Project no. SES-CT-2003-502679

BIOASH

Ash and aerosol related problems in biomass combustion and co-firing

Specific Targeted Research Project

Priority 6.1.ii; Sustainable energy systems: M-L Term

Thematic Area 6.1.3.2.3, New and advanced concepts in renewable energy technologies

Publishable final activity report

Period covered: 01/03/2004 to 28/02/2007 Date of preparation: 14/04/2007

Start date of project: 01/03/2004 Duration: 36 months

Project coordinator name: Prof. DI. Dr. Ingwald Obernberger

Project coordinator organisation name:
Graz University of Technology, Institute for Resource Efficient and Sustainable Systems
Tel.: +43 316 48130012; Fax: +43 316 4813004; email: ingwald.obernberger@tugraz.at

Table of Contents

1 PROJECT EXECUTION

1.1 Objectives of the project

The main aim of the BIOASH project was to investigate still remaining ash related problems in biomass combustion and biomass and coal co-firing systems. Therefore, BIOASH aimed at the investigation of the release behaviour of ash forming compounds from biomass fuels in fixed-bed and in pulverised fuel combustion systems and on the determination of missing thermodynamic data as a basis for investigations concerning aerosol and deposit formation. Furthermore, the project focused on research regarding advanced models for a more precise prediction of aerosol and deposit formation with respect to the release behaviour of ash forming elements from the fuel. As a third main aim of BIOASH, a new technology for cost effective and efficient aerosol precipitation in small-scale biomass combustion units was developed. Moreover, the contribution of biomass combustion and co-firing to concentrations of particulates in the ambient air were studied and a detailed evaluation of the effects of these particulates on the human organism was performed.

The BIOASH project focused on fixed-bed combustion and on combustion in pulverised fuel systems, as they are usually applied in co-firing applications.

In detail the objectives of the BIOASH project were:

- Investigations concerning the release of ash forming species from selected biomass fuels during fixed-bed and pulverised fuel combustion.
- Determination of basic thermodynamic data concerning the melting behaviour of ash mixtures containing Na, Zn, and Pb as well as the determination of the viscosity of molten ash deposits. These data were not available at the beginning of the project but have been identified as crucial within former projects.
- Further development of existing computer aided simulation tools regarding the formation of aerosols during biomass combustion, taking special account of element release from the fuel and the effects of transport properties caused by turbulence.
- Development of new codes for the simulation of deposit build-up and deposit properties with relation to the combustion of different solid biomasses, mixtures of biomasses, and co-firing of biomass and coal.
- Studies of the influence of the co-firing of biomass in coal combustion plants with special emphasis on aerosol and deposit formation as well as deposit melting behaviour. This objective aims at a better understanding of the interactions between ashes from coal and biomass combustion in order to find technical solutions to increase the co-firing ratios of biomass in coal combustion plants.
- Development, test and optimisation of a new, efficient and economically sound aerosol precipitation technology concerning the reduction of aerosol emissions from small-scale biomass combustion units.
- Investigation of the contribution of typical biomass combustion and biomass co-firing applications to ambient air pollution by particulates. Furthermore, the identification of parameters influencing the effects of particulate emissions on the human organism was an aim. Based on these investigations a better basis for the ecological evaluation of particulate emissions from the combustion of biomass fuels was derived.

The investigations concerning the objectives mentioned above were based on laboratory tests, the performance of test runs at pilot-scale and real-scale biomass combustion and co-firing plants as well as on theoretical mathematical modelling. In this context, the test runs at pilot-scale and real-scale applications were used to gain substantial high quality data for the calibration and the validation of the models developed. Woody biomass fuels (wood, bark, waste wood) as well as straw were considered. Concerning biomass co-firing in coal fired power stations sawdust was investigated.

1.2 The BIOASH-consortium

The work performed within BIOASH was based on the co-operation of a consortium which comprises a well balanced mix of research institutes and industrial partners, covering all aspects which were relevant to reach the aims of the project.

Coordinator

Graz University of Technology
Institute for Resource Efficient and Sustainable Systems (TUG)
Inffeldgasse 21b, 8010 Graz, Austria
Contact: Prof. Dipl.-Ing. Dr. Ingwald Obernberger
Tel.: +43 316 48130012; Fax: +43 316 4813004; email: ingwald.obernberger@tugraz.at

Contractors

- Technical University of Denmark, Department of Chemical Engineering, Denmark (DTU)
- Abo Akademi University, Department of Chemical Engineering, Combustion Chemistry Research Group, Finland (AAU)
- Eindhoven University of Technology, Faculty of Mechanical Engineering, Section Process Technology, the Netherlands (TUE)
- Energy Research Centre of the Netherlands, the Netherlands (ECN)
- Institute of Power Engineering, Thermal Processes Department, Poland (IEn)
- Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V., Institute of Toxicology and Experimental Medicine, Germany (FHGITEM)
- Mitsui Babcock Energy Ltd., United Kingdom (MB)
- Standardkessel GmbH, Germany (SKG)
- MAWERA Feuerungsanlagen GmbH, Austria (MAW)

1.3 Work performed and end results achieved

1.3.1 The BIOASH fuels

The BIOASH project focused on investigations concerning different biomass fuels as well as coals. Table 1 shows the fuels which were defined as the BIOASH-fuels as well as the identifiers used for the respective fuel. Table 2 gives an overview over the chemical compositions of the BIOASH-fuels used for laboratory tests. For real-scale test runs, however, some deviations from the shown compositions occurred.

