be a useful tool to evaluate the melting behaviour of biomass ashes. Thereby, thermodynamic calculations of multi-phase and multi-component systems which simultaneously can handle hundreds of chemical species are applied. For combustion systems both major and minor ash forming components must be taken into account. The reactions of the minor components are usually dependent on the reactions of the major components. However, minor elements, especially Pb and Zn as well as Cl are also of great relevance, since they contribute to a reduction of the ash melting temperatures of ash mixtures (see Figure 15). It has to be mentioned that the thermodynamic databases used must be of high quality. Small errors and deviations in data for main components give bigger errors on small components and give wrong results. In this respect, it has to be mentioned that especially concerning systems containing P only restricted thermodynamic data are presently available.
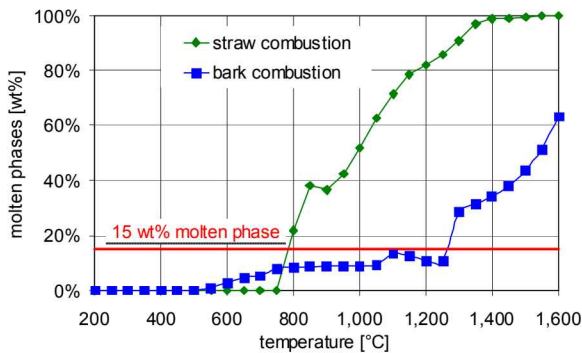


**Figure 14:** Formation of molten phases – results from thermodynamic equilibrium analyses
Explanations: results of thermodynamic equilibrium calculations concerning the bottom ash

One big advantage of thermodynamic equilibrium analyses is that they can be performed for typical grate ash as well as fly ash compositions separately. Therefore, also the significantly differing chemical composition of these fractions can be taken into account when determining their melting behaviour (e.g.: fly ashes with high amounts of alkaline metal salts show lower melting temperatures).

In Figure 14 results from thermodynamic equilibrium analyses performed for bottom ashes from bark and straw combustion are presented. In the diagram the amount of molten phase in the ash is plotted against the temperature. Since the input data for the calculations have been taken from bottom ash analyses performed during real-scale test runs, realistic ash compositions form the basis for these calculations, which is one of the big advantages of this method. From the diagram it can be derived that in the case of straw combustion a rapid increase of the molten phases at temperatures above 750°C occurs. $T_{15}$ is reached below 800°C. For ashes from bark combustion this effect happens at significantly higher temperatures of about 1,250°C. Moreover, the results of the calculations provide data about

the compositions of the molten phases as well as the changes of the compositions depending on temperature. These results can then also be compared with results from SEM/EDX analyses of molten phases of ash and slag pieces in order the get a more detailed picture of the ash melting behaviour of complex ash mixtures. Thus such calculations can be very useful to indicate relevant trends and differences between various fuels and ash fractions and form a useful tool for advanced fuel characterisation.

In Figure 15 the influence of heavy metals on the melting behaviour of Cl-containing fly ash mixtures is presented. The blue line for instance shows a typical biomass fly ash which often is almost pure $K_2SO_4$ (melting point: 1,068°C). If carbonate is formed the first melting point decreases to 940°C, and if chlorides form to 643°C. Small amounts of Na (red curve) decrease the first melting point to 609°C. The presence of Pb and Zn, even in small amounts compared to K and Na, results in molten phases at such low temperatures as 196°C.
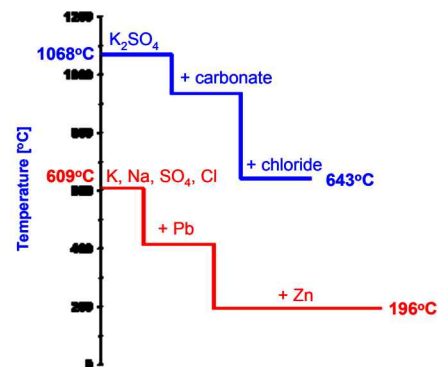


**Figure 15:** The influence of heavy metals on the melting temperatures of Cl-containing ash mixtures
Explanations: source: [9]

As it can be revealed from Figure 14 and Figure 15, ashes from different biomass fuels can show significantly different ash melting behaviours and therefore, measures to reduce problems with ash melting and slagging in combustion plants have always to be adjusted to the chemical composition of the fuel applied. Appropriate measures usually implemented in modern biomass combustion systems are grate cooling, furnace cooling by cooled walls or flue gas recirculation, the appropriate adjustment of the flue gas inlet temperatures in convective boiler sections and of the superheater steam temperatures as well as the utilisation of additives (see also next section).
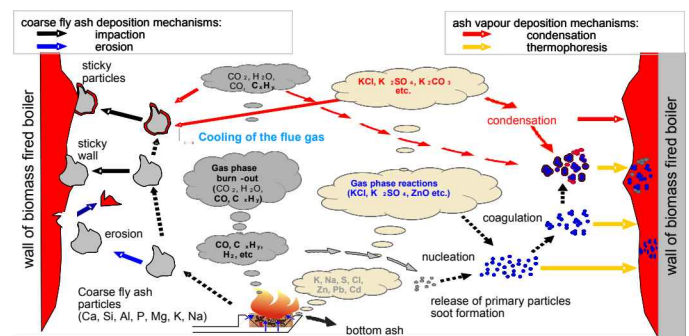


**Figure 16:** Mechanisms of deposit build-up in biomass fired boilers

Deposits are formed by coarse fly ashes as well as condensable gaseous ash forming compounds present in the flue gas. Under the typical conditions prevailing in biomass

hot water, thermal oil and steam boilers, the direct condensation of ash forming vapours on heat exchanger surfaces and inertial impaction are of major relevance concerning deposit formation. Thermophoresis also plays a certain role while other mechanisms such as turbulent eddy impaction, Brownian diffusion and diffusiophoresis are of minor relevance (see Figure 16).

With increasing deposit thickness the heat transfer through the heat exchanger tubes decreases which results in a loss of efficiency. Severe deposit formation (fouling) can block the flue gas pathways through heat exchanger sections. In Figure 17 deposits on superheater tubes of a waste wood fired steam boiler are presented.

It has to be considered that the temperature at the gas side deposit surface increases with increasing deposit thickness, which is illustrated in Figure 18. There, results gained from CFD simulations performed for a superheater tube with a surface temperature of 590°C which is exposed to a flue gas stream with 1,050°C are presented. From the simulation results it can be derived that with increasing deposit thickness the surface temperature at the flue gas side significantly increases and finally reaches more than 900°C at a deposit thickness of about 4 mm. With increasing surface temperature also the fraction of molten phases increases and therefore the deposit becomes more sticky and grows faster. Finally, higher amounts of molten phases also lead to the formation of hard deposit layers which are problematic to be removed.



**Figure 17:** Pictures of deposits formed on superheater tubes of a steam boiler during waste wood combustion
Explanations: left: typical deposit formation; right: severe deposit formation leading to the blocking of heat exchanger pathways
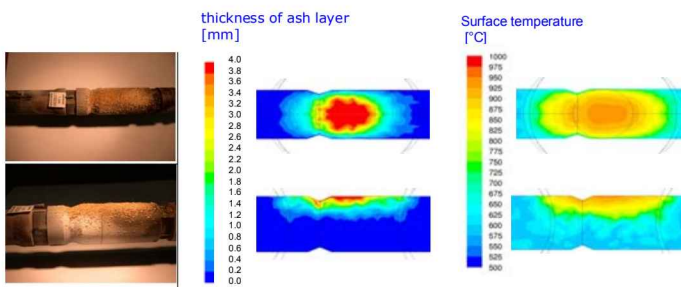


**Figure 18:** Ash deposit layer on a water-cooled deposition probe (left) compared with CFD simulations performed (middle) and influence of ash depositions on the surface temperatures (right)
Explanations: bulk flue gas temperature: 1,050 °C, clean probe surface temperature: 590 °C; figures at the top ... top view; figures at the bottom ... side view

Consequently, it is important to periodically clean heat exchanger surfaces in order to reduce deposit growth. Therefore, different automatic heat exchanger cleaning systems listed in the following are usually applied.

Fire tube boilers can be cleaned by injecting pressurised air into the tubes. Thereby, in an interval of some hours for some milliseconds an air pulse is injected which cleans the boiler tubes. The air pulse is controlled by membrane valves. To protect these valves from too high temperatures, the cleaning system is usually installed on the wall of the turning chamber between the first and the second duct (cleaning of the first duct in counter-current and of the second duct in co-current flow).

In water tube steam boilers usually soot blowers are installed to remove deposits from the superheater surfaces. If there is an increased risk for deposit formation on the tubes in the radiative boiler section, sometimes also water canons are installed. Moreover, shot cleaning by injecting small metal balls into the heat exchanger bundles is sometimes applied.

Besides these secondary measures also primary measures for the reduction of deposit formation should be considered. These measures involve the adjustment of the flue gas and tube surface temperatures to the expected properties of condensing ash forming compounds (which depend on the composition of the fuel applied) during boiler design as well as a careful control of the flue gas temperatures during operation. Moreover, additives can be used to reduce deposit formation (see next section).

Additionally, it should be mentioned that load changes can lead to changing flue gas and boiler tube temperatures. Due to thermal stresses, deposits can be partly destroyed during phases with load changes. This effect can additionally support the efficiency of automatic cleaning systems.

Corrosion is an important issue especially for biomass plants utilising fuels with high chlorine contents. For biomass combustion generally three possible corrosion mechanisms must be distinguished:

- Active oxidation
- Corrosion due to molten alkaline metal compounds and other salts
- Acid dew point corrosion

The so-called active oxidation is the most relevant corrosion mechanism in biomass boilers. The mechanism is based on the formation of Cl-containing deposit layers on the boiler tube surfaces. The first step of deposit formation is the formation of an ash layer by direct condensation of alkaline metal and heavy metal salts (chlorides and sulphates) on the boiler tube surfaces. The chemical composition of this condensed layer depends on the tube surface temperature and on the fuel composition respectively the release behaviour of alkaline metals, Cl, S and easily volatile heavy metals from the fuel to the gas phase. If the molar ratio 2S/Cl released from the fuel to the gas phase is high and flue gas temperature above 850°C occur, mainly alkaline metal sulphate vapours are formed while, if this ratio is low, the formation of alkaline metal chlorides usually dominates.

| $N_2, CO_2, O_2$ $SO_2, SO_3, MeCl$ (g) | flue gas | $SO_2$   $O_2$ |
|---|---|---|
| sulfates/chlorides silicates | ash layer | $Cl_2 + Na_2SO_4 \;\leftarrow\; SO_2 + O_2 + 2\,NaCl$ |
| $Fe_2O_3$ + ash | outer oxide layer | |
| $Fe_3O_4$ + FeS | inner oxide layer | $3\,Fe_2O_3 \;\leftarrow\; 1/2\,O_2 + 2\,Fe_3O_4$ <br> $3\,Cl_2 + Fe_3O_4 \;\leftarrow\; 2\,O_2 + 3\,FeCl_2$ |
| $FeCl_2$ | corrosion front | $4\,Cl_2 + FeS + Fe_3O_4 \;\leftarrow\; SO_2 + O_2 + 4\,FeCl_2$ <br> $Cl_2 + Fe \;\longrightarrow\; FeCl_2$ |
| low alloyed steel | tube wall | $p_{FeCl2} = 10^{-5} - 10^{-3}$ bar at 400 - 530 °C |

**Figure 19:** Schematic explanation of the active oxidation mechanism [21]

Combustion tests with chemically untreated wood fuels as

well as waste wood, performed have shown, that, when utilising chemically untreated biomass, at tube surface temperatures above 500°C the Cl concentration in the deposits starts to significantly decrease [17]. As soon as the surface temperature exceeds 550°C almost no Cl could be found in the deposits. Superheaters of modern steam boilers utilising chemically untreated biomass fuels are usually designed for steam temperatures between 480 and 540°C and thus operate in this temperature range.

In hot water boilers on the other hand, where the tube surface temperatures are rather low (around 100°C) compared with steam boilers, Cl containing deposits are found even when utilising fuels with very low Cl contents and high 2S/Cl ratios.

To start the process of active oxidation besides Cl-containing deposits also gaseous $SO_2$ is needed. $SO_2$ reacts with alkaline metal chlorides under formation of alkali metal sulphate and release of $Cl_2$. This process happens in the deposit layer and therefore, $Cl_2$ diffusing towards the inner oxide layer can form $FeCl_2$. $FeCl_2$ has, depending on the temperature, a certain volatility under reducing conditions and can therefore be vaporised. The vapour formed diffuses from the tube wall into the ash layer. There, it is oxidised again (due to the increasing partial pressure of $O_2$ towards the flue gas) and the $Cl_2$, which is released, can diffuse back to the tube wall and react there again with iron oxide. Following this process, even small amounts of Cl released in the ash layer have the potential to cause considerable corrosion damages if the residence time of the ash layer on the tube surfaces is high enough.

Three measures to reduce active oxidation can be mentioned:

- Utilisation of fuels with a high 2S/Cl ratio to enforce the formation of $K_2SO_4$ instead of KCl layers.
- Lower tube surface temperatures considerably reduce the evaporation of $FeCl_2$ and thus slow down the corrosion process.
- Frequent cleaning of the boiler tubes (implementation of automatic boiler cleaning systems) in order to keep the residence time of ash layers on the tube surfaces low and thus to limit the sulphation reactions.

Also the second corrosion mechanism depends on the presence of alkaline metal and heavy metal chlorides and sulphates on boiler tube surfaces. These chlorides and sulphates and especially mixtures of them can show comparably low melting temperatures (see also Figure 15). Molten salt phases thereby can attack the tube material. This mechanism is of minor relevance for the combustion of chemically untreated fuels. However, in the case of the combustion of waste material such as waste wood, which contains comparably high heavy metal concentrations, it can be of relevance.

