EFFECTS OF BIOMASS ON DYNAMICS OF COMBUSTION IN CIRCULATING FLUIDIZED BEDS

by

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Fludized bed technology is very suitable for the combustion of biomass. Nevertheless substitution of coal with biomass affects boiler operation and especially dynamics and controllability. Non-homogeneity of biomass and fuel feeding disturbances cause process unstability, such as variations in temperatures and pressures, which reduce lifetime of equipment and structures. Because of process unstability higher air coefficient must be used in order to avoid CO emissions, which is not economical. Combustion profiles for coal, wood and peat, measured at the VTT Processes Pilot circulating fluidized bed reactor, have been compared. Process stability and char inventories have been studied by the measurements and the model. Biofuels are usually very reactive and their combustion profiles are quite different compared to coals. Because of high reactivity and low char content combustion process with biofuels is very sensitive for fuel feeding. Also low char inventory effect on load changes combined with combustion profile that differs from coals. Because of different combustion profile heat transfer can be a limiting factor in load changes despite the high reactivity and fast oxygen response.

Key words: *combustion, coal, dynamic, biomass, circulating fluidized bed, reactivity*

Introduction

Fluidized bed technology is very suitable for the combustion of sludge from industrial processes and wood based fuels. One of the main advantages of fluidized bed combustion (FBC), which is often highlighted, is the capability of multi-fuel operation. When FBC or circulating fluidized bed (CFB) boiler has to offer stable steam and power production with fast responses it is not very simple to use many different kind of fuels, which have very different qualities and combustion profiles. The qualities of biofuels, such like heating value, particle size, moisture etc., cause often great variations in fuel feeding and these fluctuations results in a lot of problems for the control system to satisfy demands of the operator. Combustion profiles of biofuels must be known in order to control combustion process effectively. The basic understanding of how to mix biofuels, what is optimal particle size distribution and what are the impacts of biofuels on emissions are crucial questions that should be answered.

Dynamic response analyses are needed to study process controllability and stability in cofiring of *e. g.* coal and biofuels. Steady state measurements under well-controlled conditions can give important information on combustion profiles and char inventories in the furnace. For example determination of optimal char inventory in each defined operation condition can give guidelines for the fuel mixtures ratios and leads to optimal boiler dynamic and nitrogen oxide emissions.

Method

Schematic picture of the method to study fuel combustion behaviour under CFB conditions is shown in fig. 1.

The method consists of measurements in steady state and in dynamic conditions and models. By carrying out the steady state measurements and some transient tests and analysing them by the models it is possible to obtain information on fuel combustion behaviour such like volatile release and combustion of volatile matter and char.