Table 1: BIOASH-fuels

BIOASH-FUELS	
fuel	identifier
bark (spruce)	BM1
wood chips (spruce)	BM2
waste wood (quality A1-A2)	BM3
sawdust	BM4
olive residues	BM5
straw (wheat)	BM6
coal (from Poland)	C1
coal (from the UK)	C2

Table 2: Chemical composition of the BIOASH-fuels

Explanations: w.b. … wet base; d.b. … dry base; std.dev. … standard deviation

		bark BM1		**wood chips BM2**		**waste wood BM3**		**saw dust BM4**	
		mean	std.dev.	**mean**	std.dev.	**mean**	std.dev.	**mean**	std.dev.
moisture	wt.% (w.b.)	**46.99**		**40.03**		**15.92**		**51.90**	
ash	wt.% (d.b.)	**4.90**	0.43	**0.50**	0.04	**1.60**	0.17	**1.73**	0.37
C	wt.% (d.b.)	**49.90**	0.98	**48.71**	1.59	**48.24**	1.69	**49.69**	1.14
H	wt.% (d.b.)	**5.84**	0.06	**6.15**	0.09	**6.14**	0.06	**6.04**	0.19
N	wt.% (d.b.)	**0.46**	0.05	**0.08**	0.01	**0.86**	0.21	**0.17**	0.03
Ca	mg/kg (d.b.)	**13,196**	1,166	**1,189**	87	**3,051**	216	**1,247**	171
Si	mg/kg (d.b.)	**3,866**	774	**380**	60	**1,295**	394	**5,282**	982
Mg	mg/kg (d.b.)	**781**	105	**165**	23	**365**	35	**238**	30
K	mg/kg (d.b.)	**2,493**	128	**425**	11	**902**	24	**680**	55
Na	mg/kg (d.b.)	**103**	19	**32**	6	**433**	60	**84**	14
Zn	mg/kg (d.b.)	**83.5**	7.4	**9.2**	0.9	**212.7**	19.3	**9.8**	0.5
Mn	mg/kg (d.b.)	**428**	25	**167**	8	**70**	4	**90**	11
Pb	mg/kg (d.b.)	**1.3**	0.2	**0.4**	0.1	**116.4**	14.4	**0.8**	0.2
S	mg/kg (d.b.)	**369**	40	**62**	10	**503**	85	**212**	72
Cl	mg/kg (d.b.)	**165**	23	**79**	25	**591**	71	**112**	40
P	mg/kg (d.b.)	**361**	24	**67**	9	**75**	18	**72**	14
Fe	mg/kg (d.b.)	**377**	63	**75**	16	**222**	20	**247**	57
Al	mg/kg (d.b.)	**616**	107	**102**	16	**274**	27	**666**	134
Ti	mg/kg (d.b.)	**35.9**	5.5	**6.5**	1.9	**387.2**	196.7	**36.6**	19.8

		olive residues BM5		**wheat straw BM6**		**coal (Poland) C1**		**coal (UK) C2**	
		mean	std.dev.	**mean**	std.dev.	**mean**	std.dev.	**mean**	std.dev.
moisture	wt.% (w.b.)	**13.68**		**11.21**		**3.56**		**7.08**	
ash	wt.% (d.b.)	**8.86**	0.68	**8.21**	0.49	**18.92**	0.33	**7.29**	0.09
C	wt.% (d.b.)	**48.39**	0.93	**44.71**	0.78	**64.79**	1.74	**74.10**	2.11
H	wt.% (d.b.)	**5.81**	0.13	**5.83**	0.05	**4.02**	0.12	**4.66**	0.32
N	wt.% (d.b.)	**1.45**	0.13	**0.59**	0.10	**1.15**	0.04	**1.60**	0.08
Ca	mg/kg (d.b.)	**7,953**	1,063	**3,483**	139	**7,934**	382	**2,302**	104
Si	mg/kg (d.b.)	**5,006**	871	**20,186**	2,259	**41,601**	1,923	**13,361**	2,243
Mg	mg/kg (d.b.)	**2,358**	401	**396**	24	**4,527**	246	**727**	36
K	mg/kg (d.b.)	**26,631**	3,092	**14,953**	700	**3,887**	99	**1,370**	65
Na	mg/kg (d.b.)	**263**	16	**61**	14	**1,403**	45	**1,672**	53
Zn	mg/kg (d.b.)	**15.8**	2.0	**9.2**	0.7	**28.7**	3.8	**15.0**	3.6
Mn	mg/kg (d.b.)	**28.9**	4.5	**11.3**	1.1	**210.4**	7.5	**57.6**	2.0
Pb	mg/kg (d.b.)	**1.9**	0.4	**0.4**	0.0	**15.4**	1.3	**11.4**	1.2
S	mg/kg (d.b.)	**1,469**	136	**1,410**	56	**6,014**	391	**13,151**	1,010
Cl	mg/kg (d.b.)	**2,460**	352	**5,625**	754	**2,405**	255	**5,533**	732
P	mg/kg (d.b.)	**1,846**	189	**649**	83	**351**	40	**204**	26
Fe	mg/kg (d.b.)	**1,123**	156	**168**	39	**10,319**	218	**6,655**	1,080
Al	mg/kg (d.b.)	**1,239**	151	**116**	9	**21,217**	480	**8,942**	1,402
Ti	mg/kg (d.b.)	**69.5**	8.6	**7.5**	1.0	**1,087.0**	34.9	**445.1**	17.3

The BIOASH fuels have been selected in order to achieve a broad variety of different chemical compositions concerning ash forming elements. Accordingly the data presented in Table 2 show the following differences respectively similarities.

In wood fuels (BM1, 2, 3 and 4) Ca usually is the most relevant ash forming element followed by Si. BM4 however shows an exception from this tendency which might most probably be due to considerable contents of mineral impurities (sand). Regarding the alkaline metals, which are of special relevance for the BIOASH project, the K content increases from wood chips over sawdust and waste wood to bark. The Na concentrations increase from wood chips over sawdust and bark to waste wood. The same behaviour can be stated for Zn and Pb as well as for S and Cl.

Contrary to wood fuels, straw is dominated by Si. Additionally, the K, P, S and Cl concentrations are significantly higher than in wood fuels while the heavy metals Zn and Pb show lower concentrations.

Olive residues represent an extreme case concerning the K-concentrations. While the Ca and Si contents are comparable with the upper range of these elements in wood fuels, the S and Cl concentrations are significantly higher (in the range of straw). Moreover, olive residues show the highest P contents of all biomass fuels investigated. The same is true for the Fe and Al contents.