During the utilisation of chemically untreated woody biomass fuels usually no problems with acid dew point induced corrosion are observed. However, when utilising waste wood or biogeneous residues, this mechanism can become important. If a fuel contains high S- concentrations and comparably low K and Ca-concentrations, a relevant amount of S will not be embedded into the ashes by the formation of $K_2SO_4$ and $CaSO_4$ but remain as $SO_2$ in the gaseous phase. A part of the $SO_2$ reacts to $SO_3$ and then with water (flue gas moisture) to $H_2SO_4$. The acid dew point temperature (ADT) of $H_2SO_4$ significantly increases with increasing $SO_3$ concentrations in the flue gas. If the temperatures of boiler or economiser tube surfaces are below this dew point temperature, $H_2SO_4$ condensation followed by corrosion takes place. Therefore, an appropriate adjustment of the surface temperatures of economisers and hot water boilers beyond the expected acid dew points is of relevance.

For future technological developments the main aim is to increase the thermal and electric efficiency by increasing the steam parameters. Thereby, especially fouling and corrosion related problems have to be considered. For straw combustion for instance, a steam temperature of 542°C leading to an electric efficiency of 31.7% has already been achieved in the CHP plant Maribo-Sakskøbing (Denmark) as well as in other plants. Figure 20 shows a scheme of this CHP plant which utilises wheat straw and has implemented appropriate technological solutions in order to reduce corrosion particularly in the high temperature stages of the superheaters. The boiler and in particular the superheaters are specially designed to handle the harsh condition from combustion of straw and straw-like biomass fuels in a highly efficient boiler with advanced steam data. The first and second pass superheater stages are operated in the so-called slagging mode. A continuous $K_2SO_4$ slag layer on tube surfaces protects the super heater material against high temperature chlorine corrosion. The slag layer is several cm thick and is only removed when the plant is shut down due to thermal stress. By this way electric efficiencies of more than 31% can be achieved in medium-scale CHP plants at plant availabilities of above 90%.
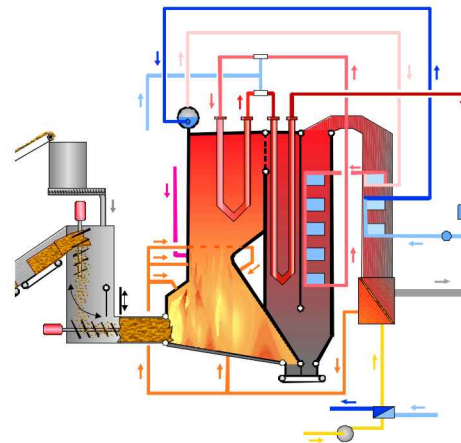


**Figure 20:** Case study for appropriate technological solutions in order to reduce ash related problems – the CHP plant Maribo-Sakskøbing (Denmark)

Explanations: source: Bioener ApS; main fuel: wheat straw; steam pressure: 92 bar; steam temperature: 542 °C; power output (gross) 10.6 MW; thermal output: 20 MW; electric efficiency (gross): 31.7 %; thermal plant efficiency: 60 %; total plant efficiency: 91.7 %

For CHP plants utilising woody biomass fuels, even higher steam parameters and consequently efficiencies should be the target for future developments. First R&D results show low corrosion potentials due to decreasing Cl-concentrations in deposits at temperatures above 540°C but further long-term tests are needed. For such tests especially newly developed corrosion probes are an useful development tool [22,23]. The correct choice of the superheater materials of course plays an important role for such advanced approaches. Moreover, the application of additives which reduce the Cl-content of deposits (e.g.: "Chlorout", see next section) can contribute to a further increase of the steam temperatures.

## Additives to reduce ash related problems

During recent years a considerable number of studies has been performed in order to investigate the effects of different additives on ash melting and corrosion in biomass boilers. The studies mainly focused on the reduction of ash melting problems as well as on reducing the formation of KCl and NaCl rich deposits. Therefore, several strategies can be distinguished.

The first strategy is to bind the K in the bottom ashes and thereby to reduce the formation of alkaline metal vapours and consequently also aerosol and deposit formation. A well known "alkaline metal catcher" for instance is Kaolin. By adding Kaolin to the fuel, K is embedded into Si-Al-phases of the bottom ashes [24, 25]. However, due to its high costs no industrial applications of Kaolin as alkaline catcher are known so far. The same effect can be achieved by blending an alkaline and Cl-rich biomass fuel with coal, peat or sewage sludge. Also in this case the Si-Al-rich phases of the bottom ashes help to significantly reduce the K release and consequently the formation of KCl. This strategy is already successfully applied in many biomass co-firing plants as well as in large-scale Finish biomass power plants, where, due to the high local availability of peat, mixtures of biomass and peat are utilised.

| Purpose | Additive | State-of-application |
|---|---|---|
| Alkaline metal catchers to reduce aerosol formation | Kaolin | R&D |
| Sulphation of chlorides to reduce corrosion | ChlorOut (ammonium sulphate) | Demonstration |
| Additives to increase ash melting temperatures | Ca-based Mg-based | R&D |
| Additives to reduce $SO_2$- HCl- and PCDD/F-emissions | Limestone Sodium bicarbonate Activated charcoal | State-of-the-art |

**Figure 21:** Additives which can be applied in biomass combustion plants in order to reduce ash related problems

The second strategy is to enforce the conversion of the problematic KCl into less problematic $K_2SO_4$. Therefore, Vattenfall AB (SWE) has developed an additive called Chlorout® [26]. Chlorout® consists of Ammoniumsulphate which is injected directly into the hot furnace. There it decomposes to ammonia and $SO_3$ and with the $SO_3$ KCl is sulphated in the gas phase before it starts to condense. As a consequence of this sulphation reaction, the concentration of KCl in deposits can be significantly reduced. Moreover, the rate of deposit build-up is reduced since the $K_2SO_4$ formed by the sulphation of the KCl partly forms submicron aerosol particles in the furnace by nucleation and condensation, and therefore the direct condensation of alkaline vapours on the superheater surfaces is reduced. The ammonium sulphate injection is thereby controlled by an in-situ alkali chloride monitor (IACM), which has also been developed by Vattenfall AB. Test and demonstration of additivation with Chlorout® are ongoing in several biomass and waste fired CHP plants [27].

Moreover, Ca and Mg-based additives can by applied in order to increase the ash melting temperature of low-melting ash mixtures. This strategy is of special relevance for the application of agricultural biomass fuels and industrial biogenic residues since these fuels are usually rather poor in Ca and Mg but show low melting temperatures due to high K and P contents.

In order to reduce $SO_2$- and HCl-emissions limestone or sodium bicarbonate in combination with a baghouse filter are used. Activated charcoal can be added to also reduce PCDD/F emissions. This technology should be applied for fuels with high Cl and S contents as well as in combination with Chlorout® (to reduce increased HCl emissions).

## GASEOUS EMISSIONS UNDER SPECIAL CONSIDERATION OF $NO_X$

$CO_2$ is a major combustion product from all biomass fuels, originating from the carbon content in the fuel. However, $CO_2$ emissions from biomass combustion are regarded as being $CO_2$-neutral with respect to the greenhouse gas effect and this is considered to be the main environmental benefit of biomass combustion.

Carbon monoxide emissions are caused by incomplete combustion which are mainly a result of inadequate mixing of combustion air and fuel in the combustion chamber, an overall lack of available oxygen, too low combustion temperatures and too short residence times. Incomplete combustion is however usually not an issue for state-of-the-art combustion plants.

$NO_X$ emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, both from gas-phase combustion and char combustion. Additional $NO_X$ may be formed from nitrogen in the air given certain conditions. However, these reaction mechanisms are not considered to be of significant importance in most biomass combustion applications due to the limited combustion temperatures. The main nitric oxide emitted is NO, which is converted to $NO_2$ in the atmosphere.
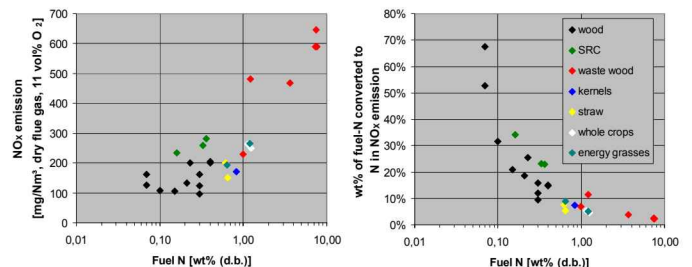


**Figure 22:** $NO_X$ emissions (left) and fuel N converted to $NO_X$ (right) in dependence of the N content in the fuel for different biomass fuels

In Figure 22 measured data of $NO_X$ emissions (left) and the percentage of fuel N converted to $NO_X$ (right) versus the N content in the fuel are shown for different biomass fuels. The figure clearly indicates that $NO_X$ emissions increase with increasing N content in the fuel while the rate of fuel N converted to $NO_X$ decreases.

In Figure 23 conversion rates of N species related to the total fixed nitrogen (TFN) formed which have been derived from tests in a lab-scale reactor for different woody biomass fuels and olive residues are depicted [28]. The dominance of $NH_3$ is obvious. NO represents the most important oxidised N species for woody biomass fuels. For chopped herbaceous biomass fuels different N species profiles occurred. NO represents the largest fraction among the N species released. Experimental data about conversion rates of N species form an important basis for subsequent CFD simulations of $NO_X$ formation in biomass combustion plants (see also next section).

In order to reduce $NO_X$ emissions from biomass combustion, several primary and secondary measures exist.

For the utilisation of chemically untreated biomass fuels, secondary measures are normally not necessary [11,29]. If secondary measures are necessary, they should always be combined with primary measures in order to efficiently utilise the $NO_X$ reduction potential available and to reduce operating costs (additive utilisation).
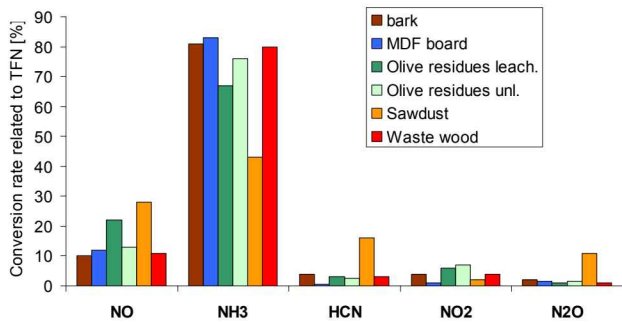


**Figure 23:** Conversion rates of N species related to TFN of woody biomass fuels and olive residues
Explanations: TFN…total fixed nitrogen (sum of NO, $NH_3$, HCN, $NO_2$ and $N_2O$); leach…leached; unl…unleached

Air staging is a widely applied primary measure for $NO_X$ reduction where primary and secondary combustion air are injected in separated zones. In order to efficiently reduce $NO_X$ emissions, the air ratio in the primary combustion chamber should be between 0.6 and 0.8 and the residence time of the flue gas in the primary combustion chamber approx. 0.2 to 0.5 s at temperatures above 800 °C. Furthermore, good mixing in the primary combustion zone is of great relevance which can be achieved by appropriate flue gas recirculation. The potential for $NO_X$-reduction by air staging is 30 to 60%.

A second possibility to reduce $NO_X$ emissions by primary measures is fuel staging, where the primary and the secondary fuel is supplied in separate zones. Due to the complexity of the system, fuel staging is usually limited to large-scale applications. Approx. 70% primary fuel and 30% secondary fuel is used. The excess air ratio in the reduction zone following the secondary fuel supply should be between 0.6 to 0.8. Natural gas, biomass producer gas, shavings or sawdust are usually utilised as secondary fuels. The potential of $NO_X$ reduction by fuel staging amounts to 50 to 70%.

If primary measures fail to achieve the targeted $NO_X$ reduction, they can be combined with secondary measures. These are selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) [11,30].
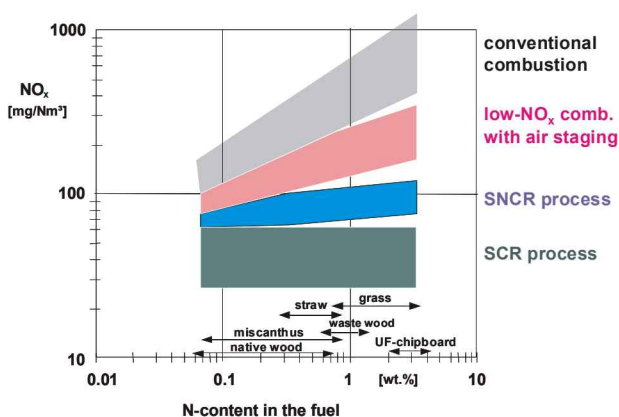


**Figure 24:** Relation between fuel N content, $NO_X$ emission reduction measures and $NO_X$ emissions
Explanations: $NO_X$ calculated as $NO_2$ and related to dry flue gas and 11 vol.% $O_2$

In the SNCR process, ammonia or urea is injected into the flue gas at high temperatures, usually between 840 and 950°C and a residence time after injection of 0.3 to 0.5 s [30]. Because of the high temperature, this process does not need a catalyst to initiate the reactions. Ammonia is injected at a rate of between 1:1 to 2:1 mole ammonia to mole of $NO_X$ reduced. About 60-90% NO reduction can be reached with SNCR. The SNCR process requires an accurate temperature control to achieve optimum $NO_X$ reduction conditions. If the temperature is too high, ammonia is oxidised to NO and if the temperature is too low, ammonia does not react at all and is emitted together with the $NO_X$. Good mixing is very important to achieve optimum $NO_X$ reduction conditions. Most SNCR processes have an ammonia slip of some ppm in the flue gas leaving the stack.

