Lecture-6

Biomass Combustion Technology

Combustion

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 oxidation. 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. 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 (ì) that describes the ratio between the locally available and the stoichiometric amount of combustion air. For typical biomass, the combustion reaction can then be described by the following equation if fuel constituents such as N, K, Cl, etc., are neglected:
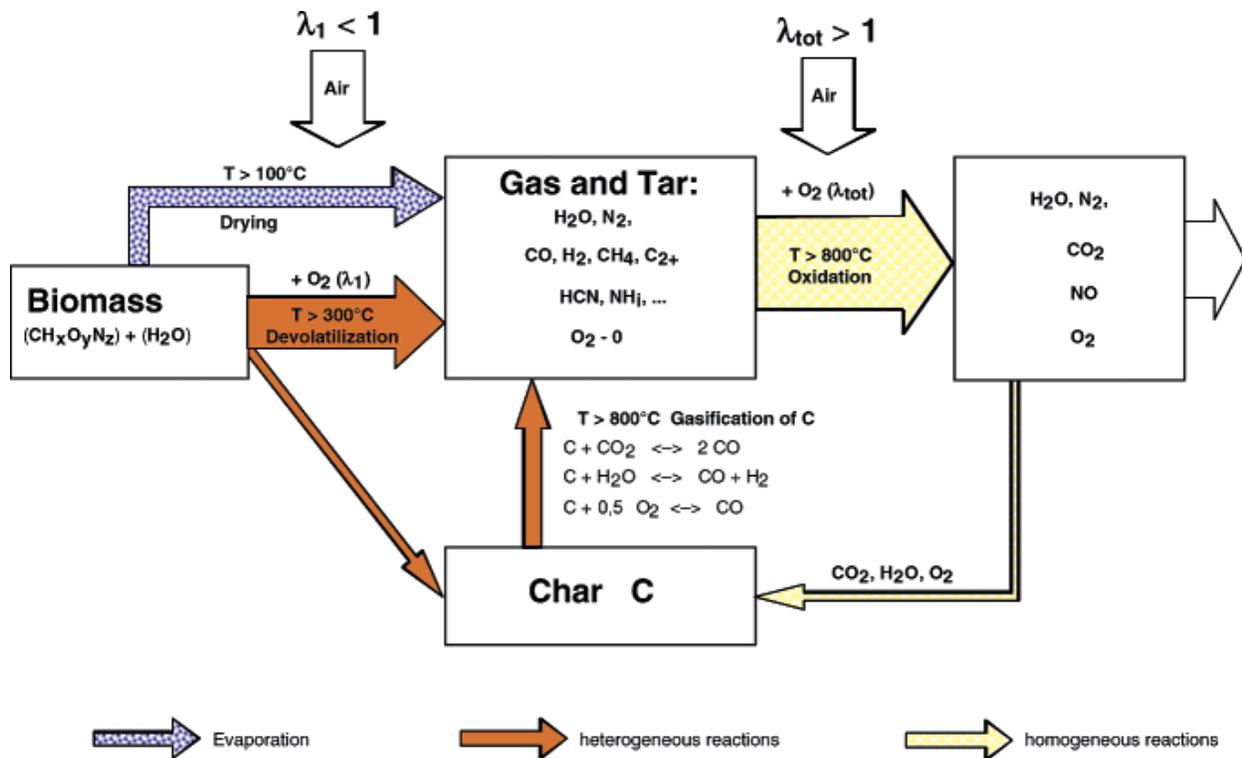
$$CH_{1.44}O_{0.66} + ì1.03 (O_2 + 3.76 N_2)$$
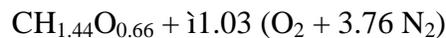
f intermediates (C, CO, H_2, CO_2, C_mH_n, etc.)

$$f CO_2 + 0.72H_2O + (ì - 1)O_2 + ì3.87N_2 (-439 kJ/kmol)$$

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 NOX (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.

$\lambda_1 < 1$

Air

$\lambda_{tot} > 1$

Air

T > 100°C
Drying

Gas and Tar:
H_2O, N_2,
CO, H_2, CH_4, C_{2+}
HCN, NH_i, ...
$O_2 - 0$

+ O_2 (λ_{tot})

T > 800°C
Oxidation

H_2O, N_2,
CO_2
NO
O_2

Biomass
$(CH_xO_yN_z) + (H_2O)$

+ O_2 (λ_1)
T > 300°C
Devolatilization

T > 800°C Gasification of C
$C + CO_2 \longleftrightarrow 2\,CO$
$C + H_2O \longleftrightarrow CO + H_2$
$C + 0,5\ O_2 \longleftrightarrow CO$