Coal significantly differs from biomass. In contrast with biomass considerable amounts of Si, Fe and Al can be found. The Cl contents are in the range of straw and therefore significantly higher than in wood fuels while the S concentrations are significantly higher than in all biomass fuels analysed. Significant differences concerning the concentration levels of almost all ash forming elements between the coal from Poland and the coal from the UK additionally must be mentioned.

A database including all analyses results achieved from the characterisation of the BIOASH-fuels has been set up during the first project year and has been supplemented during the project. This comprehensive data compilation has been used by all partners as a basis for various test runs.

1.3.2 WP 1: Release behaviour of ash forming elements from the fuels investigated

The overall objective of WP 1 was to quantify the transformation and the release of aerosol forming elements such as K, Na, S, Cl, Zn and Pb from biomass fuels as a function of biomass type and local conditions.

The investigations performed within WP 1 were based on three different but interlinked approaches:

- fuel characterisation by novel analyses methods (chemical fractionation, SEM/EDX),
- the performance of release tests at lab-scale reactors (fixed-bed combustion, pulverised fuel systems),
- thermodynamic equilibrium modelling.

Chemical fractionation analyses of selected fuels

Detailed elemental analyses and predictions of the element behaviour under different conditions can be achieved if the ash forming elements are analysed directly from the original fuel by selective leaching in comparison to the results of the total amount of elements contained in the fuel. In this case the solvents H_2O, ammonium acetate, and HCl were applied. The two first solvents are mild and they dissolve alkali sulphates/chlorides and carbonates. However, the second solvent, which is a buffer solution, functions also as an ion-exchanger and thus may also dissolve organically bound elements.

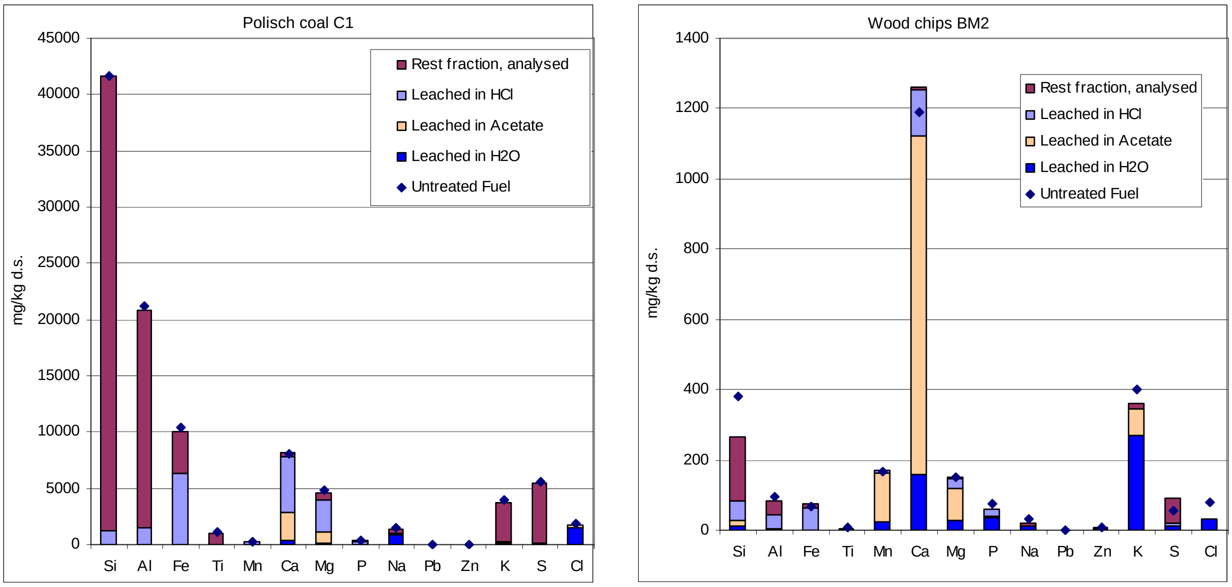


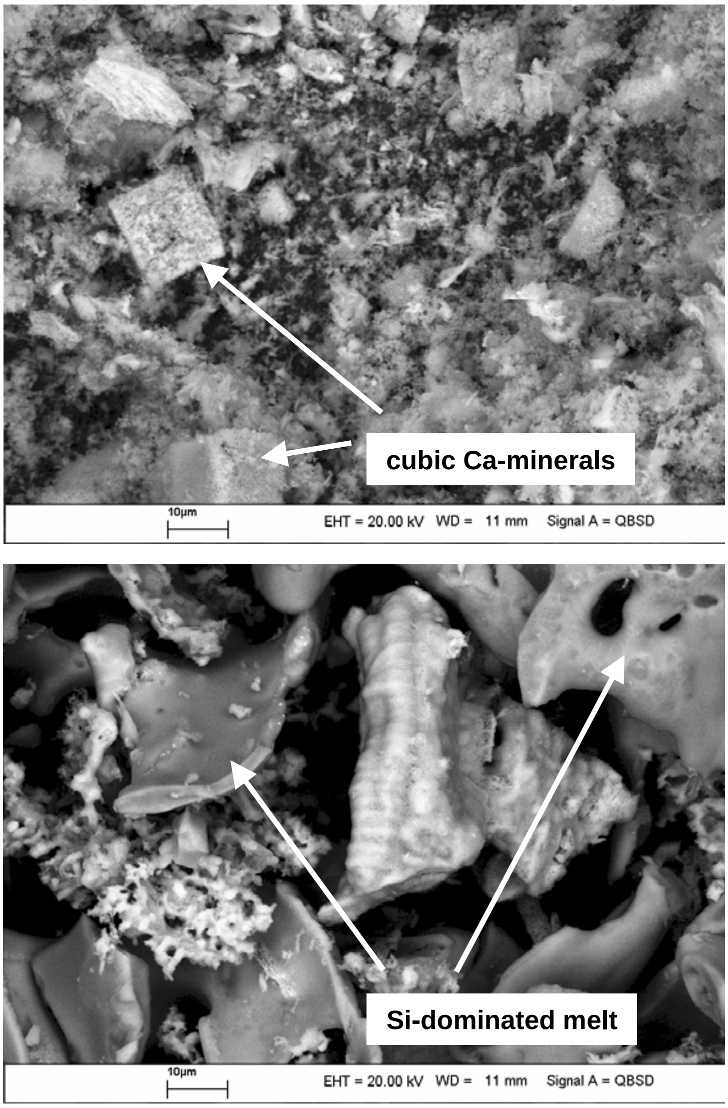
Figure 1: Fractionation results of Polish Coal C1 and wood chips BM2