The SCR process reduces NO to $N_2$ by reactions with usually ammonia or urea in the presence of a platinum, titanium, or vanadium oxide catalyst. SCR operates optimally in a temperature range of 220-270°C using ammonia, and 400-450°C using urea [30]. The stoichiometric coefficient is usually around 1.0. Approximately an 80% $NO_X$ reduction has been reported for SCR in fossil fuel combustion [31], where it is the most widely used secondary $NO_X$ control technology. However, Nussbaumer [30] reported up to 95% $NO_X$ reduction at 250°C without significant slippage of ammonia in a wood-firing system. For the SCR process in combination with biomass combustion, the long-term behaviour of the catalyst can be a problem, as deactivation is likely. In this respect, an efficient dust precipitation stage upstream the SCR unit is an important requirement. SCR systems are considerably more expensive than SNCR systems but can be economically interesting for large-scale applications due to the better conversion efficiency achievable.

Figure 24 shows the relation between fuel N content, $NO_X$ emission reduction measures and $NO_X$ emissions.

## CFD AS AN EFFICIENT TOOL TO DESIGN AND OPTIMISE BIOMASS COMBUSTION SYSTEMS

Modern simulation tools are needed to efficiently analyse the underlying processes during biomass combustion. For biomass combustion plants, CFD modelling proved to be a highly efficient tool for process analyses as a basis to optimise plant design and control concerning the following issues:

- Improved air staging, temperature control and utilisation of the primary combustion zone in order to reduce $NO_x$ emissions by primary measures.
- Efficient mixing of unburned flue gas with re-circulated flue gas and secondary air, better utilisation of the furnace and boiler volume in order to achieve an efficient flue gas burnout, a reduction of the furnace and boiler volume as well as a reduction of excess air.
- Reduction of local velocity and temperature peaks in order to reduce material stress, erosion and ash deposit formation.
- Sensitivity analyses concerning the influence of different fuels and operating conditions in order to supply a basis for an optimised plant control.

Summarising, CFD aided technology and plant development has the advantage that it leads to more compact combustion plants, considerably reduced pollutant emissions at enhanced plant efficiencies and increased availabilities due

to an adequate design of the furnace and boiler geometry. Moreover, CFD leads to a more reliable plant design as well as to reduced development times and costs. For the design of biomass combustion plants, CFD simulations are presently are applied for:

- All size classes: small-, medium-, and large-scale systems
- Different biomass combustion technologies: wood log fired boilers and stoves, fixed bed and grate furnaces, spreader stoker furnaces, pulverised fuel furnaces and fluidised bed furnaces
- Different boiler types: fire tube boilers, water tube boilers and thermal-oil boilers
- Various biomass fuels: untreated woody biomass fuels like wood pellets, sawdust, wood chips, bark and wood logs, treated woody biomass fuels like waste wood and fibre boards as well as agricultural and herbaceous fuels like straw, olive residues and miscanthus.
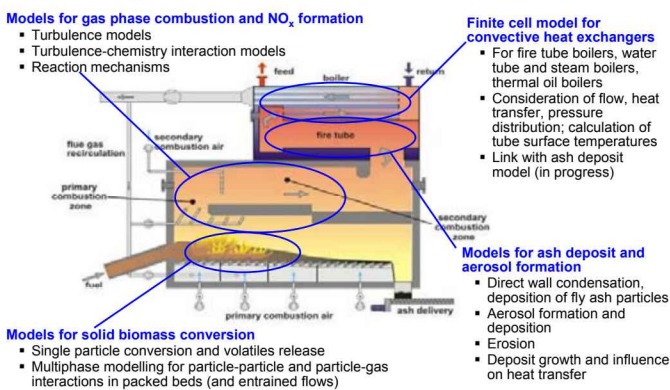


**Figure 25:** CFD simulation of biomass combustion plants – model overview

A review about state-of-the-art models for biomass combustion systems, new model approaches and of work performed in different research groups in Europe is provided by [32,33]. In the following, an overview about models for biomass combustion plants and their application is given. In Figure 25 the scheme of a biomass grate furnace with a fire tube boiler is shown in order to illustrate relevant processes in the plant and CFD modelling approaches.

**Modelling of solid biomass conversion**

In common engineering applications, the combustion of solid biomass on the grate is presently simulated by empirical 0D models or by 1D models. The empirical models serve to provide release profiles as boundary conditions for the following CFD simulation of gas phase but give no information about combustion on the grate and relevant influencing parameters. Also 1D models are not able to sufficiently describe the processes on the grate since mixing of the fuel particles with the grate bars in different grate systems and the combustion of thermally thick particles can not be captured. Therefore, research work in different groups is focussing on the development of layer models for thermally thick fuel particles and their link with 2D or 3D packed bed combustion models. In contradiction to packed beds, the combustion of solid biomass in pulverised fuel furnaces can be modelled sufficiently accurate with Lagrangian multiphase models, since the solid biomass combustion processes are of lower complexity [34]. When particles become thermally

thick, layer models can be applied and when the local volume fraction of particles is increasing (approximately > 10%), new multi-phase models accounting also for particle/particle interactions provide an improvement of prediction accuracy. Combustion of solid biomass in fluidised bed furnaces is highly complex and not fully understood so far. Therefore, no reliable CFD models for engineering purposes exist and simulations in fluidised bed furnaces are focussing only on the free board and down-stream sections.

**Modelling of gas phase combustion and NO$_x$ formation**

For turbulent reactive flue gas flow in the combustion chamber several turbulence and gas phase combustion models exist. For gas phase combustion in biomass grate furnaces usually Eddy Dissipation Models with global 2-step, 3-step or 4-step reaction mechanisms are applied. CFD simulations are successfully applied to design and optimise furnace geometries including the nozzles for the injection of secondary air and re-circulated flue gas concerning improved furnace and boiler utilisation, turbulent mixing of flue gas with air, flue gas burnout and the reduction of excess air as well as concerning the reduction of velocity and temperature peaks in order to reduce material erosion and ash deposit formation.
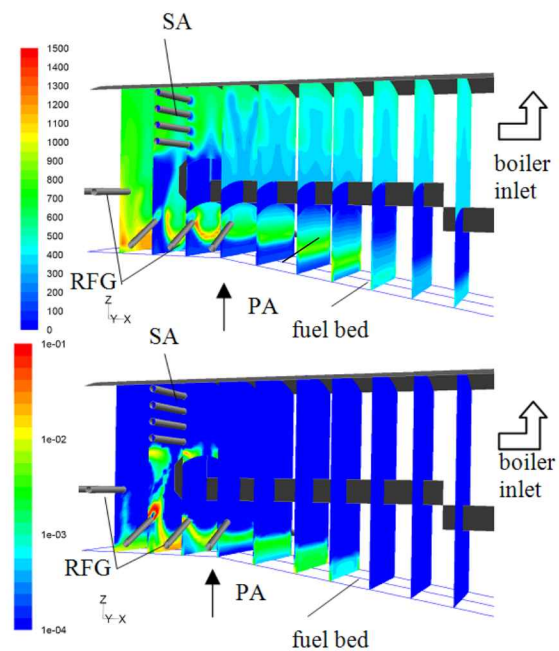


**Figure 26:** Profiles of NO (top) [ppmv] and net production rate of N$_2$ (bottom) [kg/m$^3$s] (indicator for NO$_x$ reduction) in a biomass grate furnace
Explanations: nominal boiler load 440 kW$_{th}$; fuel fibre board, fuel nitrogen content 6.5 [wt.% d.b.]; model: Eddy Dissipation Concept / reduced reaction mechanism with 25 species and 104 reactions [37]; PA…primary air; SA…secondary air; RFG…re-circulated flue gas

However, with this simple combustion models it is not possible to simulate gas phase NO$_x$ formation due to the high complexity of turbulence-chemistry interaction. However, there is a need for efficient design tools for low-NO$_x$ furnaces, since the issue of NO$_x$ emission reduction is gaining increasing importance due to continuously stricter emission limits and due to the combustion of new agricultural and herbaceous biomass fuels with high nitrogen contents. Increasing computer capacities allow for the implementation of more sophisticated gas phase combustion models in combination with detailed and reduced reaction mechanisms.

BIOS in co-operation with Graz University of Technology and the Austrian bioenergy competence centre Bioenergy 2020+ have implemented an advanced gas phase combustion model in combination with detailed and reduced reaction kinetics for the purpose of a more fundamental description of the combustion process and especially for the prediction of $NO_x$ formation [35]. In order to define the release of the $NO_x$ precursors during solid biomass combustion on the grate an empirical release model was extended by release profiles for the most relevant N-species NO, $NH_3$ and HCN [28,36]. Validation simulations showed that with this model all relevant trends concerning $NO_x$ emissions in dependence of fuel nitrogen content, air staging, flue gas residence times and temperatures could be reproduced.

Figure 26 shows an example of NO profiles (top) and profiles of the net production rate of $N_2$ (bottom) in different vertical cross-sections of a biomass combustion plant. It is shown, that in the primary combustion zone the local net production rates of $N_2$ are positive, because under air lean conditions and at appropriate reaction temperatures, NO is reduced by the reaction with the $NO_x$ precursors $NH_3$ and HCN. With this new model a simulation of the $NO_x$ formation process in biomass grate furnaces is possible with reasonable accuracy at acceptable computation times for engineering applications. This model allows studying relevant influencing parameters on $NO_x$ formation like fuel nitrogen content, air staging, flue gas temperatures and flue gas residence times in different plant zones as a basis for appropriate measures for an efficient $NO_x$ reduction by primary and secondary measures.

## Modelling of convective boiler sections and ash deposit and aerosol formation

In the last few years CFD modelling activities have been extended to the whole boiler including the convective section. Since in most cases the geometry of the tube bundles can not be resolved with a computational grid which can be handled by common computers, various CFD based heat exchanger models have been developed. At BIOS in co-operation with Graz University of Technology a porous zone based finite cell heat exchanger model describing flow and heat transfer as well as surface temperatures of the tubes for the most relevant boiler types (water tube boiler, thermo-oil boiler and fire tube boiler) has been developed. This model makes it possible to consider the furnace and boiler sections (including the secondary heat carrier, e.g. water) within simulations [32]. The results show that the CFD model gives considerably more detailed information than conventional 1D calculation methods especially in regions after deflections with high temperature gradients of the flue gas flow and that it can be applied as an efficient boiler design tool.

Ash related problems like aerosol and ash deposit formation as well as corrosion are of major relevance in biomass combustion plants especially when firing fuels with high ash content (e.g. waste wood, herbaceous and agricultural fuels). At Graz University of Technology in co-operation with BIOS and Bioenergy 2020+ a flexible and comprehensive ash deposit formation model is currently being developed in order to allow for a prediction of ash deposit formation in biomass combustion plants in dependence of fuel type and plant operation conditions [32,33,38]. With this model a world leading position could be achieved. At present, the model allows for the simulation of the time dependent ash deposit formation and the influence on

heat transfer in the furnace and the radiative section of the boiler under consideration of wall condensation of ash forming elements as well as the deposition of coarse fly ash particles. Figure 27 shows an example of the deposition mass fluxes of coarse fly ash particles (top) and ash vapours (bottom) in a pilot-scale grate furnace including the radiative section of a fire tube boiler. Generally the highest deposition mass fluxes occur in the furnace section due to high local impaction rates of fly ash particles as well as high surface and particle temperatures. The highest deposition rates by wall condensation occur in the water-cooled boiler section. They are comparably low at the beginning of plant operation but increase the stickiness of the boiler walls due to growing deposit thickness.

Coarse fly ash particles



Direct wall condensation
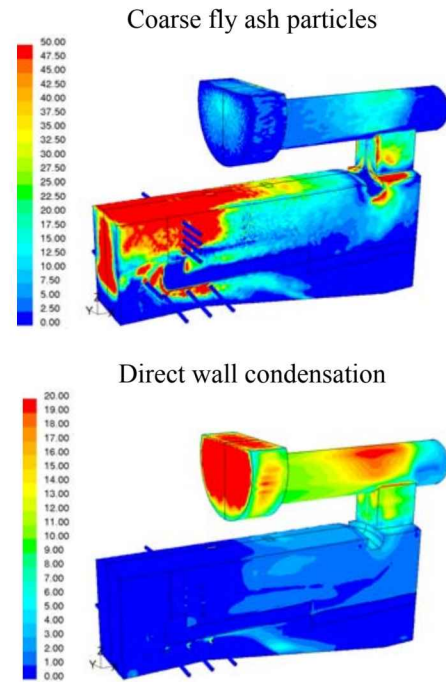


**Figure 27:** Deposition mass fluxes [mg/m$^2$s] to the walls of a biomass grate furnace and the flame tube of a fire tube boiler
Explanations: fuel: waste wood, nominal boiler load 440 kW$_{th}$; operation duration: 1 hour



Flue gas temperature [°C]        Aerosol concentration [mg/Nm$^3$] in the flue gas
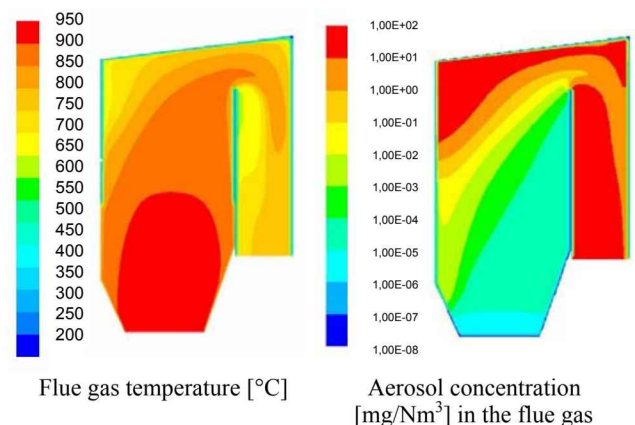
**Figure 28:** Aerosol concentrations (mg/Nm$^3$) in the flue gas and flue gas temperatures in the first and second radiative duct of a biomass fired steam boiler
Explanations: nominal boiler load: 40MW$_{th}$

Moreover, the influence of aerosols formation, deposition and erosion is considered. In Figure 28 results concerning modelled aerosol concentrations and flue gas temperatures in the first and second radiative boiler section of a biomass fired

steam boiler are depicted. Aerosols are formed when flue gas temperatures decrease below the saturation point of the ash forming vapours.

