

## Ash related problems in biomass combustion plants

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technische universiteit eindhoven

Inaugural lecture  
20 May 2005

prof.dr. Ingwald Obernberger

# ash related problems

in biomass combustion plants

/ department of mechanical  
engineering

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Inaugural lecture

Presented on May 20, 2005  
at Technische Universiteit Eindhoven

# ash related problems

in biomass combustion plants

prof.dr. Ingwald Obernberger

# Introduction

*In recent years the thermal utilisation of solid biomass for heat and electricity production has gained ever more 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<sub>2</sub> emission reduction targets defined in the Kyoto protocol. However, according to data published by the International Energy Agency in 2004 [1], global primary energy consumption has increased from 6,034 Mtoe in 1973 to 10,230 Mtoe in 2002 and this trend is expected to continue. In 2002 combustible renewables and waste accounted for 10.9% of global primary energy supply. There is a broad international consensus that the utilisation of renewable energy sources should be further enforced in order to reduce greenhouse gas emissions. In the EU, several political measures have been initiated with the aim of supporting this requirement, including the White Paper (1997), the Res-e Directive (2001), the Commitment on the Green Paper on Security of Energy Supply (June 2002), the Directive on the Energy Performance of Buildings (Dec 2002), the Directive on Liquid Biofuels (May 2003), the Commitment on Renewable Energies in Europe launched at the Bonn conference (2004), and the Directive on the promotion of cogeneration (2004).*

## **Heat and power production from renewable energy sources – the European situation**

Renewable energy sources currently represent about 6.2% of total primary energy supply within the EU 15, with combustible renewables and waste as well as hydropower accounting for the major share. However, EU policies are aimed at increasing the share of renewable energy sources in gross energy supply from 6% in 1995 to 12% in 2010 [2]. To reach this aim, the utilisation of biomass should be tripled. Furthermore, the share of green electricity should be increased from 14% (in 2001) to 22% in 2010 [3]. The use of biomass within electricity production should thereby be increased tenfold (based on 1995 values) to 828 PJ/a in 2010.

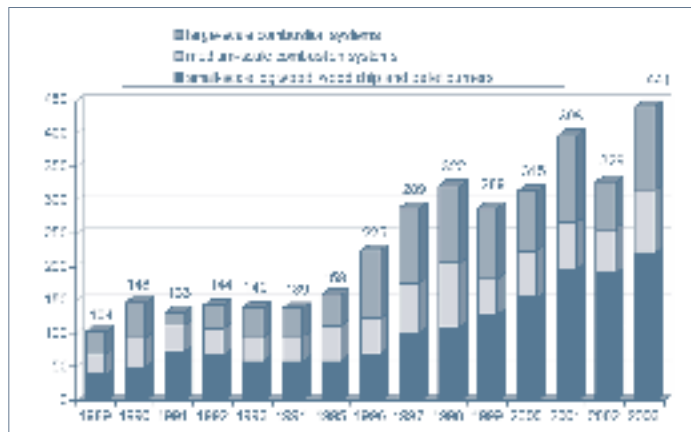
The leading countries in the renewable energy utilisation stakes in Europe are Sweden (about 29% primary energy consumption from



renewables), Finland (about 22%) and Austria (about 21%), while in 2003 the Netherlands produced only about 1.5% of their primary energy from renewables [1]. The Dutch national targets aim to increase the share of renewable energy in total energy use to 5% in the year 2010 and 10% in 2020 [4]. Moreover, the Dutch government formulated the target to increase the share of electricity from renewable energy sources in gross electricity consumption from 3.5% (1997) to 9.0% in 2010, which is in line with the targets of the respective EU directive [3]. An enormous demand for appropriate measures and activities to meet these ambitious goals will exist in the Netherlands as well as in the whole European Union in the near future. In 2003, 70% of renewable energy consumption in the Netherlands, which is about 1.1% of total primary energy consumption, originated from bioenergy followed by wind (22%) and heat pumps (3%) [5]. Austria for instance, covered 10.97% of total primary energy consumption from renewable energy sources (excluding hydropower) in 2001. 10.4% were covered by the thermal utilisation of solid biomass. 60% of these solid biomass sources are used for residential heating (small-scale combustion units) while 32% are utilised for process heat and electricity generation in industry (heat only and combined heat and power plants) and 8% are utilised in biomass district heating plants [6].

figure 1

Development of the capacities of newly installed biomass combustion systems per year in Austria between 1989 and 2003



Explanations: source [7]; data in MW

Statistics [7] reveal an almost steady increase in the number and nominal capacity of newly installed biomass combustion systems per year in Austria since the early 1990s (see figure 1). In this period, more than 52,600 biomass combustion units with a total capacity of 3,600 MW have been installed. This trend towards enforced utilisation of solid biomass for energy production is supposed to continue in the next few years.

A significant time point in these statistics is the year 1997, when small-scale pellet furnaces started to penetrate the Austrian market. The introduction of this new technology increased the number of installed small-scale applications per year from 2,280 in 1997 to 7,751 units in 2003. This example nicely demonstrates the impact of a new and innovative renewable energy technology on the market and also shows that new concepts for renewable energy utilisation have a high potential to gain broad public acceptance.

#### Technologies for thermal biomass utilisation

As already mentioned above, the thermal 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.

#### Combustion based systems

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 are currently available. The different applications can be divided into three main fields.