Explanations: d.s. … dry substance

As a simplification one can say that the main ash forming components, which are leachable in hydrochloric acid, can in some cases be assumed to constitute of relatively unreactive compounds and accordingly this fraction may be considered fairly inert. The elements leached out in water and the acetate solution can on the other hand be considered as more reactive and may participate in reactions in the combustion process already in the fuel bed with ash particles and/or further up the combustion line with fly ash particles or form by themselves submicron particles. The above split into soluble and less soluble elements can further be used in combination with thermodynamic equilibrium calculations to predict the stability of different solid and gaseous compounds in the combustion process.

In the BIOASH project 12 fuel samples (BIOASH-fuels in Table 2 and fuel samples taken during real-scale test runs at Elsterwerda (waste wood), Dolna Odra (coal, sawdust) and Ely (straw) have been chemically leached and analysed. Two examples showing clearly the fuel related differences regarding the total amount of ash forming elements as well as their leaching behaviour are presented in Figure 1. It is clear that the content of ash forming elements is significantly higher in coal than in wood, and that the dominant ash forming elements differ depending on the fuel type. For example potassium is nearly not soluble for coal while for wood almost all of it is found in the solvent solutions (observe the scale-differences). For more information see [7].

SEM characterisation of selected biomass fuels



Overall analysis of ashed bark BM1 (900°C)

Compound Formula	Compound Wt % d.s.
Na_2O	0.26
MgO	4.12
Al_2O_3	2.22
SiO_2	7.13
SO_3	1.81
Cl	0.00
CaO	73.13
TiO_2	0.26
MnO	2.52
Fe_2O_3	1.83
P_2O_5	2.93
K_2O	3.21
ZnO	0.13
PbO	0.31
Cr_2O_3	0.11
NiO	0.03

Overall analysis of ashed straw BM6 (900°C)

Compound Formula	Compound Wt % d.s.
Na_2O	2.45
MgO	1.35
Al_2O_3	0.54
SiO_2	69.32
SO_3	1.94
Cl	0.16
CaO	9.92
TiO_2	0.02
MnO	0.00
Fe_2O_3	0.59
P_2O_5	3.12
K_2O	9.98
ZnO	0.49
PbO	0.00
Cr_2O_3	0.08
NiO	0.04

Figure 2: SEM-pictures and EDX-analyses of ashed bark BM1 and straw BM6

Explanations: d.s. … dry substance; O calculated, results normalised to 100% not considering C

The fuels of interest within WP1 have also been subject to SEM/EDX studies. The fuels investigated were bark (BM1), wood chips (BM2), waste wood (BM3), sawdust (BM4), olive residues (BM5), and straw (BM6).

Each fuel sample was weighed, put in a crucible and inserted in an oven in air atmosphere for 15 minutes. The crucible was then taken out and put into an exsiccator while cooling. This was done at three different temperatures for each fuel (500, 700 and 900°C). After this, each sample (4 samples per fuel) was studied in the scanning electron microscope (SEM-EDX), where both pictures and chemical analyses were made. The observations from these analyses and photos help to understand both the physical and chemical phenomena taking place during combustion.

In Figure 2 results of analyses performed with ashed bark (900°C) and ashed straw (900°C) are presented. For bark one can clearly see the cubic Ca-minerals which are residues of Ca-oxalate particles (CaC_2O_4) and most probably consist of a mixture of CaO and $CaCO_3$. For straw the presence of a melt (mainly containing Si, Ca and K) can be identified. For more information concerning residual ash formation during biomass combustion see [8] and [10].

Release behaviour of ash forming compounds from selected fuels and interdependencies between the results from fuel characterisation and the release behaviour

The overall objective of WP 1 was to quantify the transformation and the release of Zn, Na, K, Cl and S from six biomass fuels and two coals, under both fixed-bed and pulverised fuel combustion conditions. For this purpose, the release was quantified as a function of temperature (in the range of 500 – 1,000°C) in a lab-scale fixed-bed reactor and as a function of residence time in a lab-scale entrained flow reactor (temperature: 1,400 – 1,600°C). Furthermore, the fuels as well as low-temperature ashes from the fuels were characterised by advanced techniques, including scanning electron microscopy (SEM/EDX), chemical fractionation (CF) and simultaneous thermal analysis (STA), which provided data to link the release behaviour with the fuel composition. In parallel to the experimental release investigations and fuel characterisations, global equilibrium analysis (GEA), simulating the experimental combustion conditions, were performed.

The overall aim of the work was to compare the quantitative release data obtained in the lab-scale facilities with the data from the advanced fuel characterisation techniques. Furthermore, the data from all techniques were compared to the GEA of the thermal fuel conversion systems. In addition, the release data from the lab-scale fixed-bed tests were compared to results gained from pilot-scale mass balance tests. Comparisons were made on an elemental release basis and/or a total inorganic release basis.

While large differences were seen between the lab-scale release data and the release information obtained by the fuel characterisation techniques (especially on an elemental release basis), usually a rather good correlation was found between the release data from the pilot-scale mass balance tests and the lab-scale fixed-bed release data obtained in the temperature range of 700 – 1,000°C. This is illustrated by Figure 3, which shows two examples for the comparison of the elemental release (K from bark and Pb from waste wood) according to the lab-scale fixed bed release tests, GEA, CF and pilot-scale mass balance tests.