An enhancement and further tests of the model are ongoing. Especially important is the link of the deposit formation model with the convective heat exchanger model in order to allow for a simulation of ash deposit formation in the whole plant including the convective boiler section [39]. Concluding, a powerful tool for an efficient design of biomass furnaces and boilers is under development. With such a model the influence of the fuel fired and operation conditions on the deposit formation processes can be investigated already in the design phase of a plant allowing for appropriate measures in order to reduce ash deposit formation. Even at the present state of development, the model can be applied for the support of plant designs by providing qualitative information.

## INTELLIGENT PROCESS CONTROL SYSTEMS

State-of-the-art control systems for biomass combustion plants usually work with 4 control circuits which control the load, the furnace temperatures, the pressure in the furnace, and the secondary air ratio. Each of these control circuits is responsible to set respective output parameters based on measured data and defined setpoints. They are to a large extent independent from each other. Dependencies and sometimes highly nonlinear interrelations between the different output parameters are not or only to a small extent taken into consideration. Consequently, conventional control systems work sufficiently efficient at steady state but not efficient in intermediate conditions (e.g. load changes or changes of the fuel quality). The potential of a modern biomass furnace which has an optimised furnace geometry and nozzle design is not fully utilised concerning low emission operation and high energetic efficiencies by conventional control systems.

Within recent years control systems implementing neuronal networks, fuzzy logic, and model based control gained more and more importance but are at the moment not or only to a small extent applied for biomass combustion plants.

With neuronal networks it is possible to develop a mathematical model in a fast and convenient way directly from experimental data. The major drawback of neuronal networks is the fact that the models are not based on the underlying physical relations and are only valid within the scope of the experimental data provided. Consequently, validity is not guaranteed for every state.

Fuzzy control is based on a description of a system based on fuzzy logic, which allows to deduce a mathematical model from a linguistical description of the system behaviour. Hence fuzzy control has the advantage that the operator's expertise can be used to develop a control strategy very quickly. The disadvantage of fuzzy concepts is the fact that states which are not considered by rules can lead to malfunctions and that there is no deterministic procedure for the design of a fuzzy controller. Consequently, liberties in the realisation of fuzzy controllers can degrade the results significantly. Up to now, fuzzy concepts are partly implemented in control systems for biomass combustion plants but there is no control system available which is completely based on fuzzy logic.

Model based concepts require a preferably simple mathematical model that describes the main interrelations of the physical system to be controlled [40,41,42]. Based on this mathematical model it is possible to develop a controller which takes the nonlinearity and the coupling of the different process variables explicitly into account, wherefore a well established theory is available. Consequently, the so designed model based controller is able to react more efficiently on unsteady operating conditions than the currently in combustion plants used control systems. The only disadvantage of the described model based control strategies is that they are very labour intensive in the case that no applicable mathematical model is available. If such models are available, then model based systems are evaluated to be the most suitable and efficient solution.

It is expected that new control concepts especially model based control strategies and fuzzy control will gain more importance for biomass combustion systems in the near future.

## SUMMARY, CONCLUSIONS AND OUTLOOK

Together with hydropower, biomass is the most important renewable energy source in the European Union. In the field of energetic utilisation of solid biomass, combustion is the most advanced and market-proven application. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at presence. Biomass combustion technologies, like fixed-bed, fluidised bed and pulverised fuel combustion, are currently available for different types of biomass fuels covering a wide range of plant capacities. Concerning plant size, the different applications of biomass combustion can be divided into small-scale biomass combustion systems (capacity range: $<100$ kW$_{th}$), medium-scale combustion systems (capacity: range: 100 kW$_{th}$ to 20 MW$_{th}$), large-scale combustion systems (capacity: range: $>20$ MW$_{th}$), and co-firing of biomass in coal fired power stations (capacity range: usually some 100 MW$_{th}$).

Regarding plant design, chemical and physical properties of biomass fuels are of great importance. The fuel properties affect fuel transport, storage and feeding systems as well as the grate, furnace and boiler technology. Especially ash related problems like aerosol formation, slagging, deposit formation and corrosion in biomass combustion processes are always strongly associated with the fuel chemistry, in detail, with the concentration and speciation of inorganic compounds in the fuel. Important guiding parameter are, in this respect, the molar ratios $(K+Na)/(2S+Cl)$, $2S/Cl$ and the sum of K, Na, Zn and Pb in the fuel. High molar ratios of $(K+Na)/(2S+Cl)$ indicate lower HCl and SO$_x$ emissions. The molar ratio of $2S/Cl$ indicates the preferred formation of alkaline sulphates or alkaline chlorides. K, Na, Zn and Pb are the most relevant aerosol forming elements. With increasing concentrations of these elements the probability of aerosol formation as well as deposit formation increase as well. Consequently, if an ash related problem has to be evaluated always comprehensive knowledge about the fuel is needed.

NO$_x$ emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, whereas NO$_x$ formed from nitrogen in the air is usually of minor relevance in most biomass combustion applications due to moderate combustion temperatures. NO$_x$ emissions from biomass combustion can be efficiently reduced by primary measures or combinations of primary and secondary measures. In addition, NO$_x$ modelling is of great relevance for an improved future plant design.

For biomass combustion plants, CFD modelling proved to be a highly efficient tool for process analyses as a basis to

optimise plant design and control concerning improved air staging, temperature control and utilisation of the primary combustion zone in order to reduce $NO_x$ emissions by primary measures, efficient mixing of unburned flue gas and reduction of local velocity and temperature peaks in order to reduce material stress, erosion and ash deposit formation. Consequently, CFD aided technology and plant development has the advantage that it leads to netter utilisation of combustion plants, considerably reduced pollutant emissions at enhanced plant efficiencies and increased availabilities due to an adequate design of the furnace and boiler geometry.

On-going research mainly focuses on the utilisation of new biomass fuels (annual crops, short rotation plants, waste materials from the agricultural and the food industry, etc) as well as the further development of combustion technology towards next generation ("zero emissions") systems. The main focus regarding emission reduction is on aerosol emissions as well as on $NO_X$ reduction. Concerning CHP systems new developments focus on advanced and highly efficient systems. In this respect increased steam parameters and higher availability are important targets. Regarding process control strategies for combustion plants, new concepts like model based systems will gain more and more importance. Future modelling activities aim at CFD models to simulate the whole biomass combustion plant ("virtual biomass combustion plant) interlinking solid fuel combustion, gas phase reactions, the boiler as well as emissions and ash related problems.

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# COMBUSTION FUNDAMENTALS
(Extra Reading Material)

The purpose of any combustion control system is to safely and efficiently maintain the desired boiler output without the need for constant operator attention. Therefore, the combustion process inside the furnace must be controlled while the boiler output changes in response to load demands. The basic principle of combustion control is to meet the boiler load requirements regulating the quantities of fuel and air while achieving optimum combustion and maintaining safe conditions for operators and equipment.

Menu

## Combustion Principles

Combustion is the rapid oxidation of material (the fuel) to release energy (heat). The fuel can be a solid, liquid or gas, and the amount of heat released is normally expressed in BTUs (British thermal units) or Calories. For industrial applications in the U.S., we generally use the term BTU. A BTU is defined as "the amount of heat necessary to raise one pound of water one degree Fahrenheit from 60° to 61°F." A Calorie is defined as "the energy required to raise one Kg of water one degree Celsius."

The oxygen required to release the energy from the fuel normally comes from the air and represents 20.9% of the normal atmosphere. The remainder is primarily nitrogen with traces of other elements. Standard air is defined as "air measured at one atmosphere pressure (14.696 pounds per sq. in.) and 60°F with 0% relative humidity."

In general, one cubic foot of air will release 100 BTUs of heat, regardless of the type of fuel used. (The exact number of BTUs released will vary somewhat with different fuels, but the variation is typically small, so this relationship holds true for all practical purposes.) As fuels are burned with just enough air to release the total BTUs in the fuel, the reaction is said to be "stoichiometric" or burned "on ratio"—when combustion is complete, no free oxygen or unburned fuel remains.

## Basic Combustion Reactions

Combustion is a rapid chemical combination of oxygen and the combustible elements of a fuel with a resulting release of heat. Combustion is an exothermic (heat producing) reaction. Of the three major combustible elements in any fossil fuel, carbon, hydrogen, and sulfur, only the first two have significance as a source of heat.

The basic combustion reactions for carbon and hydrogen are:

$C + O_2 = CO_2 + 14,500$ BTU for each pound of C

$2H_2 + O_2 = 2H_2O + 61,000$ BTU for each pound of H2

In the above reactions, the oxygen is supplied by air.

For complete combustion to occur, the combustible elements should be thoroughly burned, resulting in maximum heat release while using the least possible amount of air. The theoretical amount of air is the amount required to burn all the fuel when the fuel and air are mixed perfectly. This quantity is determined by combustion calculations and is called stoichiometric air or theoretical air.

Perfect mixing of fuel and theoretical air is not possible because of the large amount of fuel burned in the boiler. It is difficult to get the fuel particles or droplets fine enough to burn quickly and to get air all around each particle. Therefore, more than the theoretical amount of air is needed for complete combustion.

The extra air used is called excess air. Excess air ensures that there is enough air for complete combustion. The sum of the theoretical and excess air is called the total air.

Excess air is expressed as a percentage of theoretical air required. Thus, 25% excess air indicates that 125% total air is being supplied. In boiler operation, excess air represents a heat loss. This loss must be balanced against losses from incomplete combustion.

"The optimum balance is one of the major goals of an ongoing plant thermal performance program."

## Combustion Process

As the combustion process takes place in the furnace, oxygen in the combustion air combines chemically with the carbon and hydrogen in the fuel to produce heat. The amount of air that contains enough oxygen to combine with all the combustible matter in the fuel is called the "stoichiometric value" or "theoretical air".

It is improbable for every molecule of fuel that enters the furnace to combine chemically with oxygen. For this reason, it is necessary to provide more air than the stoichiometric requirement. For most boilers, it is customary to provide 5 to 20 percent more air that the stoichiometric requirement to ensure complete combustion. This additional air is called "excess air". A boiler firing at 1.2 times the stoichiometric air requirement would be said to be firing at 20 percent excess air. If insufficient oxygen is introduced into the furnace, incomplete combustion of fuel will occur. This wastes fuel, causes air pollution, and results in hazardous

conditions in the boiler. The unburned fuel may ignite in the boiler and result in secondary combustion, causing a dangerous explosion.

Providing too much combustion air reduces the explosion danger, but also reduces efficiency. The largest energy loss in a boiler is the heat that escapes as hot flue gas. Increasing the excess air increases this energy loss. High excess air can also result in unstable burner conditions due to the lean fuel/air mixture.

In practice, a large number of items that affect boiler efficiency are related to excess air. The proper value of excess air is a function of boiler load, fuel quantity, and air leakage through idle burners, steam temperature, flame stability, and energy losses.

To understand the combustion process in a boiler, we will first investigate the process of combustion.

## Elements of the Combustion Process

Three basic elements are required for combustion to occur:
- "Fuel" (a combustible material)
- "Oxygen" in sufficient quantity to support combustion
- Sufficient "heat" to bring the fuel to its ignition temperature and keep it there

If any of these conditions were removed, there would no longer be a fire. This is typically demonstrated using a fire triangle (Figure 1).
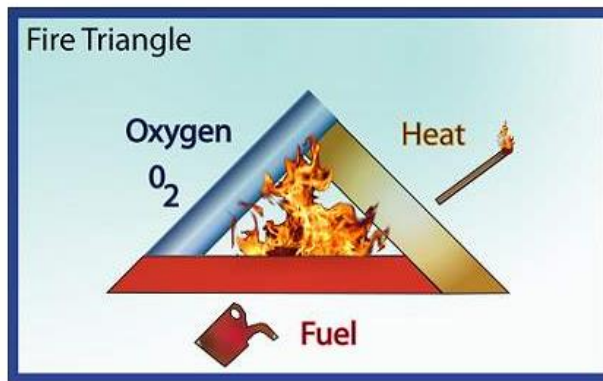


"'Figure 1: Fire Triangle'"

## Fuel

The most common combustible materials or fuels used in heating boilers are oil and gas. These materials supply a rather large amount of heat. The basic combustible elements in these fuels are hydrogen and carbon. Fuels exist as solids, liquids, and gases. All types of fuels contain carbon, hydrogen, and sulfur. The hydrocarbons readily combine with oxygen to produce a different compound and release heat. Fuels produce different amounts of heat and different byproducts when combusted. Typical heating boiler fuel constituents are shown in Table-1.

| Table-1:Typical Heating Boiler Fuel Constituents | | | |
|---|---|---|---|
| | #2 Oil | Natural Gas | #6 Oil |
| Carbon% | 86.1 to 88.2 | 65 to75 | 86.5 to 90.2 |
| Hydrogen% | 11.8 to13.9 | 23 to25 | 9.5 to 12 |
| Sulfur% | 0.05 to 1.0 | 0.1 to 0.4 | 0.7 to 3.5 |
| Oxygen% | 0 | 1.0 to 1.5 | 0.92 |
| Nitrogen% | 0 to 0.1 | 0.5 to 8 | 0 |
| Ash% | 0 | 0 to 0.1 | 0.01 to 0.5 |

## Oxygen

The oxygen needed to support combustion comes from the air that surrounds us. Air is a mixture of gases consisting mainly of about 21 percent oxygen and about 78 percent nitrogen of volume. The remaining 1 percent consists of small amounts of argon, carbon dioxide, and other gases.

Even in a simple wood fire oxygen plays a part in combustion. A chemical reaction occurs between the oxygen of the air and the wood fuel. The nitrogen and other gases in the air do not enter into the reaction, but do carry away the gases of combustion.

If a cover is put over the fire, the oxygen will be used up and the fire will go out. If the cover is removed before the fire is completely extinguished, oxygen becomes available and the fire continues.