**Small-scale biomass combustion units** (capacity range <100 kW) are mainly applied for residential heating systems. Here, different types of pellet and wood chip burners, log wood boilers, wood stoves and fire-place inserts are commonly used. These systems mainly burn woody biomass fuels such as log wood, wood chips and pellets. The **medium capacity range** covers biomass heating and biomass combined heat and power (CHP) plants in the capacity range between 100 kW and about 10 MWth. Underfeed stokers, grate-fired furnaces

and dust burners are the main technologies applied in this capacity range. 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) production systems are of increasing importance. A number of CHP technologies such as Stirling engines, the ORC process, steam engines and steam turbines are therefore available.

The **large-scale range** (>10 MW<sub>th</sub>) mainly comprises CHP plants and power plants with thermal capacities up to some 100 MW based on grate-fired and fluidised bed combustion systems. 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. Finally it should be mentioned that **co-firing of biomass** fuels in large-scale coal fired power stations also offers an interesting option for biomass utilisation. Due to the large plant sizes and the high amount of biomass fired, co-firing offers great potential for CO<sub>2</sub> reduction in the short term if applied in existing power plants. A number of different technologies for direct co-firing as well as co-firing in separate units with junction of the steam have already proven their applicability in this field. 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.

#### **State-of-the-art of biomass combustion**

Combustion is the oldest biomass conversion technology and can look back on a long history. It took mankind many thousands of years, however, to develop really mature and ecologically friendly biomass combustion systems. During the past decades, steadily increasing requirements for the reduction of harmful emissions and the improvement of plant efficiencies and availabilities have led to extensive R&D in the following topics:

- Development of primary and secondary measures for emission reduction (CO, NO<sub>x</sub>, SO<sub>x</sub>, HCl, PAH, PCDD/F).
- Improvement of the degree of automation of biomass combustion systems.

- Improvement of the overall efficiency, reliability and availability of biomass combustion plants.

As a result of these R&D efforts environmentally sound, energy efficient and user friendly combustion systems are now available for a broad range of capacities and a wide spectrum of different biomass fuels.

On-going research mainly focuses on

- Further optimisation of process control strategies for small-scale combustion units.
- Utilisation of agricultural biomass fuels (grasses, crops) in small-scale combustion units.
- Development of CHP technologies for small- and medium-scale combustion systems.
- Further improvement of the efficiency and availability of large-scale combustion plants.
- Solution of ash related problems.

The most relevant issue of the different research fields mentioned above is the solution of problems related to the behaviour of ash forming elements during biomass combustion, which include slagging, deposit formation, corrosion, ash utilisation as well as particulate emissions. As biomass fuels are ash rich in comparison to oil and natural gas, ash related problems have a strong impact on the lifetime, availability and operation of biomass combustion systems and consequently are of great economic and ecological relevance. Due to their complexity these issues are still not solved, but great strides have already been made in understanding them and developing appropriate technological mitigation measures.

#### **Ash related problems in biomass combustion units**

Solid fuels (biomass as well as coal) generally contain a considerable amount of ash forming elements, which clearly distinguishes them from liquid and gaseous fossil fuels. Bottom ashes and fly ashes emitted with the flue gas are usually formed during combustion. The fly ash can be divided into coarse fly ashes and aerosols (particles with a diameter <1 μm). These ash fractions may cause both plant internal and emission problems.

Appropriate dust separation devices must be applied to meet current dust emission standards, which is not a problem for medium- and large-scale applications since highly efficient filter systems such as baghouse filters and electrostatic precipitators are economically affordable for these

# Ash formation in biomass combustion plants

installations. For small-scale biomass combustion systems, however, no highly efficient and economically sound dust precipitators are available on the market to date, which has led to significant R&D efforts in this field. This is of special importance since many European regions are currently facing severe air quality problems regarding fine particulate matter (especially PM<sub>10</sub>), and small-scale biomass combustion systems have already been identified as a major emission source together with industry and traffic.

Plant problems caused by ashes mainly include deposit formation, slagging and corrosion. Slagging, e.g. on the grate of a combustion system, may disturb the combustion process and in extreme cases even damage the grate. Deposit formation on boiler walls and tube surfaces reduces the heat transfer and thus the efficiency of combustion units. Severe deposit formation can also lead to the blocking of heat exchanger sections, necessitating unexpected plant shutdowns for deposit removal and boiler cleaning. Furthermore, deposits can be corrosive and may thus reduce the lifetime of the installations. Considerable R&D efforts are being made to find technological solutions for these problems, especially for large-scale combustion units using waste wood or herbaceous biomass fuels.

This paper presents the latest research results on ash and aerosol (fine particulate) formation and behaviour. The knowledge of these processes forms the basis for R&D regarding all relevant ash related problems mentioned above, and is therefore essential for the development of measures concerning the reduction of fine particulate emissions as well as concerning the reduction of deposit formation and corrosion problems in biomass furnaces and boilers.