Based on the detailed comparison and evaluation of the release data gained from the different techniques, it is recommended to perform lab-scale tests in order to obtain reliable quantitative data on the release of inorganic elements under grate-firing or suspension-firing conditions. Advanced fuel characterisation by use of STA and CF, as well as GEA of thermal fuel conversion systems, provide valuable additional information on the release of inorganic elements, which supports the interpretation of the lab-scale release data. Especially GEA can, if carefully adapted to fuel and combustion conditions, be very valuable for modelling the release behaviour. Thus, for the purpose of modelling ash or aerosol formation during biomass combustion, GEA should be combined with lab-scale release measurements. Pilot-scale mass balance tests are very useful for obtaining a complete picture of the combustion behaviour of a fuel and as a basis for the appropriate design of a large-scale plant. More information is given in [7], [9] and [10].

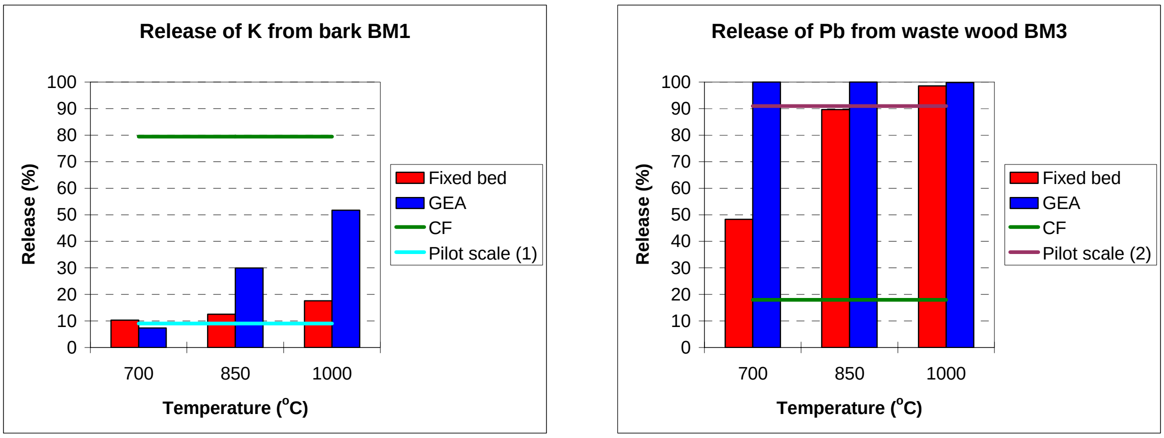


Figure 3: Comparison of the release according to lab-scale fixed-bed tests, GEA, CF and pilot-scale mass balance tests

Explanations: CF … chemical fractionation; GEA … global equilibrium analysis ;
release related to the total amount of the element contained in the fuel;
CF results related to water soluble and acetate soluble fractions;
GEA calculations were made between 400 and 1,200°C in steps of 20°C and for an air-to-fuel ratio of 1.1. The distribution of the elements between gas and condensed phases plotted as percentage of total amount of elements in the gas phase;
see WP 4 for information concerning pilot-scale test runs; method pilot scale (1) assumes that the ash forming elements released from the fuel are present in the gas phase and as aerosols; method pilot scale (2) additionally considers condensation of ash forming matter on coarse fly ash particles

1.3.3 WP 2: Data acquisition and development of high-temperature particle sampling devices

The overall goal of WP 2 was to develop new high temperature particle measurement and sampling equipment as well as to gain new data concerning the melting behaviour of ashes, the viscosity of deposits and the risk of corrosion caused by deposits.

The tasks of WP 2 were structured accordingly to the 4 main objectives:

- Development and construction of high temperature particle sampling devices to be applied during test runs at rea3-scale combustion plants as well as special deposit probes for long-term measurements and for deposit build-up measurements in large-scale boilers.
- Determination of viscosity data for typical deposits in biomass furnaces as a basis for deposit formation modelling.
- Determination of new data for thermodynamic melting sub-models that cover compositions within the system (K, Na, Ca, Mg, Pb, Zn)(SO_4, Cl, CO_3) to gain more reasonable predictions of the melting behaviour of ashes containing Pb, Zn and Na.
- Determination of data concerning the risks of corrosion caused by deposits.

Development of a new high temperature measurement equipment for the determination of particle size distributions and concentrations of aerosols in the flue gas in furnaces and boilers (high temperature impactor)

Information concerning aerosols already present in the hot furnace before entering the convective path of biomass combustion units offers highly valuable insights into aerosol and deposit formation processes. To gain this information an impactor that can operate in-situ at temperatures up to about 1,000°C has been developed, manufactured as well as subsequently tested and evaluated.

With the high-temperature low-pressure impactor (HT-LPI), which is based on the common design of a Berner-type low-pressure impactor (BLPI), it is possible to gain information on particle size distribution and concentration of aerosols sampled at high temperatures directly in the furnace. Furthermore, the chemical composition, shape and structure of the particles can subsequently be investigated by wet chemical as well as SEM/EDX analyses. The results achieved by measurements with the new impactor are of great relevance for an improved knowledge about aerosol formation processes, deposit formation processes and an appropriate aerosol and deposit formation model development. The high-temperature impactor has already proven its applicability during several field tests at pilot-scale as well as large-scale biomass combustion and biomass and coal co-firing plants. Detailed information concerning the particle size distribution, concentration, chemical composition and the shape of aerosols sampled in the boiler and the convective path have thereby been gained (see WP 4 - Figure 16 and Figure 17).

It can be stated, that with the HT-LPI a unique particle sampling device has been developed within the project which opens new possibilities concerning ash and aerosol related research in combustion processes. The present design of the HT-LPI works with a sufficient accuracy, however, in order to improve this accuracy and to further prove the results gained from the measurements, additional optimisation measures and calibration work are planned to be performed in future.

Figure 4: Photographs of the high-temperature low-pressure impactor in operation

Explanations:
1) … view through the outer casing tube into the furnace
2) … HT-LPI directly after measurement
3) … impactor stage with sampling foil and deposition peaks

Future applications of the HT-LPI are seen in R&D programs which deal with fine particle related issues during combustion processes as well as in measurement and monitoring campaigns at large-scale plants. Therefore, TUG aims at a broad application of this unique device within research projects and also expects a strong interest of furnace and boiler manufacturers as well as engineering companies regarding measurement campaigns with the HT-LPI in order to get more and valuable insights into the formation and behaviour of ash forming elements in the furnace and boiler section. More information about the HT-LPI can be found in [2].