Char C

CO_2, H_2O, O_2

Evaporation   heterogeneous reactions   homogeneous reactions

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. 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 ì < 1.5) thus enabling high efficiency on one hand and high temperature with complete burnout on the other hand. If good mixing is achieved, the concentrations of unburnt pollutants can be reduced to levels close to zero (e.g., $CO < 50$ mg/m3 and $C_XH_Y < 5$ mg/m3 at 11 vol % O_2). However, an accurate process control is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and ì (CO/ì-controller) or of CO and temperature have been developed. Air staging applies air injection at two levels as well. In addition to conventional two-stage combustion, primary air needs to be understoichiometric (ì 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 NOX in biomass combustion and are described below.
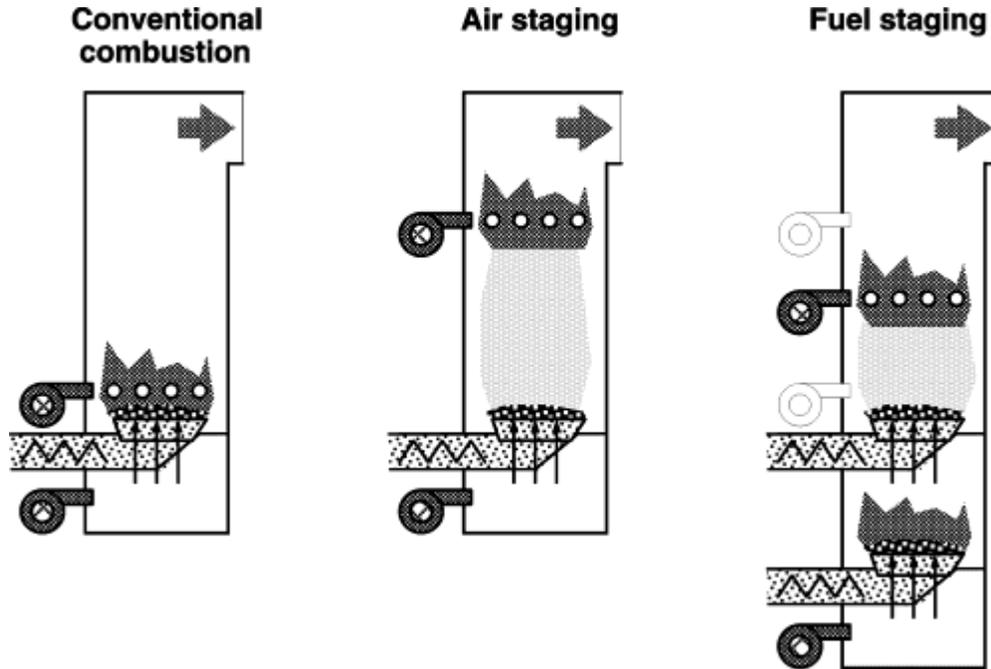
Figure. Principle of conventional two-stage combustion, air staging with reduction zone, and fuel staging with reduction zone.10

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. 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. 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. NOX Emissions. In combustion processes, NO and NO_2 (summarized as NOX) Can be formed in three different reactions. Thermal NOX and prompt NOX are formed from nitrogen in the air at high temperatures and in the case of prompt NOX in the presence of hydrocarbons. Further, fuel NOX can be formed from nitrogen-

containing fuels. For biomass combustion, fuel bound nitrogen is the main source of NOX emissions, while thermal and prompt NOX 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 NOX 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 N2 in reactions such as NO + NH_2) N_2+ H_2O. During the past 10 years, staged combustion technologies have been developed as a primary measure for process internal NOX reduction based on this concept, thus leading to the above described techniques of air staging and fuel staging. Both measures enable a NOX reduction on the order of up to 50% for wood with low and up to 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. The relatively high temperature can limit the application in practice due to undesired ash softening and deposit formation. For fuel staging, similar results are achieve 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. 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 NOX abatement. The most relevant techniques are selective non-catalytic 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 NOX 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 NOX 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.

Particulate Emissions

Biomass combustion leads to relatively high emissions of particulates, i.e.,well above 50 mg/m3 at 11 vol % O2.[4,25] The majority of the particulates are smaller than 10 ím (i.e., particulate matter PM 10) with a high share of submicron particles (PM 1). 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.

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. Distinct heating systems are often in the size range from 0.5 MWth to 5 MWth with some applications up to 50 MWth. Combined 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 0.5MW and 10 MW.35 Stirling engines (10 kW to 100 kW) 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), which are not applicable for dedicated biomass combustion due to limited local biomass availability.