As mentioned above, biomass fuels contain considerable quantities of ash forming elements in addition to their main organic constituents (C, H, O, N). The most important of these elements are Si, Ca, Mg, K, Na, S, Cl as well as heavy metals such as Zn and Pb. Table 1 shows typical compositions of the most commonly used solid biomass fuels. These data reveal extreme variations in ash content and ash composition between as well as within the different types of biomass fuels. Wood has a much lower ash content, for example, than bark, waste wood and herbaceous fuels.

table 1

Chemical composition of different solid biomass fuels

parameter	wood chips		bark		straw		waste wood (quality assorted)	
	mean	s	mean	s	mean	s	mean	s
ac wt. % d.b.	0.9	0.7	3.5	0.6	5.6	1.7	3.2	1.5
C wt. % d.b.	50.40	0.32	50.31	0.51	45.82	2.17	48.28	0.43
H wt. % d.b.	5.91	0.28	5.79	0.26	5.38	0.43	5.54	0.14
O wt. % d.b.	42.65		40.12		42.65		41.53	
N wt. % d.b.	0.12	0.02	0.24	0.20	0.58	0.83	1.40	0.53
S mg/kg d.b.	242	225	499	156	981	419	835	479
Cl mg/kg d.b.	56	28	202	52	3,597	3,945	696	430
Si mg/kg d.b.	1,317	854	3,936	2,417	14,791	6,321	4,068	2,343
Ca mg/kg d.b.	3,195	2,317	11,287	2,525	3,105	1,131	4,846	1,676
Mg mg/kg d.b.	395	256	1,351	391	867	590	994	464
K mg/kg d.b.	907	376	2,368	603	6,603	4,471	875	227
Na mg/kg d.b.	61	40	176	117	547	786	1,002	721
Zn mg/kg d.b.	35	29	115	26	23	25	405	151
Pb mg/kg d.b.	1.1	0.7	2.1	1.0	0.8	0.7	149.3	108.8
GCV MJ/kg d.b.	20.07	0.27	20.10	0.56	17.96	0.97	18.75	0.32

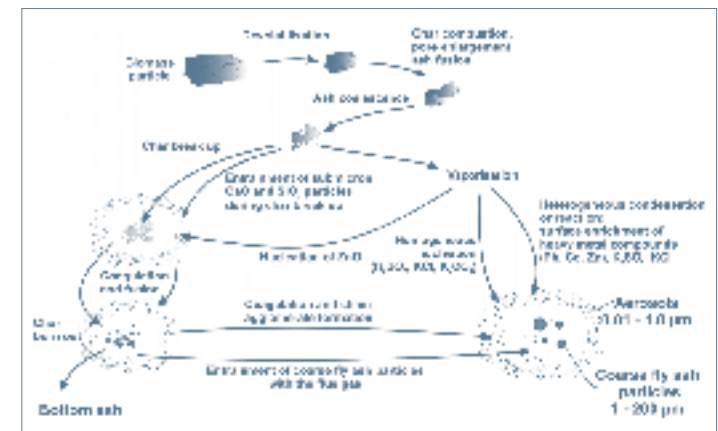
Explanations: ac ... ash content; d.b. ... dry basis (non ash free); GCV .. gross calorific value; mean ... mean value; s ... standard deviation; no standard deviation is given for O, since this value is calculated from the difference of the other main constituents

There are generally two sources for inorganic ash forming matter in biomass fuels. On the one hand, ash forming elements originate from the plant itself, as they are part of the structure of the fibres (e.g.: Si, Ca) or are macro or micro plant nutrients (e.g.: K, P, S, Zn). On the other hand, inorganic matter in biomass fuels can also come from contamination with soil, sand or stones. Coatings, paints, glass pieces and metal parts are major sources of contamination in waste wood. During the combustion of solid biomass fuels, the behaviour of ash forming elements follows a general scheme, which is depicted in figure 2. The following gives a brief description of the basic principles of ash formation during biomass combustion. A discussion of the detailed mechanisms relevant to aerosol formation will follow in the next section. 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 char combustion. During these steps the ash forming elements behave in two different ways according to their volatility. Non-volatile compounds such as Si, Ca and Mg are engaged in ash fusion as well as coagulation processes. Once the organic matter has been 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 on, due to supersaturation in the gas phase, these ash forming vapours start to nucleate (formation of submicron aerosol particles) or condense on surfaces of existing particles. The submicron particles are so-called aerosols and form one important fraction of the fly ashes. The second fly ash fraction is formed by small coarse ash particles from the fuel bed entrained with the flue gas. Depending on their particle size they are either precipitated from the flue gas in the furnace or boiler or are entrained with the flue gas forming coarse fly ash emissions. 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 the modelling of aerosol formation and therefore are a major issue in ongoing European research projects [8].

Another relevant issue is that almost complete combustion must be achieved regarding charcoal as well as flue gas burnout. Otherwise tars and hydrocarbons can also form aerosols by nucleation and condensation processes when the flue gas temperature decreases, causing a significant increase in aerosol emissions. In modern biomass combustion systems these organic emissions can be kept to a minimum using appropriate combustion and process control technologies and will therefore not be discussed in more detail in this paper. Nevertheless, organic fly ash emissions can be a concern in old biomass combustion devices [8, 9, 10].

figure 2

Ash formation during biomass combustion





# Coarse fly ashes and aerosols

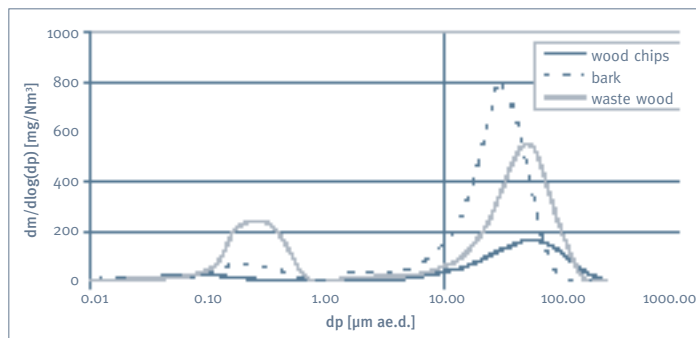
## Coarse fly ashes and aerosols – particle size distributions and concentrations in the flue gas

As explained above, the fly ash consists of aerosols and coarse fly ashes. The formation pathways and the particle sizes of these two fractions are completely different.