New high-temperature measurement equipment for deposit sampling

IEn’s task was to develop a long-term deposit probe. To enable long-term measurements, the probe has to be properly cooled. The body of the deposit probe is water cooled, whilst the tip with the deposition rings is cooled by air. The advantage of using more than one deposition ring is the possibility to obtain several deposition samples from one sampling campaign, which can be analysed using different methods. A set of 5 new deposition probes (see Figure 5) was developed, constructed and applied within WP 4.

To observe deposit build-up on the rings, a small and cheap mini-camera was integrated in two of IEn’s probes. An optical probe cooled with air only was originally constructed in order to gain experience regarding the camera cooling at boiler conditions. Additionally, it is a useful tool that can be applied to diagnose depositions on e.g. superheater tubes.

Moreover, AAU developed and manufactured a short, air cooled probe with on-line measurements of the inner and outer surface temperature of the probe as well as of the cooling air and of the flue gas temperature at the position of the probe. Also, the pressure difference between the inlet and outlet of the cooling air can be logged. The new AAU probe was tested and evaluated during the test runs at pilot and large-scale combustion plants (see WP 4). Results of deposit measurements are given in WP 4. Details concerning the development of AAU’s long-term deposit probe for on-line monitoring of deposit growth can be found in [1].

Figure 5: Deposition probes developed by IEn

Explanations: A) probe tip with deposition rings after measurement
B) view into the second duct of Elsterwerda CHP plant using probe 3
1) length: 1.5 m, air and water cooled optical probe
2) length: 3.0 m, air and water cooled probe with deposition tip
3) length: 1.5 m, air cooled optical probe
4) length: 3.0 m, air and water cooled probe with deposition tip and optical observation system
5) length: 1.5 m, air and water cooled probe with deposition tip and optical observation system

Viscosity data for deposits sampled in biomass combustion and biomass and coal co-firing plants

To predict the deposition of coarse fly ash particles on to steam super- and reheaters in pulverised coal-fired boilers with biomass co-firing, the stickiness of biomass ash particles was investigated by measuring their viscosity in the temperature range of 1,000 – 1,600 °C.

Viscosity measurements were performed on ash samples produced from straw and olive residues, as well as on a series of synthetic slags. The viscosity measurements focused on the ternary system of SiO_2-CaO-K_2O, which was selected as a common 'denominator' of wood-type fuels and certain main-stream agricultural residues.

The viscosity measurements were carried out using a rheometer with a rotating bob submerged in the liquid slag, determining the viscosity from the measured torque on the bob. Procedures were developed to measure high-temperature viscosities in the mentioned system in a reproducible way. The composition of the slag, and of phases present during the measurement were confirmed by rapid quenching and subsequent analysis of each slag investigated. The results were found to be reproducible, and in good agreement with existing literature data.

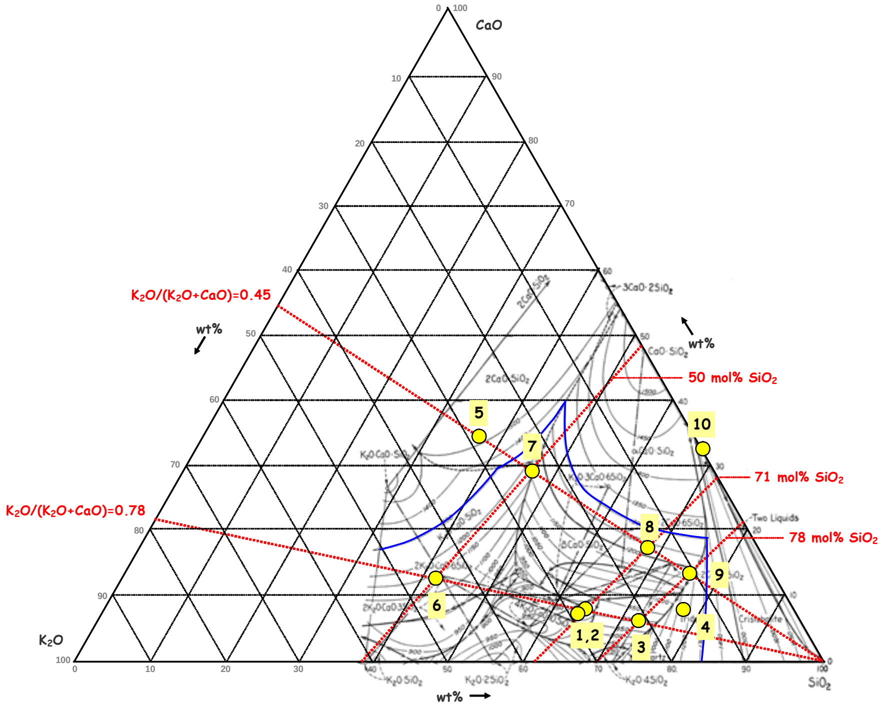


Figure 6: Composition of slags investigated

Figure 7 shows the measured viscosity of the slags investigated as a function of temperature.

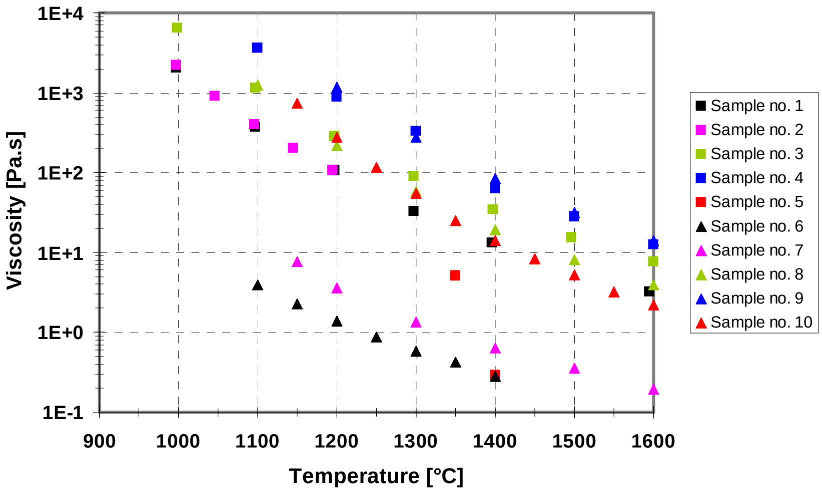


Figure 7: Measured viscosity of the slags investigated

A wide range of compositions has been investigated, as is indicated by the 10 slags in the ternary phase diagram in Figure 6. Altogether 60 unique viscosity data were measured for mainly silica dominated slags, with CaO mass fractions up to 30 wt.% and K_2O mass fractions up to 42 wt.%.