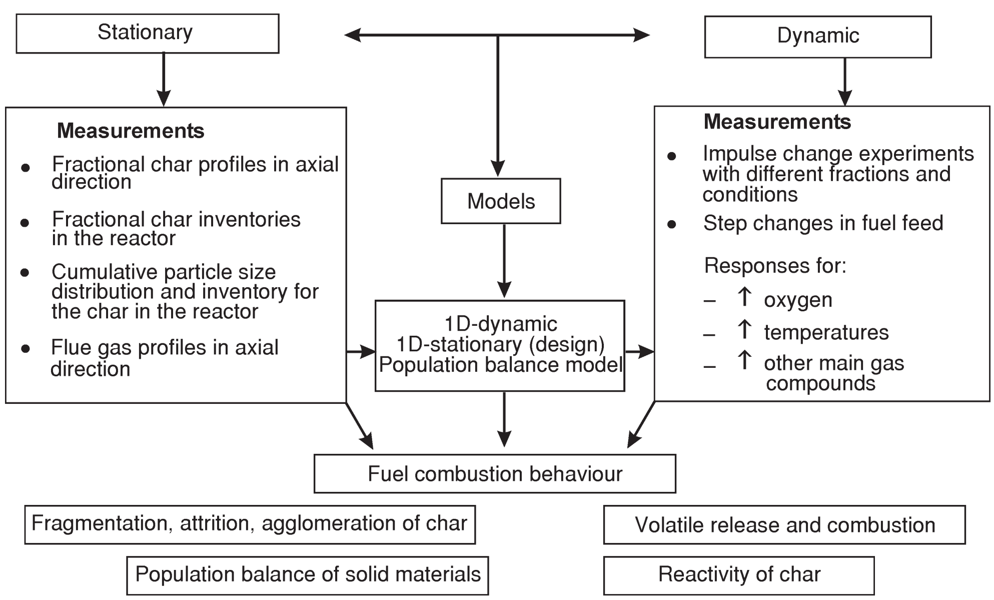

Figure 1. Methods to characterise fuel combustion behaviour

Experiments

Experiments have been carried out with a circulating fluidized bed reactor. Schematic picture of the pilot CFB reactor, used for the experimental tests, is shown in fig. 2.

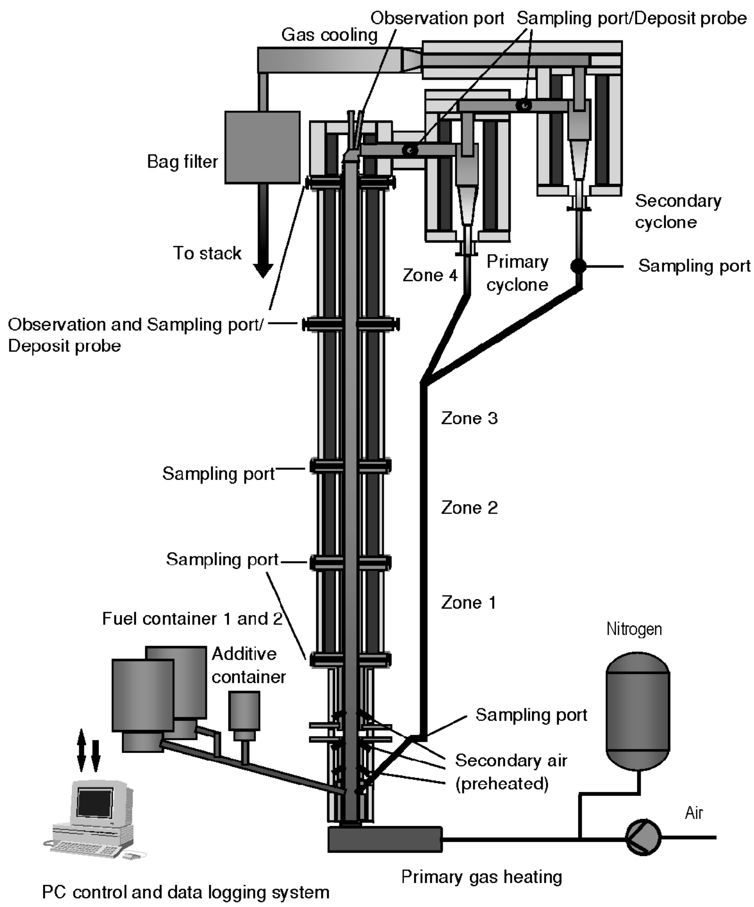

Figure 2. Schematic diagram of the laboratory scale circulating fluidized bed reactor

The height of the riser is 8000 mm and the inner diameter 167 mm. The use of ceramic construction materials has minimized the catalytic effect of the reactor walls on combustion reactions. The reactor is equipped with several separately controlled electrically heated and water/air-cooled zones in order to control the process conditions (for example oxygen level, temperature and load) almost independently. The reactor is controlled by PC-computer to which all measurement data are collected. There are several ports in the freeboard area for sampling and observation. The reactor is equipped with FTIR spectrometer and traditional on-line analysers of main flue gas compounds. Bag house filter has been mounted after the gas cooler in order to collect the finest fly ash from the flue gas.

Fuel can be fed to the reactor by two separated fuel containers. Also there is own feeder route for additives for example limestone. Fuel containers are mounted on the top of scales in order to determine mass flows of fuels.