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. To 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. 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. 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 while grate furnaces can also be applied for highash and water content.
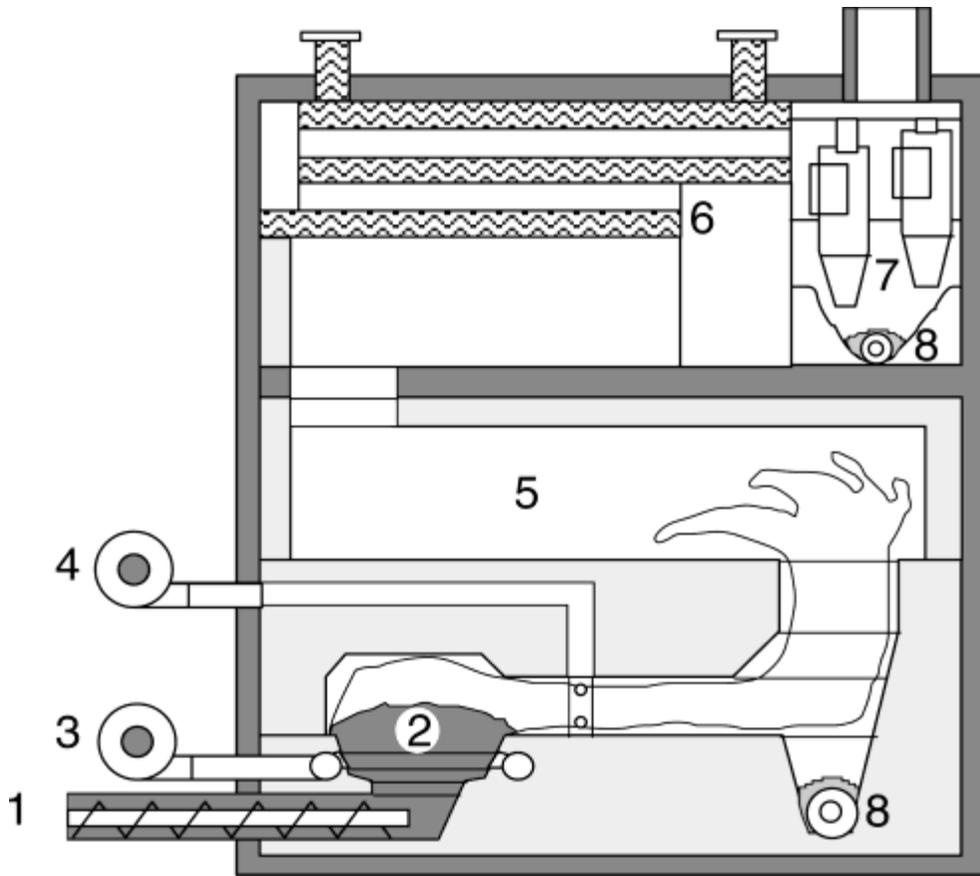
Figure . Understoker furnace with primary and secondary air, mixing zone, and post combustion chamber. 1 Screw feeder, 2 understoker zone with glow bed, 3 primary air, 4 .secondary air, 5 post combustion chamber, 6 heat exchanger,7 cyclone, 8 ash removal

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. 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 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 NOX emissions are achieved.

Co-combustion

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 co-firing can reduce emissions of SOX and NOX. 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:

(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).

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 savings of CO2 taxes can therefore motivate biomass co-firing.

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 to 700 MW with a few units between 5 and 50 MW. 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 power plant in the Netherlands that burns the majority of the local urban waste wood and demolition wood. 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 wood-based fired plant reaches 30% efficiency.

b. As an alternative, the biomass can also be burnt on a separate grate at the bottom of a pulverized coal boiler. 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.

Effects of Co-combustion on Plant Operation and Emissions

Co-firing can have several effects on the emissions and the plant operation: positive effects are that SOX and NOX emissions usually decrease due to the lower sulfur and nitrogen content in biomass than in coal. Furthermore, alkali components in biomass ash can have an effect of SOX removal. Since biomass has a high volatile content, it can also be used as reburn fuel for NOX reduction from the coal combustion, which gives a further potential for significant decrease of the NOX emissions. Besides NO and NO_2, also N_2O can be significantly reduced by co-firing of biomass in coal-fired fluidized bed boilers.

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-SOX installation) has to be considered when co-firing biomass. The ash quality can be negatively influenced 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.

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 combination 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.

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 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.
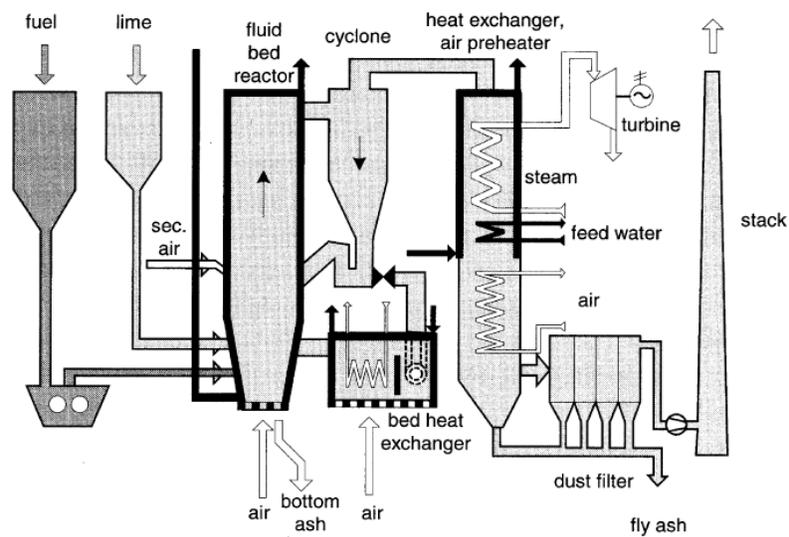
Combustion and co-combustion of biomass