## Heat

The "ignition temperature" is the temperature that will start a fuel to rapidly ignite with oxygen causing combustion to take place. A chemist would call this process "oxidation". Combustion is a form of oxidation that produces heat and light.

If you have ever tried to light a large log in a fireplace with a match, you notice it is very difficult. The large log does not release heat rapidly enough to maintain the ignition temperature of the log. If you shave off pieces of the log and light them with a match, the results will be much different. The burning shavings produce enough heat to maintain ignition. This same concept applies to liquid fuel. Trying to light a container of oil would be difficult, but atomizing the fuel will allow it to burn easier.

## How Fuels Burn

Some things burn more readily than others. As fuel is heated, several different gases are released. These gases are hydrogen, carbon monoxide, and hydrocarbons similar to methane. Finally, all that is left is solid carbon and impurities. If air is added to the solid carbon, oxygen from the air will penetrate the surface and break away atoms of carbon. The carbon atoms combine with the oxygen. The products of combustion are carried away by the moving air. This process continues until the burnable carbon has disappeared and only impurities remain.

Only vapors burn, not liquids or solids. Each type of fuel has a different volatility. "Volatility" is a measure of how rapidly the liquid turns into vapors. The vapors still must be raised to at least its flash point before ignition can occur.

## Fuel/Air Ratio

Fossil fuels burned in a boiler contain two basic elements: hydrogen and carbon. If these elements are combined, the compound is called "hydrocarbon". The fuel gas used for ignition is a hydrocarbon. A chemical analysis of the fuel determines how much air must be mixed with it for complete combustion. The relationship between fuel and air is called the "fuel/air ratio".

If you have ever worked on an older car with a carburetor, you probably adjusted the fuel/air "mixture". The mixture is typically adjusted by controlling the amount of fuel entering a carburetor. Supplying too much fuel is called a "rich" mixture and causes excess emissions or smoke from the exhaust. Supplying too little fuel is called a "lean" mixture and causes poor heat generation and a rough running engine.

## Fuels

Fuels can generally be classified as gaseous, liquid, or solid. In cases where a solid fuel is finely ground, such as pulverized coal, and can be transported in an air stream, its control characteristics approach those of a gaseous fuel. Liquid fuels, as they are atomized and sprayed into a furnace, also have control characteristics similar to those of a gaseous fuel. The control

treatment of a solid fuel that is not finely ground is quite different from that of a gaseous or liquid fuel.

Whether a fuel is a gas, a liquid, or a solid is determined by the ratio of its two primary chemical ingredients, carbon and hydrogen. Natural gas has an H/C ratio of in excess of 0.3. Fuel oil has an H/C ratio of above 0.1. Since hydrogen is the lightest element and the molecular weight of carbon is six times that of hydrogen, a decrease in the H/C ratio increases the specific gravity and the density of the fuel.

## Basic and Ideal Combustion

An ideal fuel burning system would have the following characteristics:
- No excess oxygen or unburned combustibles in the end products of combustion
- A low rate of auxiliary ignition-energy input to initiate the combustion process
- An economic reaction rate between fuel and oxygen compatible with acceptable nitrogen and sulfur oxide formation
- An effective method of handling and disposing of the solid impurities introduced with the fuel
- Uniform distribution of the product weight and temperature in relation to the parallel circuits of heat absorbing surface
- A wide and stable firing range, fast response to changes in firing rate, and high equipment availability with low maintenance

In actual practice, some of these characteristics must be compromised to achieve a reasonable balance between combustion efficiency and cost. For example, firing a fuel with no excess air above the theoretical amount would require an infinite residence time at temperatures above the ignition point at which complete burnout of the combustibles takes place. Thus, every firing system requires a quantity of air in excess of the ideal amount to attain an acceptable level of unburned carbon in the byproducts of combustion leaving the furnace. This amount of excess air is an indicator of the burning efficiency of the firing system.

## Basic Combustion

As we have learned, combustion can occur when the following conditions are met:
- Fuel
- Heat
- Oxygen
- Chemical reaction

All flammable material has a "FLASH POINT" and an "IGNITION POINT."
- The flash point of fuel is the lowest temperature at which sufficient vapors are given off for in a momentary flash when an ignition source is applied near the surface.

The ignition point is the temperature at which the ignited material provides enough heat to maintain combustion.
- As a flammable mixture is heated, the rate of chemical combination of oxygen with the carbon and hydrogen increases. Eventually, the combination rate becomes high enough to be continuously self-supporting. We call this "combustion".

Regardless of the fuel, it must be vaporized in order to burn. Oil, a liquid, and coal, a solid, must be heated to the point where gaseous vapors are rapidly given off. It's these vapors which burn, NOT the solid or liquid. This is what makes it possible, for example, to put out a match in a bucket of light oil that is below its flash point.

Natural gas consists primarily of methane ($CH_4$). The heat is released as the carbon (C) and hydrogen ($H_2$) combine (react) with oxygen and produce water ($H_2O$) and carbon dioxide ($CO_2$).

## Ideal Combustion

Efficient combustion of any fuel depends on its chemical and physical characteristics, and how well it is mixed with combustion air. Three important factors - time, temperature, and turbulence

- control the completeness of combustion and influence the design of boiler equipment and operating practices.

- TIME- Normally, combustion reactions are so rapid that the time to complete them seems instantaneous. A good example is the combustion of gasoline in an internal combustion engine. However, natural gas or a droplet of oil will travel several feet in the furnace and require a finite period of time between the start of ignition and the completion of burning.
- TEMPERATURE- If a mixture of air and fuel is heated gradually, a temperature will be reached at which outside heat is no longer required and rapid combustion occurs. This temperature is referred to as the ignition temperature and is defined as the temperature at which more heat is generated by the combustion process than is lost to the surrounding atmosphere. At this point, combustion becomes self-sustaining. Below this point, the fuel/air mixture will not burn freely and continuously unless external heat is supplied.
- TURBULENCE- If the fuel and air are mixed in swirling paths, instead of each flowing in streamlined paths, combustion will be greatly improved because the mixing of fuel and air is more complete. The proper amount of air for a given amount of fuel means nothing if the two are not mixed.

At oil burning plants, the oils burned must be heated on their way to the burner. This accomplishes two tasks. First, the oil flows more readily when heated; secondly, it atomizes better.

CAUTION!
Strict adherence to fuel oil temperature limits is advised. Carbon formation tends to increase at high temperatures, leading to clogged strainers and burner tips, and at extremely high or low temperatures, the booster pumps tend to "cavitate" (lose prime), a condition that could lead to equipment damage. At low fuel oil temperatures, inadequate combustion will occur at the burners. This leads to a loss of boiler efficiency and if not corrected, possibly to hazardous furnace conditions.

The speed at which the chemical reaction between the carbon, hydrogen, and oxygen occurs is crucial to flame performance. By atomizing the oil into very small droplets, more surface area of the oil is available for the oxygen to come in contact with. The more surface area, the quicker the reaction will occur.

Good combustion is very rapid, has a high flame temperature, and is very turbulent. Turbulence is a key factor in boiler furnace combustion. If the turbulence is high, the mixing of the oxygen and fuel will be good, therefore, combustion will occur very rapidly and the result will be a high flame temperature. If the turbulence is low, mixing will not be as good; therefore, more time is required for complete combustion and the result is lower flame combustion and a lower flame temperature.

The chain of events is as follows:

1. First, the fuel is gasified.
2. Second, it is mixed with air so the mixture is in the flammable range.
3. Third, the mixture's temperature is raised to the ignition point.
4. Fourth, combustion takes place with time, temperature, and turbulence.

The precise amount of air required to complete combustion with no excess is called "theoretical air." In real combustion systems, an excess amount of air is required above the theoretical amount to complete combustion. This is because mixing of the fuel and air (turbulence) is not perfect and some of the oxygen does not come in contact with the fuel while in the flame zone where temperatures are sufficient for combustion. This additional amount of air is commonly referred to as "excess air' and is expressed as "percent excess air." Since excess air is supplied to the combustion process, all of the available oxygen in the air will not be used.

The oxygen that is not used is referred to as "excess oxygen" and is expressed as "percent excess oxygen." The quantity of excess air required is dependent on several parameters including

boiler type, fuel properties, and burner characteristics. $O_2$ is preferred for monitoring furnace performance for the following reasons:

- The relation of $O_2$ to excess air is relatively invariant with fuel composition, whereas $CO_2$ relations vary considerably.
- $CO_2$ measurements require more precision than excess $O_2$ measurements to obtain the same accuracy.
- Excess $O_2$ is more associated with excess air, i.e., as excess air goes to zero, excess $O_2$ follows.
- Excess $O_2$ instrumentation is generally less expensive and more reliable.

When measuring $O_2$ or $CO_2$, beware of stratification of gases within the duct and the possible intrusion of outside air through leaks in the breaching, air heater seals, etc. Multiple point measurements as close to the boiler outlet as possible are preferred.

The chemical reactions occurring between the fuels and oxygen within the flame are:

$$C + O_2 = CO_2 + \text{Heat Energy}, \quad 2H_2 + O_2 = H_2O + \text{Heat Energy}$$
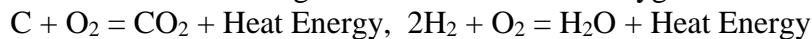
If there is a lack of oxygen, some of the carbon will not be completely oxidized and carbon monoxide will be formed. Another way to look at a lack of oxygen is to recognize that since fuel flow can be adjusted, we can also say that the furnace is "fuel rich." This condition is to be avoided. Excess fuel will carry over to other portions of the furnace, through the air preheaters, and out of the stack as black smoke (THIS IS A "FUEL RICH" CONDITION TO BE AVOIDED). When this happens, only a portion of the carbon's heat energy is released.

Carbon monoxide is, itself, a fuel, with a heating value of 4,355 BTU/lb. It is, therefore, classified as a "combustible". By comparison, pure carbon has a heating value of 14,500 BTU/lb. Oil fuel contains small amounts of sulfur and ash which are transformed into sulfur oxides and particulates. These are important from the standpoint of boiler operation and structural integrity. The oil ash (particulates) sticks to tubes and boiler surfaces and leads to boiler fouling if not cleaned regularly (usually with soot blowing equipment). "A portion of the sulfur oxides combines with the water vapor (formed in the combustion process) to form sulfuric acid, which is the primary chemical responsible for boiler corrosion."

| % BY WEIGHT | | | | | | |
|---|---|---|---|---|---|---|
| Fuel | Carbon | Hydrogen | Oxygen | Nitrogen | Sulfur | Heating Value (Btu/lb) |
| #2 Oil | 87.0 | 11.9 | 0.6 | -- | 0.5 | 19,410 |
| #6 Oil | 86.6 | 10.9 | 0.7 | 0.4 | 1.5 | 18,560 |
| Natural Gas | 75 | 23.5 | -- | 1.0 | -- | 23,100 |

## Gaseous Fuels

The most used gaseous fuel is natural gas. Natural gases vary in their chemical analysis and, thus, in their heating values. The average heating value is approximately 1,000 Btu per standard cubic foot, but may range from 950 to over 1,100 Btu/scf. Note that, in all cases, the amount of methane is over 80% by volume.

Table 2: Selected Samples of Natural Gas from US Fields

| Sample No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Source of Gas | PA | So. CA | OH | LA | OK |
| Analyses | | | | | |
| Constituents,% by vol | | | | | |
| $H_2$ Hydrogen | --- | --- | 1.82 | --- | --- |
| $CH_4$ Methane | 83.40 | 84.00 | 93.33 | 90.00 | 84.10 |
| $C_2H_4$ Ethylene | --- | --- | 0.25 | --- | --- |
| $C_2H_6$ Ethane | 15.80 | 14.80 | --- | 5.00 | 6.70 |
| CO Carbon monoxide | --- | --- | 0.45 | --- | --- |
| $CO_2$ Carbon dioxide | --- | 0.70 | 0.22 | --- | 0.80 |
| $N_2$ Nitrogen | 0.80 | 0.50 | 3.40 | 5.00 | 8.40 |
| $O_2$ Oxygen | --- | --- | 0.35 | --- | --- |
| $H_2S$ Hydrogen sulfide | --- | --- | 0.18 | --- | --- |
| Ultimate,% by wt | | | | | |
| S Sulfur | --- | --- | 0.34 | --- | --- |
| $H_2$ Hydrogen | 23.53 | 23.30 | 23.20 | 22.68 | 20.85 |
| C Carbon | 75.25 | 74.72 | 69.12 | 69.26 | 64.84 |
| $N_2$ Nitrogen | 1.22 | 0.76 | 5.76 | 3.06 | 12.09 |
| $O_2$ Oxygen | --- | 1.22 | 1.58 | --- | 1.41 |
| Specific Gravity (rel. to air) | 0.636 | 0.636 | 0.567 | 0.600 | 0.630 |
| Higher heat value | | | | | |
| Btu/cu. ft. @60°F and 30 in. Hg | 1,129 | 1,116 | 964 | 1,002 | 974 |
| Btu/lb of fuel | 23,170 | 22,904 | 22,077 | 21,824 | 20,160 |

Natural gas is the only major fuel that is delivered by the supplier as it is used. Figure 2 shows a typical supply system for natural gas.
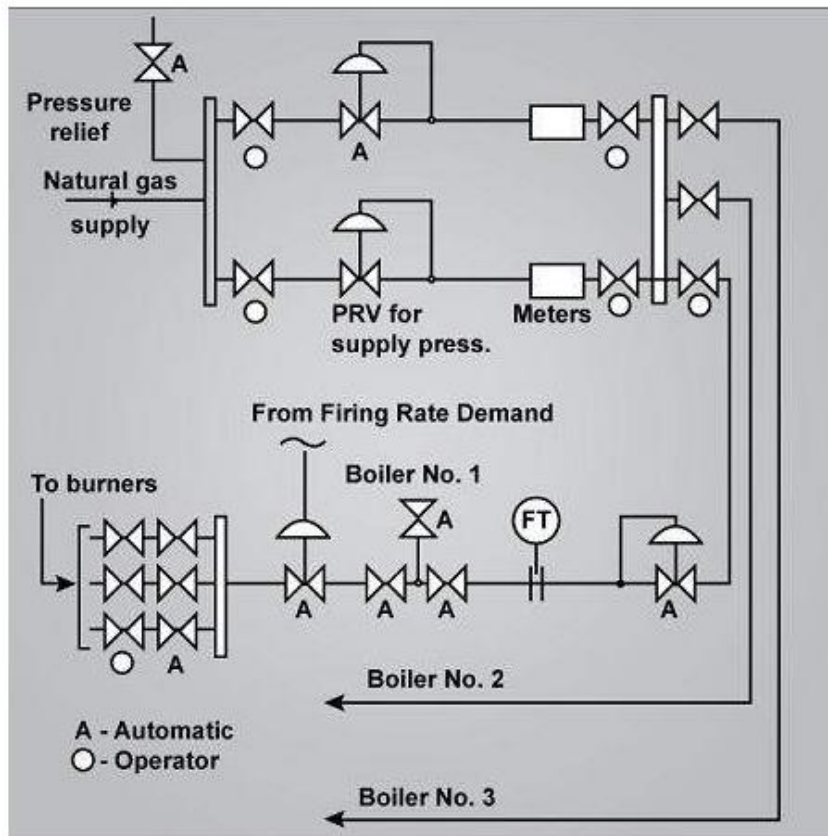


Figure 2: Gas Pressure Reducing and Metering Arrangement.