The particle size distribution of coarse fly ashes at boiler outlet is typically in the range of some  $\mu\text{m}$  to about  $200 \mu\text{m}$  with a distribution peak at about  $30$  to  $70 \mu\text{m}$  (see also figure 3) [11]. The exact shape of the particle size distribution curve as well as its peak depend on the fuel, the geometry of the furnace and the particle precipitation in the different furnace and boiler sections. The mass of coarse fly ashes at boiler outlet can range between some  $\text{mg}/\text{Nm}^3$  up to more than  $1,000 \text{ mg}/\text{Nm}^3$  depending on different parameters like for instance the ash content of the fuel, the load and the operating conditions of the combustion unit (see next section).

figure 3

Particle size distribution of coarse fly ashes and aerosols



Explanations: dp ... particle diameter; ae.d. ... aerodynamic diameter; data related to dry flue gas and 13 vol.%  $\text{O}_2$ , results from measurements at boiler outlet of a grate-fired combustion unit; aerosol measurements performed with a low-pressure cascade impactor; coarse particle sampling carried out with a cyclone and subsequent analysis of the particle size distribution using a sedimentation method

The typical particle size range of aerosols is  $<1 \mu\text{m}$ . The mass mean diameter of the particle size distribution is usually in a range between  $0.1$  and  $0.5 \mu\text{m}$  and increases with increasing aerosol mass as a result of coagulation effects. The concentration of aerosols in the flue gas depends on the amount of aerosol forming elements released from the fuel during combustion. Typical values are  $20 - 50 \text{ mg}/\text{Nm}^3$  for softwood,  $50 - 100 \text{ mg}/\text{Nm}^3$  for hardwood and bark as well as  $>100 \text{ mg}/\text{Nm}^3$  for straw and waste wood (all data related to dry flue gas and 13 vol.%  $\text{O}_2$ ) [12].

It can clearly be seen that coarse fly ash and aerosol formation differ significantly when using different biomass fuels. The reasons as well as the parameters influencing the formation and behaviour of these two fly ash fractions are explained in the following sections.

Both fractions must always be considered, however, in regard to ash related problems in biomass combustion units, because they either both contribute to these problems or influence each other during their formation process.

## Coarse fly ashes

### Formation and influencing parameters

During combustion, ash particles and charcoal particles are entrained from the fuel bed with the flue gas. These particles form the coarse fly ash fraction. Particles which are too large to follow the flow patterns of the flue gas in the furnace are precipitated by impaction on furnace walls or by gravitational settling. Entrained charcoal particles undergo combustion processes and should reach a complete burnout before the flue gas enters the convective boiler section. In modern biomass combustion systems, the amount of organic carbon in the fly ash is usually well below 5 wt.% (d.b.), which is an important guiding value for complete combustion.

The remaining coarse fly ash particles enter the heat exchanger section where again precipitation and impaction of particles on boiler tube surfaces take place.

The particles which pass the heat exchanger section are emitted with the flue gas and form the coarse fly ash emissions (right hand peak in figure 3).

Consequently, the concentrations of coarse fly ashes in the flue gas increase with increasing disturbance of the fuel bed, which means e.g.

- increasing load of the combustion unit,

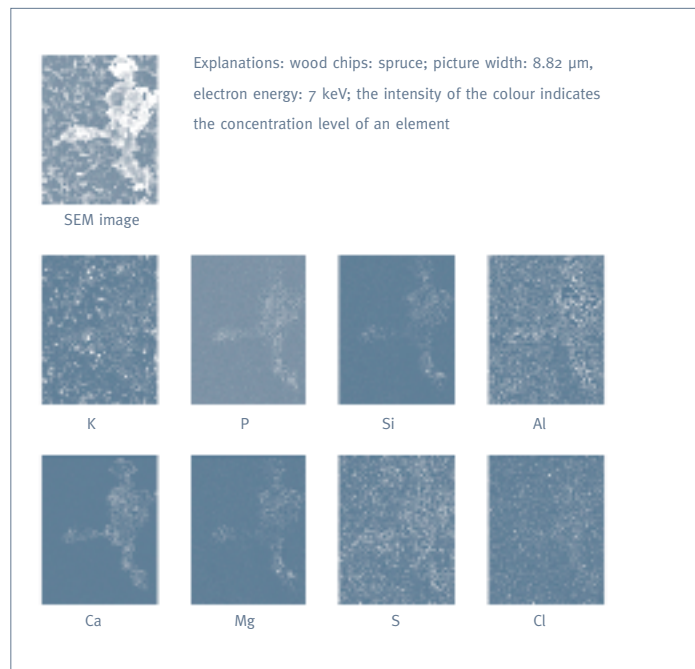
- uneven distribution of the primary combustion air flow over the fuel bed (in fixed-bed combustion systems),
- uneven distribution of the fuel over the fuel bed (in fixed-bed combustion systems).