Combustion air can be divided to primary and secondary air. The secondary air can be fed to three different levels of the reactor. In this work the uppermost (1.4 m above the air grid) feeding point is used for the secondary air and only minimum flow (21 Nl/min.) is used in other feeding points to prevent clogging of air nozzles. Oxygen concentration of primary air can be controlled by mixing nitrogen gas to primary air.

Gas samples can be taken from different levels of the freeboard and also before and after cyclones, gas cooler and bag house filter. Traditional on-line analysers of main flue gas compounds are connected to the flue gas line between the gas cooler and bag house filter. Samples from solid materials can be taken from the primary cyclone (circulated material), secondary cyclone (fly ash), gas cooler (fly ash), bag house filter (fly ash) and above the air grid (bottom ash).

The gas-solid sampling probe can draw simultaneously gas and solid samples from the freeboard. The nozzle of the sampling probe was chosen to enable isokinetic sampling. Solid materials are collected from the flue gas by a cyclone and subsequent filter. After the cyclone and filter sample gas is conducted along the heated sample line to FTIR spectrometer and O_2-analyser. The gas-solid sampling probe is cooled by air and the sample is diluted by nitrogen gas in order to quench the chemical reactions.

Steady state measurements

Gas and solid samples have been taken from different levels of the riser during steady state operation. These samples combined with pressure and temperature measurements describe combustion profile in detail.

Temperature profiles along the pilot CFB reactor are shown as an example in fig. 3.

Temperatures along the riser give good insight about where combustion takes place and where heat is released. Temperature profile for wood is quite different than for coal, measured under the four different process conditions, as seen in Figure 3. Release of moisture and volatile and subsequent volatile combustion is most dominant phenomena for the wood. Drying of particles and low char content leads to low bed temperature and after the secondary air feed there is clear increase in temperature because of combustion of volatiles. Combustion profiles, which are dependent on the fuel, affect greatly the boiler control. When the composition of fuel mixture is changed, also combustion profile

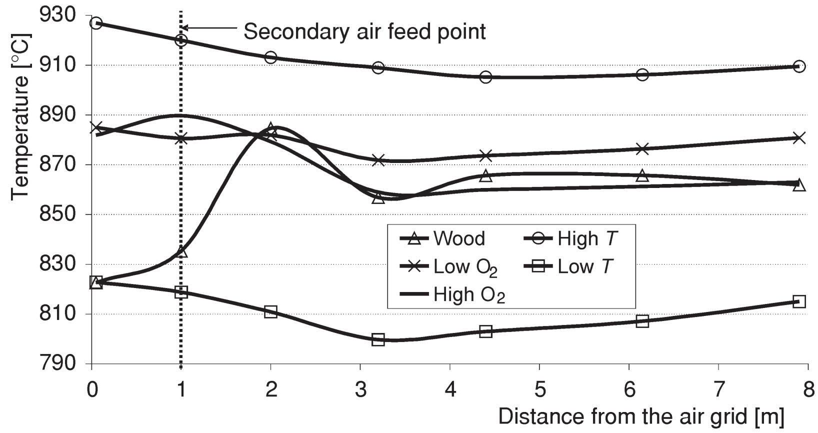

Figure 3. Comparison of temperature profiles for coal, under different process conditions, and wood

and subsequently temperature profiles are changed. Dense fuels like coal burn in the lower part of the reactor while biofuels burn usually upper than coal. This is due to high volatile content and low density of char. Also fuels that contain lot of volatile matter are easier fragmented.

Also gas profiles along the riser provide a lot of information of combustion process. Especially carbon dioxide (CO_2) and oxygen (O_2) concentrations indicate the rate of fuel oxidation. In fig. 4 O_2 concentrations, measured at VTT's CFB pilot plant, are shown for coal, wood, and peat.