## Liquid Fuels

The most common liquid <u>fuel</u> is fuel oil, a product of the refining process. While crude oil as produced from the well is sometimes used, the most common fuel oils used for boiler fuel are the lightweight No. 2 fuel oil and the No. 6 grade of heavy residual fuel oil. Figure 3 shows a typical supply system for oil fuel.
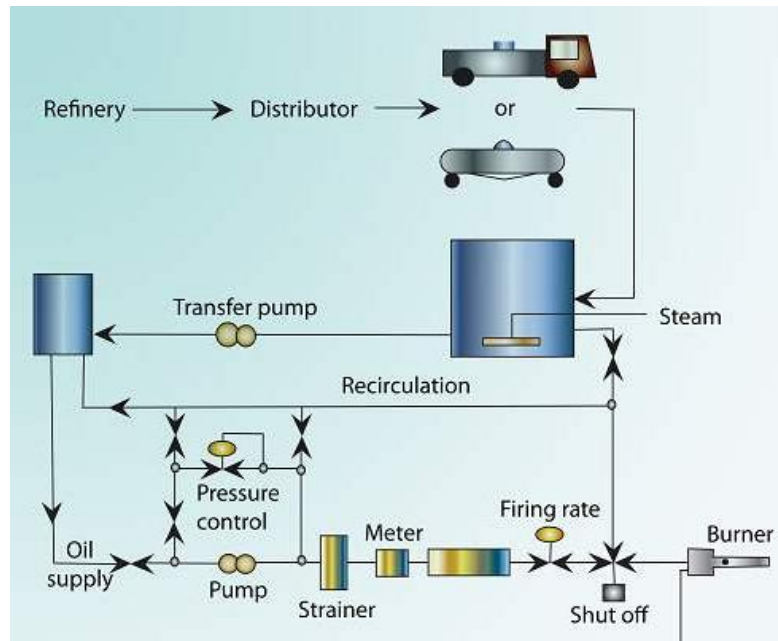


Figure 3: Typical Fuel Oil Pumping and Heating Arrangement.

If the fuel is No. 2 fuel oil, heating of the fuel is normally unnecessary. If the fuel is a heavy oil such as No. 6, it is usually necessary to <u>heat</u> the oil in the tanks so that it can be easily pumped through the system. If heavy fuel oil in a tank is unused for a period of time, the tank heating may cause the evaporation of some of the lighter constituents, ultimately making the oil too thick to remove from the tank by any normal means.
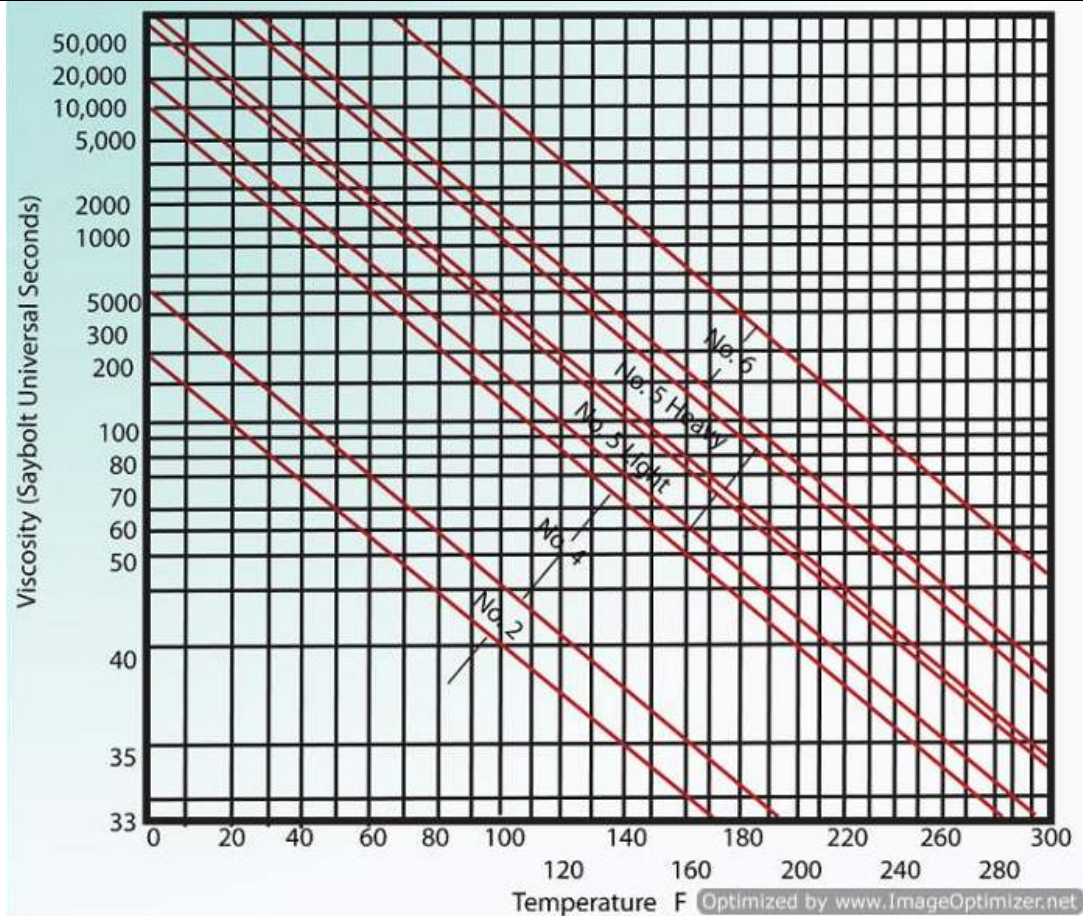
Figure 4: Fuel Oil Temperature vs. Viscosity.

Most burners are designed for a viscosity of 135 to 150 Saybolt universal seconds (SSU). A very important aspect of oil firing is viscosity. The viscosity of oil varies with temperature: the hotter the oil, the more easily it flows. Indeed, most people are aware that heavy fuel oils need to be heated in order to flow freely. What is not so obvious is that a variation in temperature, and hence viscosity, will have an effect on the size of the oil particle produced at the burner nozzle. For this reason, the temperature needs to be accurately controlled to give consistent conditions at the nozzle.

## Physical Combustion Requirements

In the previous section, we discussed the requirement for combustion using the fire triangle. The same process holds true in a furnace. "Combustion" is the rapid oxidation of fuel in a mixture of fuel and air with heat produced and carried by the mass of flue gas generated. Combustion takes place only under the conditions shown in Figure 5.



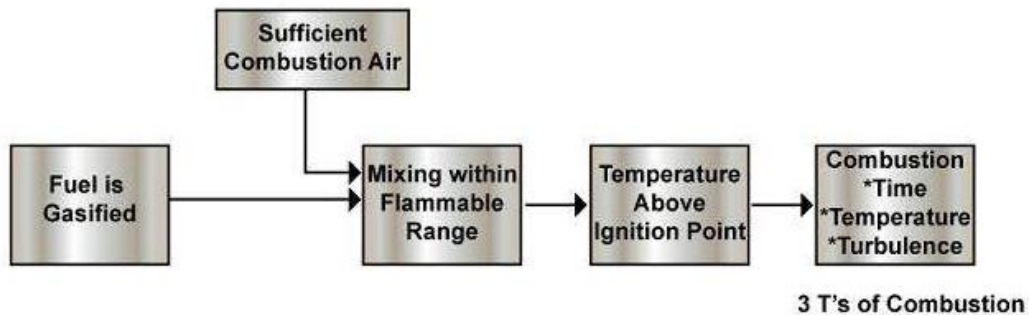Figure 5: Combustion Requirements.

Time, Temperature, and Turbulence are the three '"T's"' of combustion. A short period of time, high temperature, and very turbulent flame indicates rapid combustion. Turbulence is the key because fuel and air must be thoroughly mixed if the fuel is to be completely burned. When fuel and air are well mixed and all the fuel is burned, the flame temperature will be very high and the combustion time will be shorter. When the fuel and air are not well mixed, complete combustion may not occur, the flame temperature will be lower, and the fuel will take longer to burn.

Less turbulence and longer burning has been known to produce fewer nitrous oxides (Nox). In some cases, combustion has been delayed or staged intentionally to obtain fewer nitrous oxides or to obtain desired flame characteristics. The fuel must be gasified. The oil must be atomized so that the temperature present can turn it into gas. The ignition temperature and flame temperature are different for different fuels if all other conditions are the same. Typical ignition temperatures when mixed with air are shown in Table 3.

Table 3: Typical Ignition Temperatures

| FUEL TYPE | IGNITION TEMPERATURE |
|---|---|
| Light Fuel Oil | 600°F |
| Heavy Fuel Oil | 765°F |
| Natural Gas | 1,000°F |

Note that the gases have the highest temperature required for ignition. Liquids have the lowest ignition temperatures when properly atomized and mixed with air. Natural gas cannot be ignited if less than 64% of the theoretical air required for combustion is present.

For any fuel, a precise amount of combustion air is needed to furnish the oxygen for complete combustion of that fuel's carbon and hydrogen (see Figure 6). The precise amount of air is called the 'theoretical air' for that particular fuel.
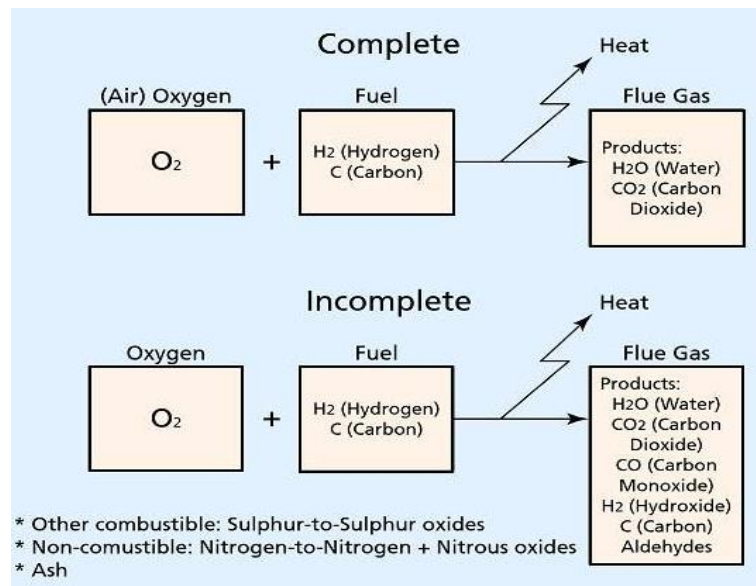
Figure 6: Basic Combustion Chemistry and Products of Combustion.

The amount of carbon and oxygen for complete combustion of carbon is represented by the formula: $C + O_2 = CO_2 + 14,100$ Btu/lb °C

Twelve pounds of carbon combine with 32 pounds of oxygen to form 44 pounds of carbon dioxide + heat.

The formula for combustion of hydrogen is: $2H_2 + O_2 = 2H_2O + 61,000$ But/lb $H_2$

Four pounds of hydrogen combine with 32 pounds of oxygen to form 36 pounds of water.

A simple example of the many incomplete combustion reactions resulting in intermediate hydrocarbon compounds is the partial combustion of carbon, resulting in carbon monoxide rather

than carbon dioxide. In this case, some of the potential heat from the carbon remains in the carbon monoxide.

$$2C + O_2 = 2CO + 4{,}345 \text{ Btu/lb C}$$
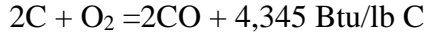
Twenty-four pounds of carbon combine with 32 pounds of oxygen to form 56 pounds of carbon monoxide. With the right conditions of time, temperature, and turbulence, and by adding more oxygen to the carbon monoxide, it will further oxidize to carbon dioxide, releasing additional heat energy.

$$2CO + O_2 = 2CO_2 + 4{,}345 \text{ Btu/lb CO}$$
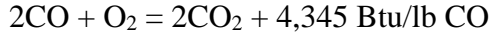
As indicated, the combustion process produces heat, but a low percentage of this heat is not useful in transferring heat to the boiler water. As hydrogen combines with oxygen to form water, the combustion temperature vaporizes the water into superheated steam. This vaporization absorbs latent heat. As the gases pass through the boiler and exit from the system, the gases retain the vaporized water in the form of superheated steam and the heat is lost from the process. The hydrogen content of the fuel determines this amount of heat loss. It is important to keep in mind that combustion air must be furnished for the total combustion or on the basis of the HHV, while only the LHV has any effect on the heat transfer of the system.