Furthermore, coarse fly ash emissions usually increase with increasing ash content and decreasing particle size of the fuel. Furnace designs providing areas with low flue gas velocities or sharp turns of the flue gas duct can, however, help to enhance coarse fly ash precipitation in the furnace and thereby decrease emissions.

Finally the combustion technology itself also influences the coarse fly ash emissions. Dust injection burners or fluidised bed incinerators, where the combustion concept is based on the dispersion of the fuel in a gas flow, show significantly higher fly ash emissions than fixed-bed systems such as grate-fired furnaces and underfeed stokers.

figure 4

SEM image and X-ray mapping images of a coarse fly ash particle and aerosols from wood chip combustion in a grate furnace

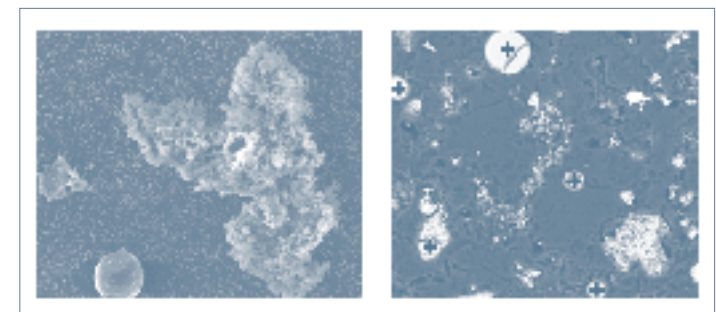


#### Structure and chemical properties of coarse fly ashes

figure 4 shows an image of a typical coarse fly ash particle surrounded by aerosols sampled during spruce combustion on a polycarbonate filter. Coarse fly ash particles sampled during bark (left image) and waste wood (right image) combustion are presented in figure 5. The images were taken with a scanning electron microscope (SEM). Figure 4 also shows x-ray mapping images obtained by energy dispersive x-ray spectrometry (EDX). The data in figure 4 clearly indicate that the coarse fly ash particle mainly consists of Ca, Mg, P, Si and Al, while the surrounding aerosols are mainly formed by K, S and Cl. The main ash matrix elements (Si, Ca, Mg) are usually bound as oxides, but also phosphates and sulphates are formed. Coarse fly ashes provide surfaces for the condensation of ash forming vapours during their passage through the boiler sections, and their surfaces can therefore be enriched with alkaline and heavy metal salts.

figure 5

SEM image of coarse fly ash particles from bark and waste wood combustion in a grate furnace



Explanations: bark (left image): particle sampling with polycarbonate filter, picture width: 38.2  $\mu\text{m}$ ; waste wood (right image): particle sampling with a cyclone; particles embedded in resin, the resin block was cut and subsequently polished, picture width: 110  $\mu\text{m}$

#### Aerosols

##### Formation and influencing parameters – general aspects

The formation pathway of aerosols is much more sophisticated. As mentioned above, aerosols are formed by gas-to-particle conversion processes of ash forming vapours, which have been released from the fuel during combustion. Consequently, the concentration of aerosol forming elements in a fuel, or more precisely, the release of aerosol forming

elements from the fuel during combustion, is the most relevant parameter for aerosol formation. Aerosol formation cannot be influenced to a relevant extent by primary measures using state-of-the-art plant designs and process control strategies.

Results from recent research have shown [11, 12], however, that different aerosol formation pathways can be defined for different types of biomass fuels. The following section gives a short characterisation of aerosol particles from biomass combustion to provide a better understanding of the subsequent detailed discussion of aerosol formation mechanisms.

#### Structure and chemical properties of aerosols

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 6 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. Carbonates are formed if there is not enough S and Cl available to bind all the K and Na released from the fuel. This behaviour is confirmed by the results of the EDX analyses presented in figure 6.

Additionally, easily volatile heavy metals such as Zn and Pb 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 [11, 12, 16].

Figure 6 also shows, however, that non-volatile compounds such as Ca can also be found in the submicron aerosol fraction. This phenomenon, which is generally in contradiction with the classic aerosol formation theories based on gas-to-solid phase transition, is discussed in the next section.