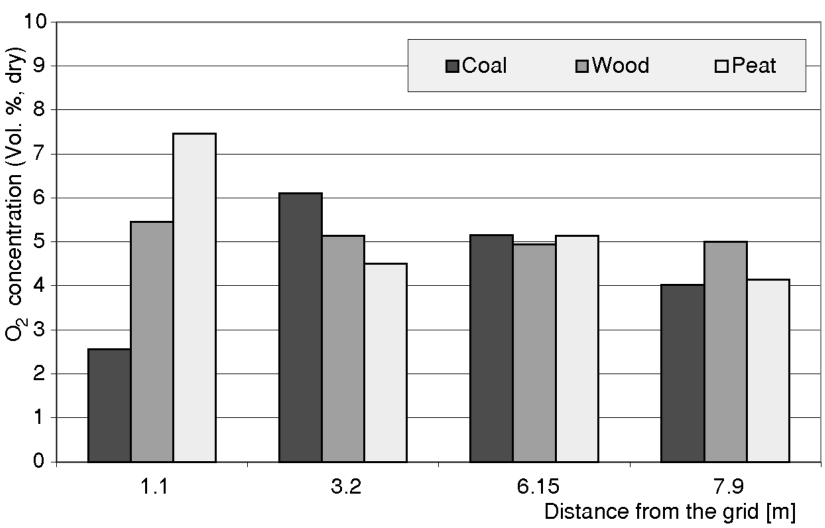

Figure 4. O_2 profiles shown for coal, wood and peat

A clear difference between the fuels can be observed. As in earlier chapter discussed, bituminous coal is burned mostly in bed and lower part of the reactor. In coal combustion the char inventory is rather high compared to that of biofuels. This char uses most of the oxygen, which explains low O_2 concentrations at the bottom part of the CFB reactor. The same kinds of results were earlier obtained by Knöbig *et al.* [1]. However, they didn't get remarkable difference between wood and peat, which means that there are also other matters affecting to combustion process than amount of volatiles and char in fuel. These are *e. g.* fuel particle size and moisture content.

Steady state flue gas oxygen concentrations have been also studied as seen in fig. 5. Despite steady state operation there are fluctuations in oxygen concentrations, which describe unstability of the process.

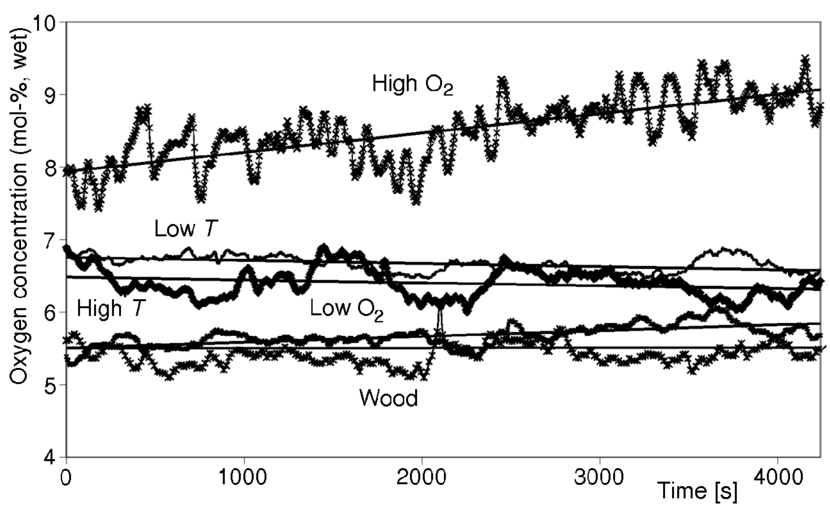

Figure 5. Flue gas oxygen concentration for coal under four different process conditions [2] and wood. Also linear trends have been fitted for the concentrations

Variation of oxygen concentration gives information on combustion and fuel feeding. For instance a correlation between char inventory and standard deviation of oxygen calculated by eq. (1) can be found as seen in fig. 6:

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{O_2,i} - \bar{Y}_{O_2,i})^2} \tag{1}$$