## Air

The air supply for the combustion process must be adequate for theoretical combustion and also provide "excess air" to ensure complete combustion. As shown in the graph of Figure 7, as the air is increased the combustion is improved. Once the excessive air becomes too great, the loss of heat reduces boiler efficiency.
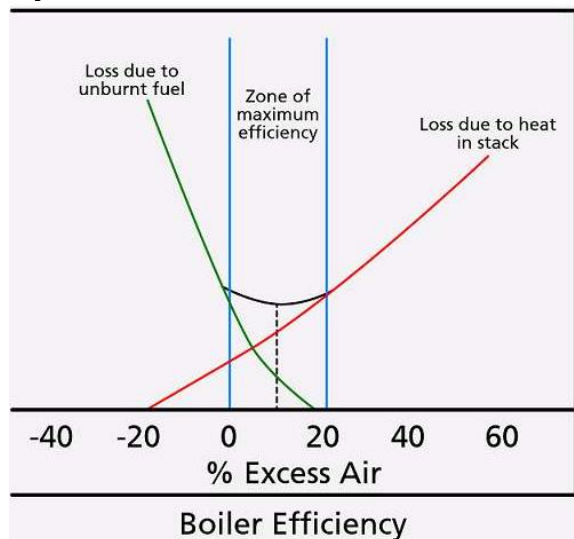


Figure 7: Boiler Efficiency Graph

Excess air can be determined by the amount of oxygen in the flue gas and calculated by:

Excess air (%) = $\dfrac{(K*21)}{(21 - \% \text{ oxygen}) - 1} \times 100$ , where: K = 0.9 for gas and 0.94 for oil.

Typical measurements of oxygen in the flue gas are shown in "'Table 4'".

| Table 4: Typical Ignition Temperatures | | |
|---|---|---|
| EXCESS AIR REQUIRED AT FULL CAPACITY | | |
| Fuel | % Oxygen in flue gas | % Excess air, minimum |
| Natural Gas | 1.5 to 3 | 7 to 15 |
| Fuel Oil | 0.6 to 3 | 3 to 15 |

An adequate flow of air and combustion gases is required for the complete and effective combustion of fuel. Flow is created and sustained by the stack and fans. "Draft" is the difference between atmospheric pressure and the static pressure of the combustion gases in a furnace. The flow of gases can be created by four methods:

- Forced draft
- Induced draft
- Balanced draft
- Natural draft

## Forced Draft

Forced draft boilers operate with the air and combustion products maintained above atmospheric pressure. Fans at the inlet to the boiler system, called "forced draft" (FD) fans, provide sufficient pressure to force the air and flue gas through the system. FD fans supply the necessary air for fuel combustion and must be sized to handle the stoichiometric air plus excess air needed for burning the fuel. They also provide air to make up for air heater leakage and for some sealing air requirements.

Radial airfoil (centrifugal) or variable pitch (axial) fans are preferred for FD service. FD fans operate in the cleanest environment in the plant associated with a boiler. Most FD fans have inlet silencers and screens to protect the fans from entrained particles in the incoming air.

Both the air temperature at the power plant and the elevation above sea level affect air density and, therefore, are a direct influence on fan capacity.

## Induced Draft

Induced draft boilers operate with air and combustion pressure below atmospheric. Static pressure is progressively lower as gas travels from the inlet to the induced draft fan. Induced draft (ID) fans exhaust combustion products from the boiler. In doing so, they create sufficient negative pressure to establish a slight suction in the furnace (0.2 to 0.5 inches of water). An airfoil centrifugal fan is typically used.

Natural draft boilers operate with draft formed by the stack alone.

## Balance Draft

Balanced draft boilers have a forced draft fan at the boiler inlet and an induced draft fan at the system outlet. This reduces both flue gas pressure and the tendency of combustion gases to escape the furnace. Most modern boilers are balanced draft.

The FD fans supply combustion air. The forced draft fans, in conjunction with O2 trim, maintain the proper fuel/air ratio for maintaining proper combustion and furnace safety. Flow is controlled by modulating the inlet vanes controls airflow.

## Air Heaters

Air preheaters reclaim some heat from the flue gas and add it to the air required for combustion. Use of preheated air will speed up combustion at all loads, improve combustion at low loads and increase efficiency.

## Burners and Controls

Burners are the devices responsible for:

- Proper mixing of fuel and air in the correct proportions, for efficient and complete combustion
- Determining the shape and direction of the flame

Coal, as a boiler fuel, tends to be restricted to specialized applications such as water-tube boilers in power stations. This section reviews the most common fuels for heating boilers.

## Oil Burners

As previously mentioned, oil must be atomized for optimal combustion. Oil burners are classified according to the method used for atomization:

- Air-atomizing burners
- Steam-atomizing burners
- Mechanical-atomizing burners

The ability to burn fuel oil efficiently requires a high fuel surface area-to-volume ratio. Experience has shown that oil particles in the range of 20 to 40 µm are the most successful. Particles which are:

- Bigger than 40 "µ"m tend to be carried through the flame without completing the combustion process
- Smaller than 20 "µ"m may travel so fast that they are carried through the flame without burning at all

Each of the burner types uses a nozzle to provide the spray of liquid fuel. The rate of combustion is limited by vaporization of the liquid fuel. The greater the surface area of the fuel, the greater the combustion capability.

Warm up guns normally use air atomization of light oil or steam atomization of heavy oil. Fuel pressure requirements for mechanical atomization are much higher. Table 5 is a summary of oil atomization systems.

Table 5: Summary of Oil Atomization Systems

| FAMILY | TYPE | FLOW CONTROL | MAJOR CHARACTERISTICS |
|---|---|---|---|
| Mechanical | Simplex | P2fuel, adjusting fuel feed rate | Fuel system simplicity, poor turndown |
| Constant differential pressure | Preturn, adjusting fuel feed rate | Consistent over wide load range | |
| Constant supply pressure | Preturn, adjusting return valve | Used in large boilers; variable spray angle | |
| Two-fluid (using steam or air) | Constant differential pressure (T-jet) | Pfuel, adjusting fuel feed rate | Saves steam at low load. Delta p may be adjustable. |
| Constant steam (or air) pressure (Y-jet) | Pfuel, adjusting fuel feed rate | Excellent atomization, very wide turndown capability; air atomization economical for small boilers or warm-up guns only | |
| Rotary | Spinning cup or disk | Adjusting fuel feed rate | Large sizes limited by bearings |

Figure 8 shows a typical burner assembly:
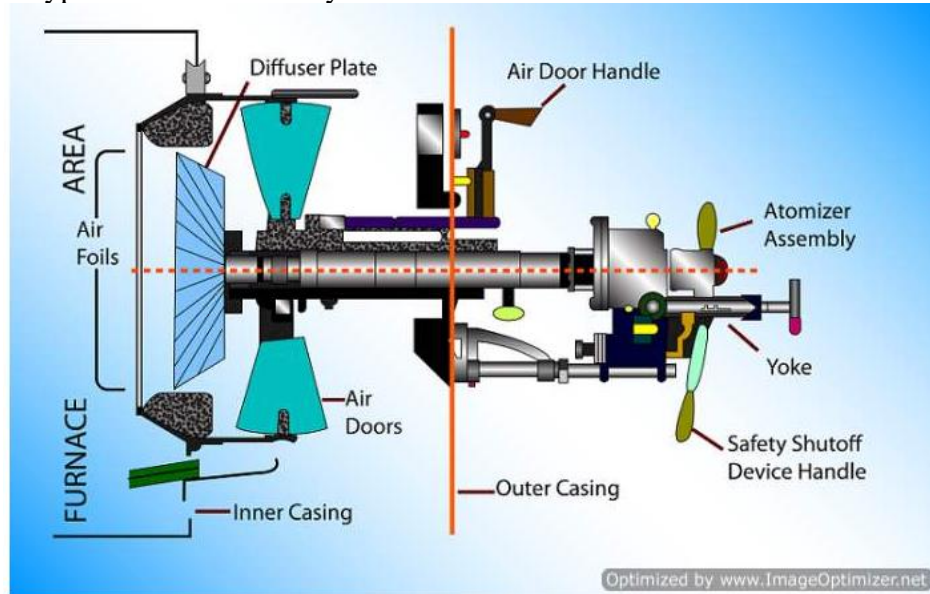

Figure 8: Typical Burner Assembly

## Pressure Jet Burners

A pressure jet burner (Figure 9) is simply an orifice at the end of a pressurized tube. Typically, the fuel oil pressure is in the range of 105 to 218 PSI.

In the operating range, the substantial pressure drop created over the orifice when the fuel is discharged into the furnace results in atomization of the fuel. Putting a thumb over the end of a garden hosepipe creates the same effect.
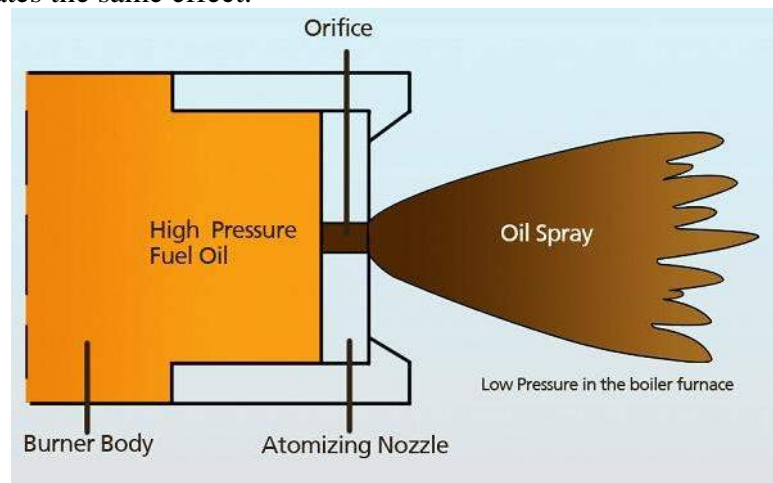

Figure 9: Pressure Jet Burner.

Varying the pressure of the fuel oil immediately before the orifice (nozzle) controls the flow rate of fuel from the burner.

Advantages of pressure jet burners:
- Relatively low cost
- Simple to maintain

Disadvantages of pressure jet burners:
- If the plant operating characteristics vary considerably over the course of a day, then the boiler will have to be taken off-line to change the nozzle.
- Easily blocked by debris, this means that well maintained, fine mesh strainers are essential.

## Rotary Cup Burners

In a rotary cup burner (Figure 10), fuel oil is supplied down a central tube, and discharges onto the inside surface of a rapidly rotating cone. As the fuel oil moves along the cup (due to the absence of a centripetal force), the oil film becomes progressively thinner as the circumference of the cap increases. Eventually, the fuel oil is discharged from the lip of the cone as a fine spray.
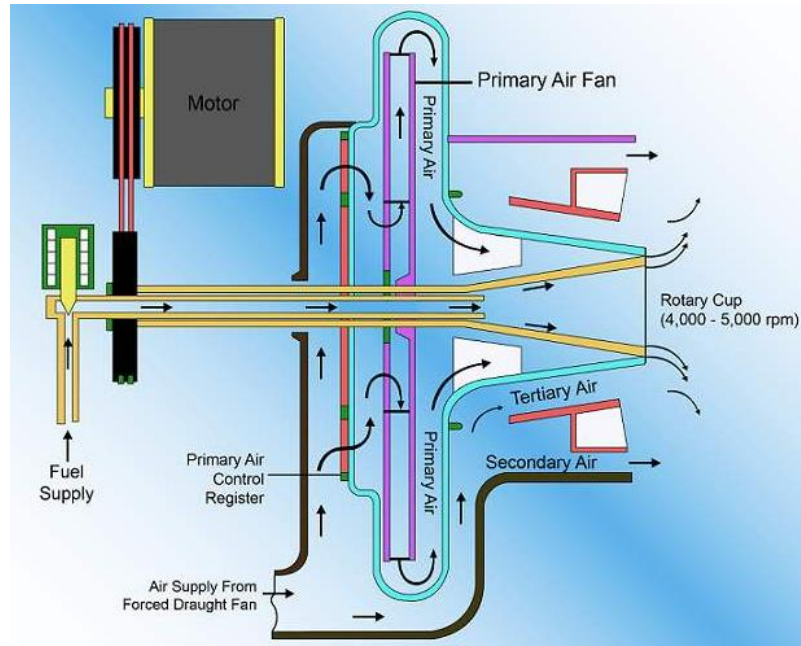


Figure 10: Rotary Cup Burner

Because the atomization is produced by the rotating cup, rather than by some function of the fuel oil (e.g., pressure), the turndown ratio is much greater than the pressure jet burner.

Some advantages of rotary cup burners are that they are robust, have a good turndown ratio, and fuel viscosity is less critical. The major disadvantage of rotary cup burners is they are more expensive to buy and maintain.

## Gas Burners

At present, gas is probably the most common fuel used in the facilities. Atomization is not an issue with a gas, and proper mixing of gas with the appropriate amount of air is all that is required for combustion. Two types of gas burners in use are low-pressure and high-pressure.

## Low-Pressure Burner

These operate at low-pressure, usually between 2.5 and 10 mbar. The burner is a simple venturi device with gas introduced in the throat area and combustion air being drawn in from around the outside (Figure 11).
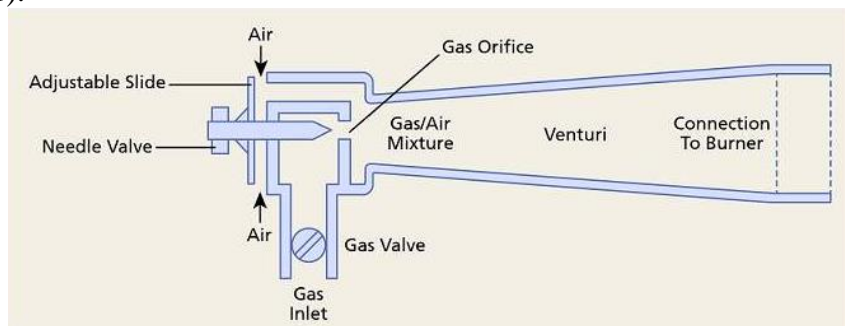


Figure 11: Low-Pressure Gas Burner

## High-Pressure Burner
These operate at higher pressures, usually between 12 and 175 mbar, and may include a number of nozzles to produce a particular flame shape.