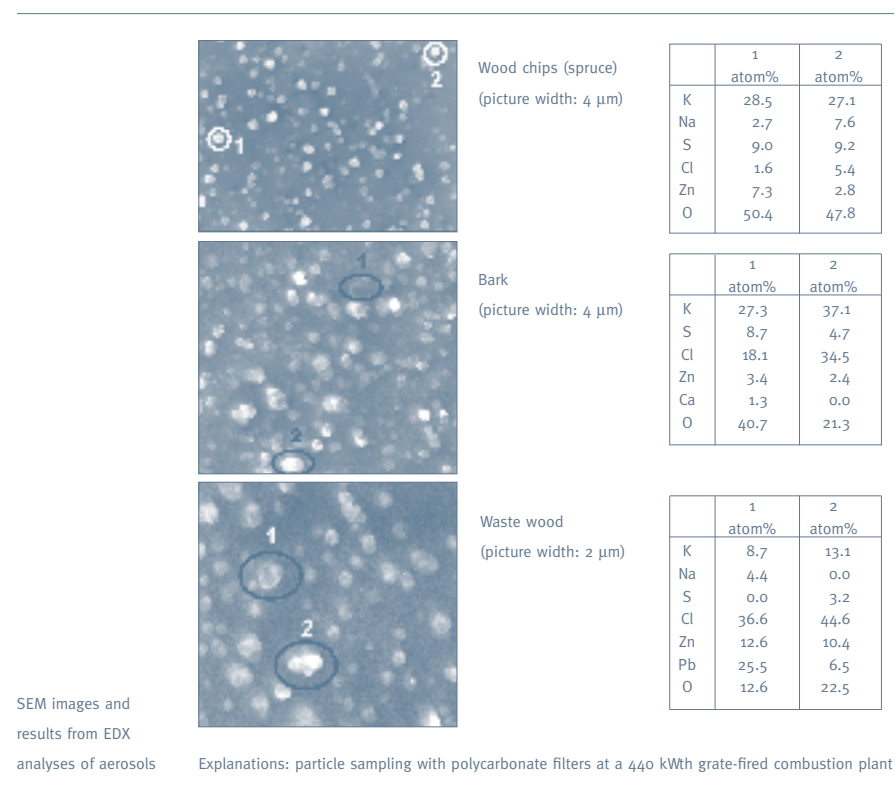


figure 6

#### Detailed aerosol formation pathways

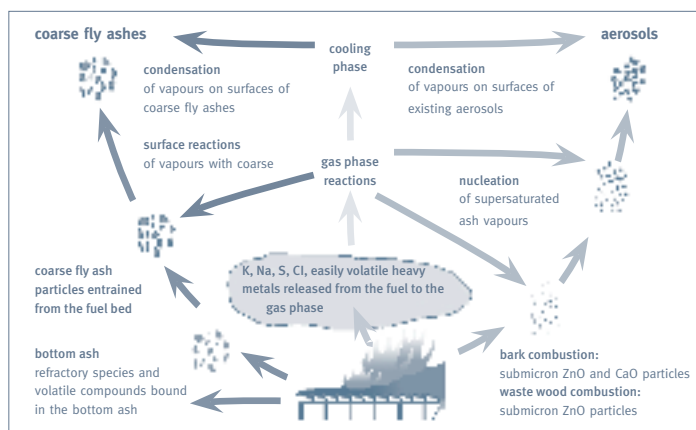
In order to investigate aerosol formation processes in fixed-bed combustion units, the Institute for Resource Efficient and Sustainable Systems, Graz University of Technology, performed a considerable number of test runs in biomass combustion plants equipped with different furnace and boiler technologies using a broad range of solid biomass fuels [12, 16, 17].

The particle size distributions of aerosols downstream of the boiler as well as the chemical compositions and shapes of the particles have thus been determined. The results and experiences gained from these test runs as well as theoretical considerations provided the basis for postulating different aerosol formation processes for different biomass fuels, which are discussed in the following and are summarised in figure 7.

The first step of aerosol formation in biomass combustion processes is always the release of aerosol forming elements from the fuel. K, Na, S, Cl as well as easily volatile heavy metals such as Zn and Pb are released from the fuel bed to the gaseous phase. These elements subsequently undergo homogeneous gas phase reactions. The most important compounds formed are K and Na chlorides and sulphates. As soon as the partial pressure of a single compound exceeds the saturation pressure, which can be due to a high formation ratio of the specific compound, due to different thermodynamic properties of a new compound formed or due to the cooling of the flue gas, gas-to-particle conversion takes place. This can happen either by homogeneous nucleation (the formation of aerosol particles) or condensation of these vapours on existing surfaces (see also figure 2). These surfaces can either be other particles (aerosols or coarse fly ashes) or, e.g., boiler tubes. Nucleation and condensation are always competing processes, which means that if the existing particles provide enough surface area, nucleation might be suppressed and the dominating process is then particle growth by condensation. Once particles have been formed, however, they start to coagulate due to Brownian motion, diffusion and turbulent impaction. The typical particle size distribution of the aerosol fraction measured at boiler outlet thus depends on the time-temperature profile of the biomass combustion plant.

figure 7

Fly ash and aerosol formation pathways in fixed-bed combustion systems

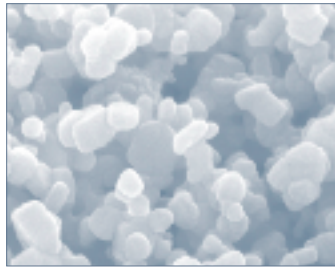


The mechanism explained usually prevails during the combustion of chemically untreated wood chips and straw, where K, Na, S and Cl are the dominating elements involved in aerosol formation. This formation pathway has been confirmed by the shape and chemical composition of the aerosols sampled at boiler outlet and results from theoretical modelling of the aerosol formation process [12, 15].

Zn-rich fuels (such as bark and especially waste wood) make aerosol formation more complex, which is mainly due to the exceptional position of Zn within aerosol formation. Under reducing conditions, as commonly prevalent in the fuel bed of a fixed-bed biomass furnace, elemental Zn can be released to the gas phase. As soon as the vapour pressure of oxygen rises, Zn is oxidised into ZnO. Since the saturation pressure of ZnO is low, ZnO nucleation takes place immediately, resulting in the formation of particles in a size range of some nm. This process is assumed to happen directly after the ash vapours have left the fuel bed. The higher the concentration of Zn in a fuel, the higher the relevance of this ZnO particle formation step for all subsequent processes, because the ZnO particles provide a large surface area for the condensation of ash forming vapours. Especially during waste wood combustion, the amount of ZnO particles can be so high that subsequent formation of aerosols by nucleation of other vapours (e.g.: KCl, K<sub>2</sub>SO<sub>4</sub>) is totally suppressed by condensation on the ZnO surfaces. As a result, particle formation takes place immediately above the fuel bed (in the primary combustion zone) when burning Zn-rich fuels, while the combustion of biomass fuels with low Zn concentrations is supposed to result in nucleation of ash forming vapours upon cooling of the flue gas (in the boiler section). This behaviour has been confirmed by measurements with a newly developed high-temperature low-pressure impactor (HT-LPI), which was specially designed for the purpose of taking particle samples directly from the hot furnace at temperatures up to 1,100°C in order to get more insight in particle formation processes [11]. Figure 8 shows a SEM image as well as EDX analyses of aerosol particles sampled with this new impactor upstream of the boiler inlet. The results of the EDX analyses clearly indicate that at this position, ZnO particles have already been formed but almost no nucleation or condensation of alkaline compounds has occurred.