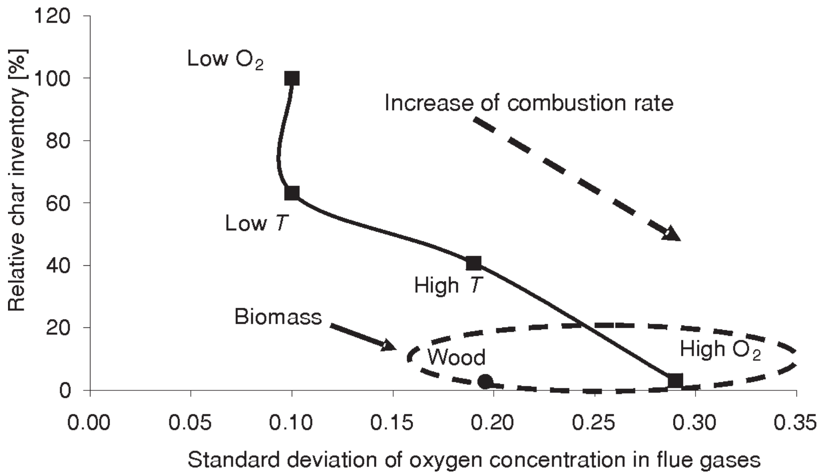

Figure 6. Char inventory as a function of standard deviation of flue gas oxygen concentration. Black line marked with ■ is for coal under four different process conditions [2]. Wood is marked with ●

Char inventory is low in biomass combustion and hence variation of oxygen is rather significant. Also feeding of biofuels is often more difficult than conventional fuels. Above-mentioned reasons cause typically unstability of the process during biomass combustion.

Dynamic measurements

When steady state conditions have been determined some transient experiments can be carried out, which are typically as seen in fig. 7.

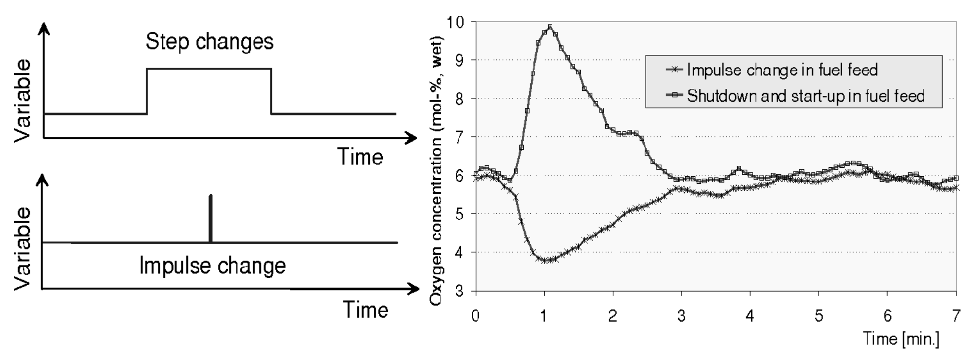

Figure 7. Schematic picture of dynamic experiments. Step- or impulse-type change in fuel feeding rate; Simultaneous measurement for response of oxygen concentration

Fuel batch is fed into the reactor in impulse change experiments. Step change can be produced for instance by shutting down the fuel feed for a while. Temperature and flue gas responses are measured during these changes. The response of oxygen is most important considering combustion of volatile and char. Typical responses for the peat and coal are shown in fig. 8 during impulse change experiments.