The compositions of the slags have been selected to be able to identify clear trends of viscosity as a function of slag composition. It was found that, at fixed $K_2O/(K_2O+CaO)$ weight ratios, the viscosity increases with an increasing SiO_2 concentration, and at fixed SiO_2 concentrations, the viscosity decreases with an increasing $K_2O/(K_2O+CaO)$ weight ratio.

The resulting data are useful as a basis for predicting the deposition by impaction of ash particles, or the behaviour of molten slags in general.

Determination of new data for thermodynamic melting sub-models

A new thermodynamic database was developed for ash reactions in oxidising and reducing conditions. Reactions between flue gas, char and ash particles as well as melting properties of different ash fractions in biomass and coal combustion can be estimated. The database was used to calculate the ash reactions during combustion of the eight BIOASH-fuels in a wide temperature range. The results have been put together into a GEA-Atlas (Global Equilibrium Analysis Atlas).

Analyses have been performed to estimate the release of metals into the gas phase during the combustion of the eight fuels. Chemical equilibrium between ash and gas was assumed and the portion of the metals released was calculated as a function of temperature in oxidising conditions. Results show big differences in the release of K, Na, Pb and Zn between different fuels mainly due to differences in the main ash composition.

Moreover, the influence of lead and zinc on the first melting temperature of alkali salts was determined experimentally with thermal analysis. It was found that the first melting temperature decreases gradually when Pb and Zn is added. The first melting point of a K-Na sulphate-chloride mixture is app. 600°C. Addition of Pb results in decrease to 400°C and further addition of Zn to below 200°C (see Figure 8). This has a significant effect on the ability of condensing particles to stick to metal surfaces. The experimental data were used to develop a non-ideal thermodynamic model for the melting of complex salt mixtures.

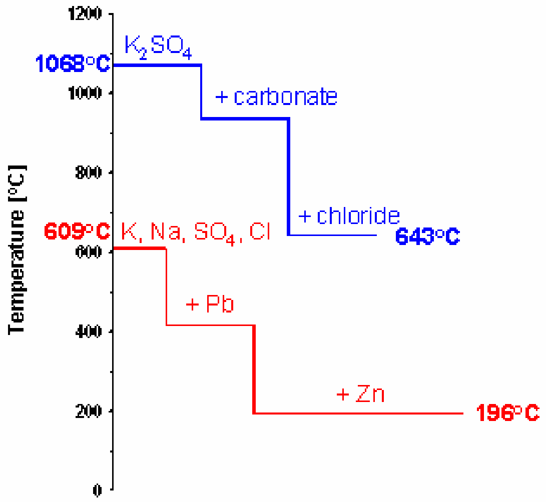


Figure 8: Decrease of the first melting point of complex salt mixtures

A program was developed to estimate the melting behaviour of deposit and fly ash samples taken during measurement campaigns. Based on SEM/EDX-analyses of the deposits, the composition of the condensable fraction (K, Na, S, Cl, Pb, Zn) can be extracted and the chemical composition of ash forming elements in the flue gas at typical boiler conditions can be estimated. Furthermore, the portion of molten phases as a function of temperature can be calculated. Results gained from the calculation of melting properties of deposits sampled during real-scale test runs within WP 4 show that Zn is either as solid ZnO, Zn-sulphates or $ZnCl_2$ in the melt, depending on the Cl/S-ratio and the Zn/(K+Na)-ratio. Deposits from different fuels are very different. The location on the probe and surface temperature are important for the deposition chemistry.

A paper [13] dealing with the influence of aerosol particles on the melting behaviour of ash deposits in biomass fired boilers linked to the work within BIOASH has been presented at the international seminar "Aerosols in biomass combustion" in Graz on the 18th of March 2005 which was organised by the BIOASH project coordinator (TUG) in close cooperation with IEA Bioenergy, Task 32, "Biomass Combustion and Co-firing".

Results from tests concerning the corrosive potential of aerosols and fly ashes

Data concerning the risks for corrosion of superheater tubes caused by ash deposits were obtained by DTU. Lab-scale corrosion tests were performed, in which pieces of superheater material coated with different types of synthetic deposits were exposed to conditions (flue gas and temperature) simulating waste wood combustion.

Table 3: Synthetic flue gas composition, simulating waste wood combustion

O_2	CO_2	SO_2	HCl	N_2	H_2O
8 vol.% dry	14 vol.% dry	140 ppmv dry	175 ppmv dry	balance	2-3 vol.% wet

Using scanning electron microscopy in combination with energy dispersive X-ray analysis (SEM/EDX), the chemistry of the corrosion layers was identified, and the thickness of the oxide layers was determined, for each exposure time and for each deposit type. In this way, the influence of deposit composition on the corrosion rate was investigated.

In general, the oxide layer had a non-uniform thickness within the sample, which made it difficult to derive corrosion rate laws. However, the results clearly showed that the presence of metal chlorides in deposits strongly enhances the corrosion attack (chlorine-induced corrosion). Unrealistically high corrosion rates (150–1,000 µm/month, depending on the deposit chemistry and the exposure time) were observed when deposits only consisted of mixtures of chlorides of K and/or Zn and/or Pb.