# Summary and conclusions

SEM image and results from EDX analyses of particles sampled with a high-temperature low-pressure impactor



Zn	93.6 wt. %
Si	2.4 wt. %
K	1.4 wt. %
S	1.1 wt. %
Fe	0.5 wt. %
Ca	0.5 wt. %
P	0.3 wt. %
Al	0.2 wt. %

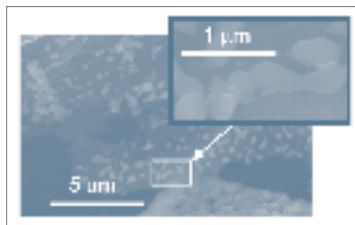
SEM picture width: 1.1  $\mu\text{m}$ ; particle sampling took place in the secondary combustion zone of a grate-fired combustion unit at a temperature of about 1,100°C; fuel: waste wood; analytical results normalised to 100% without oxygen

figure 8

Another process relevant to aerosol formation during bark combustion was investigated in connection with the high Ca concentration in bark (see figure 6). SEM/EDX analyses of aerosols from bark combustion have shown that they contain CaO particles in a size range  $> 0.3 \mu\text{m}$ . Since Ca cannot be evaporated under the conditions prevailing in a fixed biomass bed, another mechanism must be responsible for the formation of these particles. SEM/EDX analyses of fuel bed chars from bark combustion indicate that the char contains Ca structures consisting of submicron and almost spherical CaO particles (see figure 9) [18, 19]. It can therefore be assumed that CaO particles from these structures are entrained from the fuel bed due to thermal defragmentation within the process of char combustion. These particles can then act as seeds for surface condensation of other ash forming vapours.

figure 9

SEM image and EDX analyses of a charcoal particle from bark combustion



	atom%
Ca	33
K	24
Mg	2
Mn	1
Cl	1
O	39

Explanations: grate combustion; analytical results excluding C

A comprehensive characterisation of aerosols and coarse fly ashes formed during biomass combustion is now available as a result of the extensive research carried out during the past decade. These data have provided the basis for identifying the formation mechanisms of aerosols and coarse fly ashes.

With respect to the formation of coarse fly ashes, it has been shown that the application of a state-of-the-art combustion system enabling an even distribution of the fuel and the combustion air over the grate may help to reduce particle emissions in fixed-bed furnaces. Furthermore, appropriate fuel preparation and storage measures for the reduction of mineral impurities will also help to decrease coarse fly ash formation. Due to their comparatively large particle sizes (between some  $\mu\text{m}$  and about 200  $\mu\text{m}$ ) coarse fly ashes can easily be precipitated from the flue gas with cyclones and multi-cyclones, but the reduction of coarse fly ash formation may be of relevance with respect to the reduction of deposit formation in furnaces and boilers.

In case of a complete combustion aerosols are formed by gas-to-particle conversion of ash forming vapours. However, if no complete combustion is achieved, aerosols can also originate from condensation of gaseous organic compounds (tars, hydrocarbons). Particle precipitation as well as deposit formation are important issues in regard to aerosols. The small particle sizes of significantly less than 1  $\mu\text{m}$  require highly sophisticated dust separation devices for emission control. Furthermore, aerosols contribute to deposit formation and may contribute to corrosion.

The research results on aerosol formation clearly indicate that the fuel used is the governing parameter for the mass of aerosols formed during biomass combustion. The K, Na, S, Cl, Zn and Pb concentrations in the fuel determine the mass of aerosol emissions as well as their chemical compositions. Consequently, the amount of aerosols formed during combustion can be ranked as following: softwood < hardwood < bark < waste wood and straw.

The experiences and results of the test runs and the application of a newly developed aerosol formation model revealed different formation mechanisms depending on the chemical composition of the biomass



fuels. The nucleation of K sulphate and chlorine vapours is the most important particle formation mechanism in the combustion of chemically untreated wood and straw. CaO particles released from the fuel as well as ZnO particles formed directly above the fuel bed influence aerosol formation during bark combustion by providing additional surface area for the condensation of K compounds. The high Zn concentrations in waste wood lead to the formation of a large number of ZnO particles in the flue gas right above the fuel bed, which usually provide sufficient surface area to suppress nucleation of ash forming vapours by surface condensation.

As the different formation mechanisms indicate, the first steps of aerosol formation may occur in different furnace and boiler regions depending on the fuel used. While aerosol formation during waste wood combustion starts right above the fuel bed, particle formation during the combustion of chemically untreated wood and straw is assumed to occur during the cooling phase in the boiler. These results concerning the different pathways of aerosol formation and the properties of aerosols formed during biomass combustion are to be used in the

future to develop more sophisticated models for deposit formation in furnaces and boilers, which combine aerosol formation modelling and computational fluid dynamics (CFD).