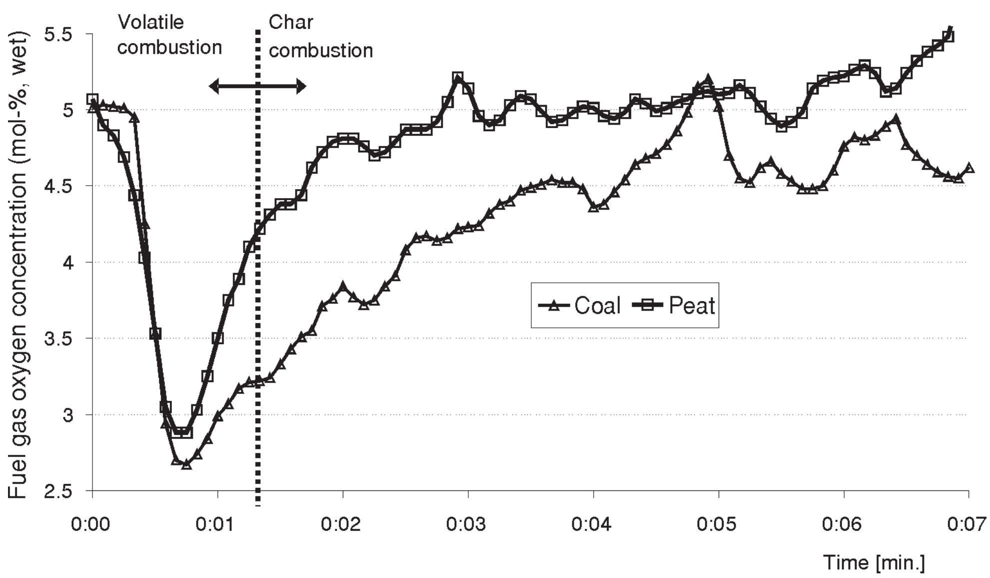

Figure 8. Comparison of the flue gas responses for the coal and peat during impulse change in fuel feed

Volatiles release and their combustion are prevailing phenomena in combustion of biofuels. Char of the biofuels such like wood has much lower density compared to char of coals. Fuel characteristic of peat is quite similar to characteristic of biofuels and due to that char combustion part is not that significant in the peat response as seen in fig. 8. Impulse change responses for coal and biomass are shown in fig. 9.

If figs. 8 and 9 are compared, the differences between coal, peat and biomass are clearly seen. The combustion behaviour of biomass and coal are very different and combustion characteristic for peat is between of these. For the control system of the boiler different types of responses set demands to change the operation depending on the type of fuel in order to achieve well controlled combustion process. Also frequency response techniques can be utilized to identify experimentally a poorly known process [3]. Based on the responses of impulse changes in fuel feed the available frequency band for the each fuel can be obtained.

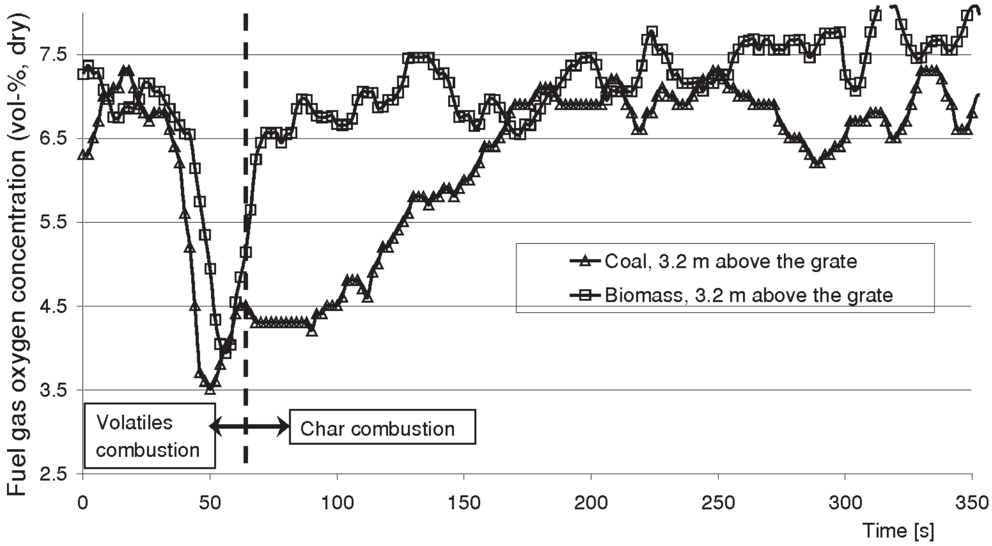

Figure 9. Comparison of the flue gas responses for coal and biomass during impulse change in fuel feed