## Dual Fuel Burners
The usual arrangement is to have a fuel oil supply available on site, and to use this to fire the boiler when gas is not available. This led to the development of "dual-fuel" burners ("'Figure 12'"). These burners are designed with gas as the main fuel, but have an additional facility for burning fuel oil.
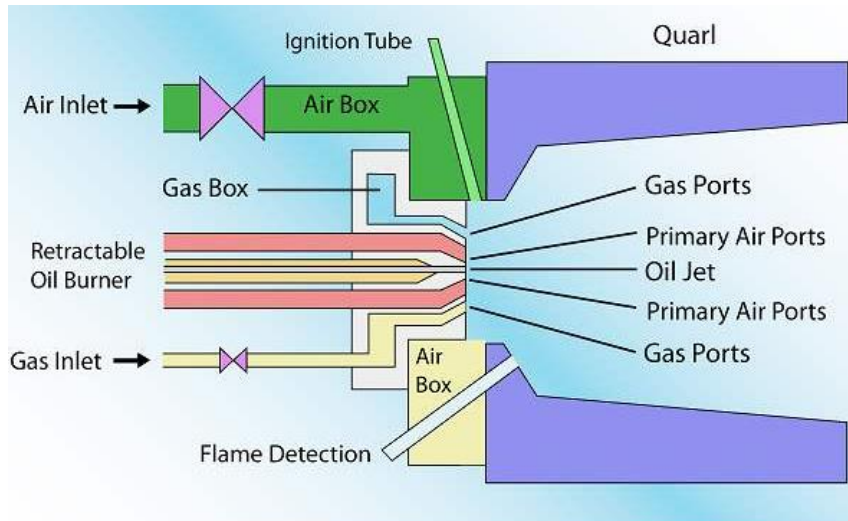


Figure 12: Dual Fuel Burner

The following procedure is an example of how the changeover from gas to oil is accomplished:
1. Isolate the gas supply line.
2. Open the oil supply line and switch on the fuel pump.
3. On the burner control panel, select 'oil firing';(this will change the air settings for the different fuel.)
4. Purge and refire the boiler.

This operation can be carried out in quite a short period. In some facilities, the changeover may be carried out as part of a periodic drill to ensure that operators are familiar with the procedure, and any necessary equipment is available.

However, because fuel oil is only "standby," and probably only used for short periods, the oil firing facility may be basic. On more sophisticated plants, with a highly rated boiler plant, the gas burner(s) may be withdrawn and oil burners substituted.

There is more to a burner than just blowing fire into a boiler or another heating device. Just what is a burner supposed to do?

- Provide heat to a boiler.
- Control the outlet temperature or pressure of a boiler.
- Provide a high turndown so that it does not shut off over the full range of boiler load demands.
- Burn the fuel in the most efficient way possible to keep fuel consumption low.

The following are some basics about how a burner functions. Natural gas will be used as the basic fuel, but fuel oils follow the same rules. Before we start, here are a couple of terms and their meaning that you'll need to understand.

"Excess Air"- The extra amount of air added to the burner above that is required to completely burn the fuel

"Turndown"- The ratio of the burner's maximum BTUH firing capability to the burner's minimum BTUH firing capability.

## Chemistry of Combustion

Natural gas is primarily composed of methane, or CH4. When mixed with the proper amount of air and heated to the combustion temperature, it burns. Figure 13 'shows the process with the amount of air and fuel required for perfect combustion.
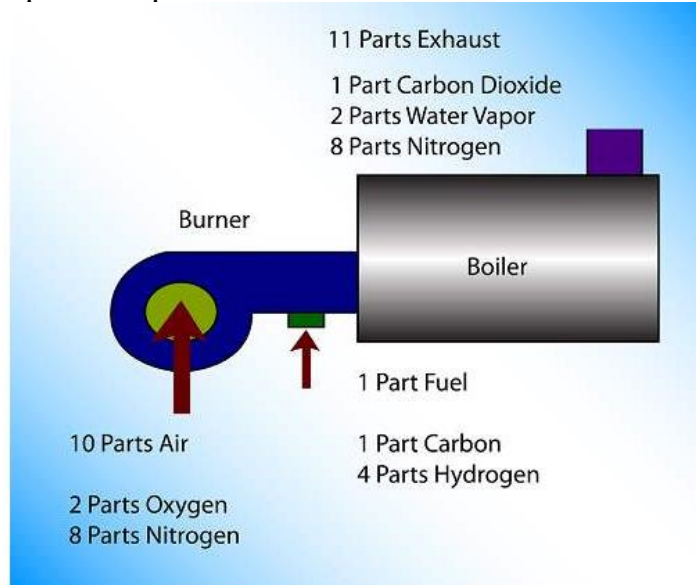
Figure 13: Combustion Process

Perfection is absolutely impractical, however. Extra or excess air must be added to assure safe burner operation. Forced draft burners use fans to supply air for combustion. The fan on a burner moves a constant volume of air, not molecules. Any change in temperature or barometric pressure causes a change in the number of air molecules that the fan moves.

The control valves and pressure regulators used to meter the fuel are not perfect devices either so the gas flow cannot be perfectly constant. The gas train is designed to control volume much like the fan, so a change in gas temperature will also change the number of molecules burned.

To ensure safe operation at all air and fuel temperatures and at all barometric conditions, the gas burner requires that excess air be supplied.

## Excess Air and Efficiency

The good news about excess air is that it provides a measure of safety. The bad news is that it wastes fuel. A prominent manufacturer of burners says that "the heat lost in excess air represents waste heat, and proper burner design will help reduce this to a practical minimum." The less excess air used results in the least amount of "waste." Let's examine just why excess air is a waste of fuel.

The boiler is merely a heat exchanger device designed to absorb heat from combustion products and to transfer that heat into water. When excess air is added to the perfect, or stoichiometric, amount of air, obviously more mass is forced through the boiler. In a boiler, there is a modulating control that meters air and fuel so that the proper amount of heat is added to maintain the proper pressure or temperature. Because of this control, the same BTU's are absorbed per hour, no matter the amount of excess air that is supplied.

The chart below shows various temperatures leaving a heat exchanger when supplied with different amounts of gas at the same temperature.

EFFECT OF FLOW RATE TO EXIT TEMPERATURE

| GAS FLOW (SCFM) | EXCESS AIR (%) | GAS INLET TEMP. (°F) | GAS OUTLET TEMP (°F) |
|---|---|---|---|
| 5555 | 0 | 1400 | 532 |
| 6111 | 10 | 1400 | 610 |
| 6666 | 20 | 1400 | 681 |

As the mass flow is increased through the heat exchanger, the outlet temperature is increased. The mass amount is analogous to the amount of excess air used by a gas burner.

In a boiler, as the excess air is increased, the stack temperature rises and the boiler's efficiency drops. It takes fewer BTU's of input to the burner to get the same number of BTU's out of the boiler if lower excess air can be used. Therefore, one of the most important functions of a burner is to burn the fuel at the lowest possible excess air to achieve the greatest overall boiler efficiency.

## Excess Air, Efficiency and Turndown

An important function of burners is turndown. This is usually expressed as a ratio and is based on the maximum firing rate divided by the minimum controllable firing rate.

Figure 14 shows a simplified burner head. The air is brought into the head by means of a forced draft blower or fan. The gas is metered into the head through a series of valves. In order to get proper combustion, the air molecules must be thoroughly mixed with the gas molecules before they actually burn.
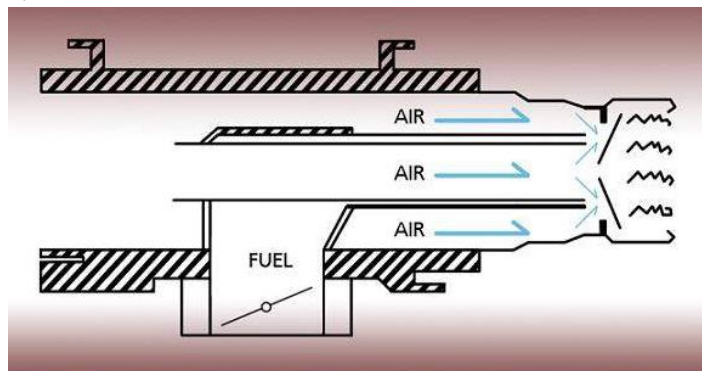


Figure 14: Simplified Burner Head

The mixing is achieved by burner parts designed to create high turbulence. If insufficient turbulence is produced by the burner, the combustion will be incomplete and samples taken at the stack will reveal carbon monoxide as evidence.

Since the velocity of air affects the turbulence, it becomes harder and harder to get good fuel and air mixing at higher turndown ratios since the air amount is reduced. Towards the highest turndown ratios of any burner, it becomes necessary to increase the excess air amounts to obtain enough turbulence to get proper mixing. The better burner design will be one that is able to properly mix the air and fuel at the lowest possible airflow or excess air.

Figure 15 graphically displays how excess air affects the efficiency and operating cost of a boiler. The data was compiled on an actual boiler.
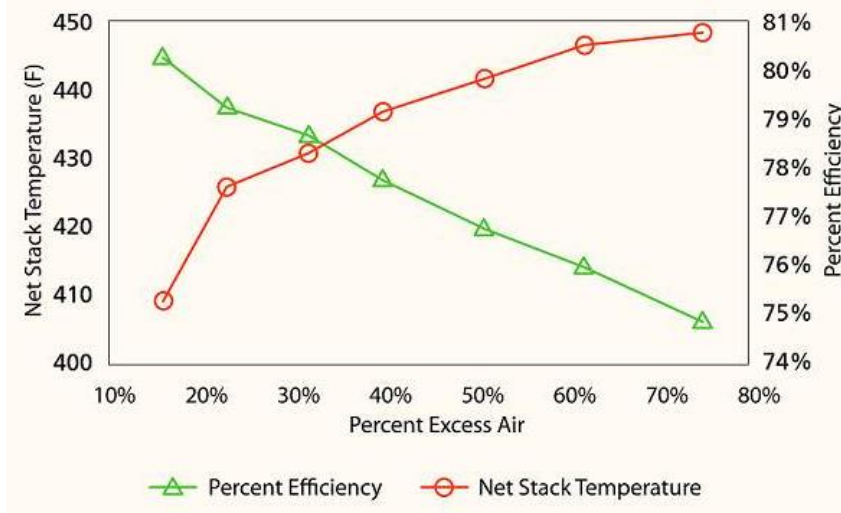
Figure 15: Effect of Excess Air on Boiler Efficiency

Figure 16 shows the savings realized with a 100 horsepower load at various efficiencies caused by different excess air levels.
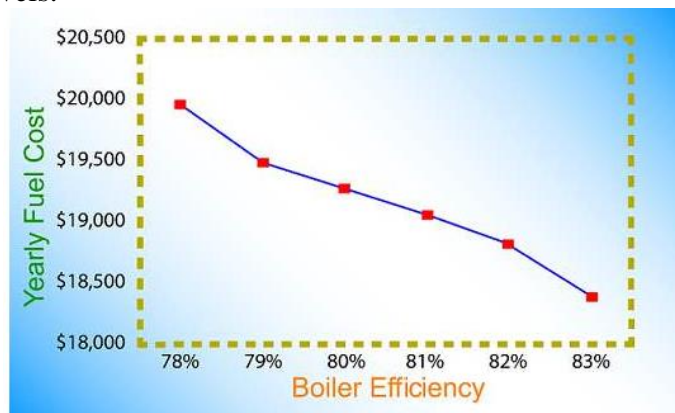

Figure 16: Effect of Excess Air on Fuel Costs

There are several strong reasons why high turndown and low excess air are important. The first is the operating cost of the burner. You have seen how excess air affects the operating cost, but the turndown ratio of a burner has a big affect as well. Every time the burner starts and stops there is a cost associated. Air is always blown through the boiler to ensure that there is no unburned fuel remaining. These purges make the boiler work like a chiller because it takes energy out of the system. Two other reasons for having a high turndown relate to lowered maintenance costs and better process or heating control.

Do not confuse turndown with "fully modulating" burners. Having a fully modulating burner with only the typical turndown of 1.7 to 1 is like having a car that can only go between speeds of 59 MPH and 100 MPH. It is a "fully modulating" car, but try driving it to the grocery store. You would not only look silly, but think of the how the gas mileage would drop.

'''Figure 17''' shows how the turndown ratio of a burner impacts the fuel cost needed to run a 100 horsepower boiler for heating. When you combine the effects of low excess air and high turndown, the operating cost savings can range from 10% to 15% below a brand new burner that does not have those characteristics.

Figure 17: Effect of Turndown on Fuel Costs

Process control is enhanced with a high turndown. If the load is smaller than the burner can turn down to, it cycles on and off. When off, the pressure or temperature falls off. On some boilers, we have seen steam pressures drop from 100 psig at burner shutdown to about 40 psig before the burner comes on again. That can cause problems in a manufacturing plant that depends on constant steam pressure. Even on hot water heating systems, control problems occur because of low turndown boilers. Valves hunt and temperature control becomes erratic. With a high turndown, those fluctuations are eliminated because the burner tracks the load down to the point where it shuts off only when the load is very slight. There is enough stored energy in the system to take up the small fluctuations at that point.

Maintenance costs are reduced with a high turndown burner because there is much less thermal cycling taking place in the boiler. When a burner cycles, the refractory and metal parts expand and contract. Although those materials are built to take it, their life is prolonged if everything stays the same temperature. Gas valves, ignition transformers, etc. are all less prone to fail if they never have to cycle. If the burner stays on, they don't have to turn on and off and, therefore, last longer.