However, there is still a lack of reliable data and models describing the release behaviour of aerosol forming species from the fuel, which are of relevance for the modelling of aerosol formation. At the moment, aerosol formation can only be predicted if release data from measurements are available, which is usually not the case, and therefore assumptions concerning the initial conditions for aerosol formation must be made. Future research should therefore focus on the development of models which are able to describe the release of ash forming elements from the fuel in order to increase the prediction accuracy of aerosol formation modelling.

Finally it should be mentioned that it is well known, that the impact of particulates on the human organism increases with decreasing particle size. Consequently, aerosols are predestined to contribute to health risks. However, actually no detailed information about the health risks of aerosols from biomass combustion compared with fine particulate emissions from other sources are available. In this field a high demand for additional research is given.

The knowledge about the formation pathways and chemical compositions of aerosols formed during the combustion process, significantly contributes to a better understanding of the mechanisms involved in deposit formation and corrosion processes in biomass boilers. By combining advanced fuel characterisation tools with the knowledge available concerning aerosol and fly ash formation, models to predict the risks for deposit formation and corrosion can be worked out with respect to the fuels used in a combustion unit, and appropriate measures to reduce these ash related problems can be considered already during the design phase of a plant.

## Aims and objectives for my work at TU/e

My main aims and objectives for my work as a part-time professor for “Thermochemical Biomass Conversion” in the Department of Mechanical Engineering at Technische Universiteit Eindhoven (TU/e) are the following:

First of all I would like to strengthen and improve the knowledge and competence in the field of “Thermochemical Biomass Conversion” at TU/e by supplying expertise and experience in this field, which I have gained through my work at Graz University of Technology and the engineering company BIOS BIOENERGIESYSTEME GmbH in Graz over the past 10 years.

A lecture entitled “Thermochemical Biomass Conversion” has been established at TU/e in the course of my appointment. This lecture aims at the education of students in this new and important field of energy utilisation from solid biomass and at the initiation and supervision of internships and MSc theses in this working area.

Another focus of my work will be the co-ordination and further development of R&D activities and the support of ongoing activities in the field of thermochemical conversion of solid biomass in the Division of Thermo Fluids Engineering at TU/e. Within this aim, international and national R&D projects covering MSc and PhD thesis work will be carried out.

In addition, I am committed to improving the co-operation between TU/e and interested companies active in the field of thermochemical biomass conversion (on an international level). Drawing on my background in basic and applied research, development and the demonstration of new technologies (as a first step towards market introduction), my aim is to establish strong links between the university and industry in order to cover the entire development chain from basic research through to the demonstration of new developments.

An important step towards this goal is the participation of TU/e in the Austrian Bioenergy Centre, an Austrian Centre of Competence, where scientific and industrial partners (on an international basis) carry out joint R&D projects in the field of “Thermal Biomass Utilisation”.

Finally, I would like to strengthen the co-operation and the utilisation

of synergies between TU/e and Graz University of Technology in Austria through my work at both institutions. Examples of how this objective is being achieved are ongoing student exchanges, joint (international) R&D projects and the shared use of laboratory and measurement equipment. This international co-operation between universities will be of increasing importance in the near future and is also supported by the EU.

## Acknowledgement

First and foremost I would like to thank the Executive Board of Technische Universiteit Eindhoven (TU/e) for my appointment as part-time professor for “Thermochemical Biomass Conversion” in the Department of Mechanical Engineering. It was a great honour for me to accept this appointment.

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## Curriculum Vitae



**Prof.Dipl.-Ing.Dr.Ingwald Obernberger has been appointed part-time professor at Technische Universiteit Eindhoven (TU/e) for “Thermochemical Biomass Conversion” in the department of Mechanical Engineering as of June 1st 2003.**

Prof.Dipl.-Ing.Dr.Ingwald Obernberger (1962) graduated from Graz University of Technology in Austria (GUT), where he completed his PhD with distinction in 1994. Since then he has been Managing Director of the engineering company BIOS BIOENERGIESYSTEME GmbH and Head of the *Thermal Biomass Utilisation Group* at the Institute for Resource Efficient and Sustainable Systems (GUT), where he since 1995 has lectured on *Thermal Biomass Utilisation*. His appointments include scientific adviser to the European Commission, DG TREN, section Biomass and Waste, since 1996; Assistant Professor for *Environmental and Energy Engineering* at GUT, since 1997; Austrian representative in the International Energy Agency (IEA), Bioenergy Agreement, TASK 32, *Biomass Combustion and Cofiring*, since 1998; and member of the editorial board of the international scientific journal *Biomass and Bioenergy*. Since June 2003 he has been Professor (part-time) for “Thermochemical Biomass Conversion” at TU/e and key researcher at the Austrian Bioenergy Centre, Graz.

Moreover, Prof.Dipl.-Ing.Dr.Ingwald Obernberger is coordinator of several national and international R&D projects in the field of thermal biomass utilisation and author of a considerable number of scientific publications. His main research areas are the characterisation of the physical and chemical properties of biomass fuels and ashes, ash related problems in biomass combustion plants, the development of biomass furnace and flue gas cleaning technologies, the simulation of reacting flows in the gas phase of fixed bed biomass furnaces and boilers as well as the development of innovative small-scale biomass CHP technologies.

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