Generally most of the maximum disturbances are caused by fuel feeding in power production processes. Especially biofuel processes suffer from variations of fuel quality. Different control methods to compensate these problems have been developed. One of these methods is the combustion power control. Principle of this control strategy is to optimize need for oxygen based on measurements and balance calculations. This kind of methods will be needed in biofuel combustion if stable power production must be achieved. [4, 5]

Model

1D-dynamic model [2, 6, 7] can be used for the analyses of fuel combustion behaviour. For example such like fuel reactivity and effect of changes of fuel feeding or mixture ratio on gas responses and fractional char inventories can be studied. Mass balances are calculated for the main flue gas compounds, volatile matter and char fractions. Fragmentation and attrition of char are taken into account by using rate coefficients.

Volatile release from the fuel batch is calculated by equation

$$\frac{\mathrm{d}m_v}{\mathrm{d}t} \quad \frac{1}{\tau_v}[m_0 \quad m_v(t)] \tag{2}$$

where m_0 is initial mass of volatile matter in fuel batch, m_v is mass of released volatile matter and time constant τ_v is calculated by equation:

$$\tau_v \quad b\mathrm{e}^{\frac{A}{T}\ \frac{d}{d_{\mathrm{ref}}}\ ^{n}} \tag{3}$$

Moisture release is described by equation, which has same form as eq. (2). The fuel fed into the reactor is assumed to be distributed instantaneously according to measured distributions for char fractions and flue gases along the reactor height. Hence total mass balance for char fractions are calculated zero-dimensional and then char fractions are distributed based on measured profiles.

By comparing simulated and measured responses it is possible to obtain parameters for the sub-models of combustion as seen in fig. 10.

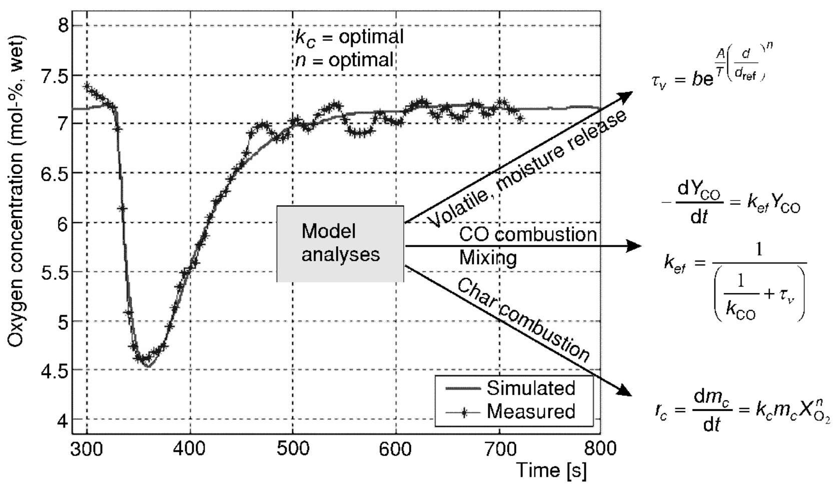

Figure 10. Comparison of simulated and measured responses in order to obtain parameters for sub-models of combustion

Parameters for example volatile and moisture release, carbon monoxide combustion and char combustion can be obtained based on model analyses. Different fuels and particle size fractions can be easily tested and analysed by this method and correlation for instance between particle size and devolatilization rate (time constant τ_v) can be found.

A simulation example is shown in fig. 11 calculated by the 1D-dynamic model.

Fuel feeding is decreased 10% and a little bit later it is increased 10%. These kinds of disturbances are usually caused by fuel feeding system or it can be also caused by the control system, which is not fast enough. Flue gas oxygen responses are calculated for the coal and the wood during the disturbances. Calculated (dashed lines) responses and responses (solid lines) in which the time delays of the sample lines and the dynamic of the analyser have been taken into account are shown in fig. 11. The variation of oxygen concentration is much higher in wood combustion, which is mainly due to low char in-

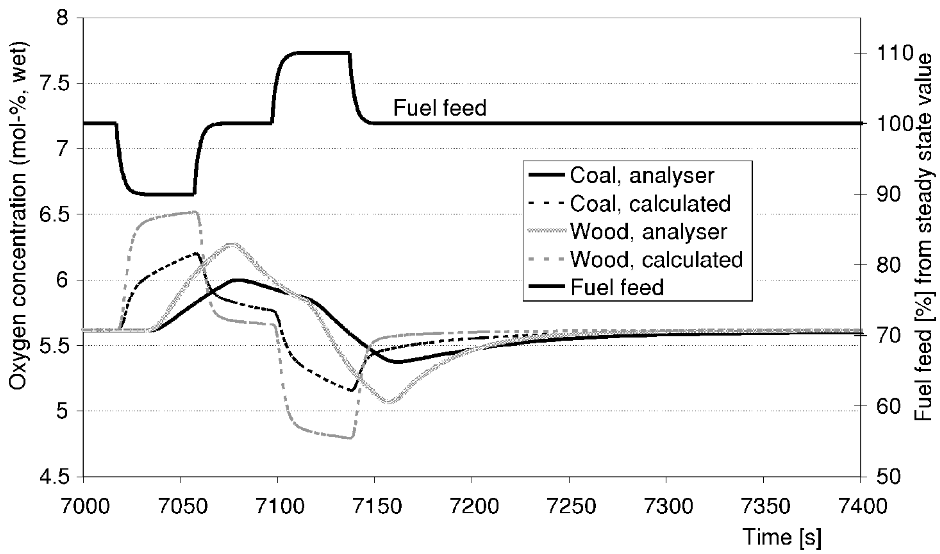

Figure 11. Flue gas oxygen responses during fuel feeding disturbances

ventory. Also effects of analyser and sample line on the results are clearly seen. The real responses are faster and more extensive than those detected by the analyser (and simulated here). This example shows how sensitive the process is for fuel feeding disturbances in biomass combustion. Also dynamics of analyser and sample line must be known in order to control process effectively.

Conclusions

The method, developed for coal and peat, can be used also to study biomass combustion behaviour and dynamics in CFB conditions. This method gives appropriate insight about effect of substitution of coal with biofuels on dynamic of combustion. Biofuels have great variation in quality and their volatile content is usually high, which leads to low char inventory and unstable process in CFB combustion. Higher air coefficient must be used in combustion of biofuels to avoid CO-emissions. Also faster measurements and control systems are needed to achieve stable operation in biomass combustion. Fluctuations in fuel feeding cause variations in temperatures and pressures, which reduced lifetime of structures and equipment.

Biofuels are usually very reactive and their combustion profiles are quite different compared to coals. Because of high reactivity and low char content, combustion process with biofuels is very sensitive for fuel feeding. Also low char inventory effect on load changes combined with combustion profile that differs from coals. Because of different combustion profile heat transfer can be a limiting factor in load changes despite the high reactivity and fast oxygen response.

Acknowledgments

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Nomenclature

A – constant, [K]
b – constant, [s]
d – particle diameter, [m]
k – global chemical reaction rate coefficient, [s^{-1}]
k_c – chemical reaction rate coefficient, [kg m^{-2} s^{-1}]
k_{ef} – reaction rate coefficient, [s^{-1}]
m – mass, [kg]
n – exponent, reaction order, [–]
r – combustion rate, [kg s^{-1}]
s – standard deviation, [–]
t – time, [s]
T – temperature, [K]
X – volume fraction, [–]
Y – mass fraction, [–]

Greec letters

τ – time constant, [–]

Subscripts

c – char
CO – carbon monoxide
O_2 – oxigen
v – volatile
0 – initial

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