For the deposit system ZnO-KCl-K_2SO_4, the corrosion rates were the highest (230–1,100 µm/month, depending on the exposure time) for a mixture of 1 mol ZnO, 0.4 mol KCl, and 0.3 mol K_2SO_4 (60% "sulphation" of the deposit). Figure 9 shows the resulting oxide layer and the distribution of the elements Fe, K, Zn, S, and Cl in the oxide layer and the deposit after 2 weeks of exposure. The lowest corrosion rates (27–258 µm/month, depending on the exposure time) were observed for a mixture of 1 mol ZnO, 0.2 mol KCl, and 0.4 mol K_2SO_4 (80% "sulphation" of the deposit).

A straightforward relationship between the S/Cl ratio of the deposit (or "degree of sulphation" of the deposit) and the corrosion rate could not be found, but the results indicate that the formation of a melt (probably containing K, Zn, S and Cl) may have an influence on the corrosion rate (melt-induced corrosion). The exact corrosion mechanisms could however not be identified in this study, because of the lack of phase diagrams for the chemical systems involved and because of the complexity of the system, due to possible interactions between the deposit and the flue gas (containing HCl and SO_2). Further work is needed to investigate these complex interdependencies in order to find the link between the deposit composition and the corrosion potential.

The corrosive potential of deposits consisting of mixtures of chlorides of potassium and/or zinc and/or lead decreases as follows: KCl-$ZnCl_2$-$PbCl_2$ > KCl-$ZnCl_2$ > KCl-$PbCl_2$ > $ZnCl_2$-$PbCl_2$. Concerning the influence of heavy metals on the corrosive potential of a deposit thus Zn seems to have a stronger effect on increasing the corrosion rate than Pb. The presence of both zinc (chloride) and lead (chloride) in a deposit results in the highest corrosion rates, if potassium (chloride) is present as well. Investigations in the system ZnO-KCl-K_2SO_4 show that Zn (from ZnO) is reactive and diffuses through the deposit and oxide layers, so it is probably involved in the formation of melts at the metal/scale interface, thereby affecting the corrosion rate. Since the quantity of ZnO in the deposit was not varied for this system, no further conclusions on the effect of Zn on the corrosion potential can be made.

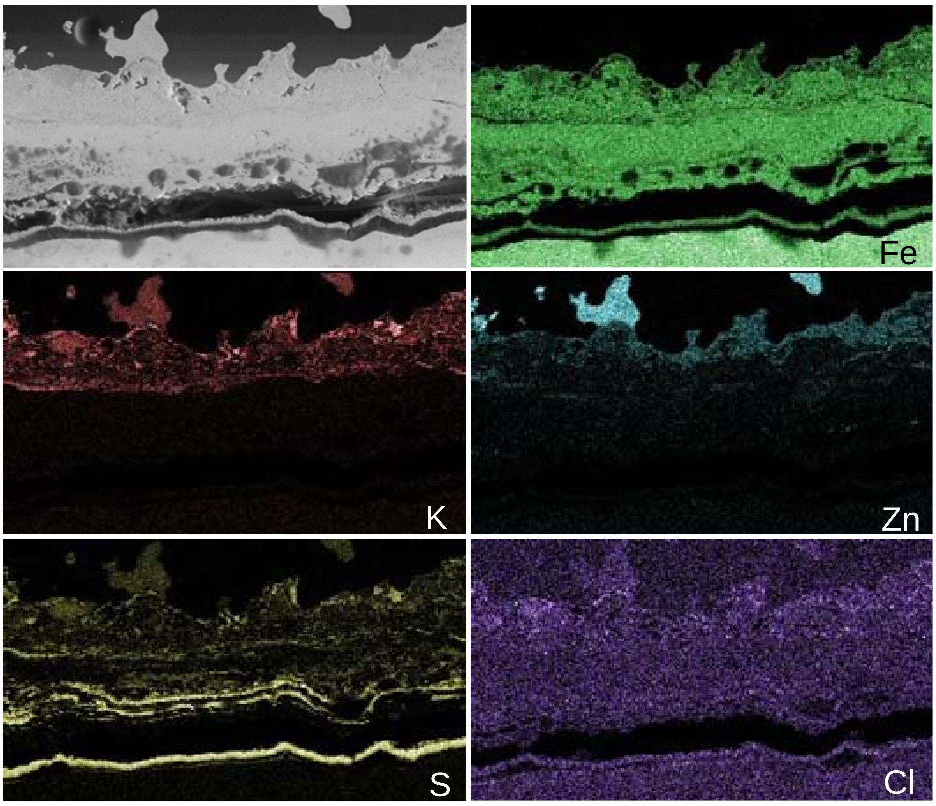


Figure 9: SEM micrograph (upper left picture) and element mappings of the corrosion products

Explanations: Exposure of a piece of superheater tube covered with a mixture of 1 mol ZnO, 0.4 mol KCl and 0.3 mol K_2SO_4 (representing 60% 'sulphation' of the deposit) for 2 weeks at 500°C to a gas mixture simulating the flue gas of waste wood combustion; picture width: 1,250 µm.

1.3.4 WP 3: Advanced aerosol formation and deposit formation modelling

One goal of WP 3 was to develop a practical tool for the prediction of the timescales involved in aerosol formation processes based on new fundamental insights in turbulent flows.

The improvement of a basic aerosol formation model, developed by TUG by using and implementing the data gained from WP 1 and WP 2 to gain a better quantitative prediction of aerosol formation during combustion was another main objective.

Moreover, the development of a user friendly deposit formation prediction tool for boiler manufacturers, engineering companies and plant operators was a main goal which is strongly connected to the important objective to implement the aerosol formation models and the deposit prediction tool developed into CFD-calculation routines, especially developed to simulate the reacting flow in biomass furnaces and boilers, in order to make them directly applicable for furnace and boiler design calculations.

Evaluation of influences of turbulence on aerosol formation and aerosol growth processes

A numerical case study concerning the influence of the most relevant design and operation parameters on the motion of fly ash particles in heat exchanger tube bundles of water tube and steam boilers was performed in order to gain knowledge about particle impaction on the tubes. Furthermore, the data gained from these simulations can be used to link the deposit formation model developed within the project with heat exchanger models. This is a major and relevant step towards the CFD based simulation of ash deposit formation in the whole combustion plant including the convective section of the boiler.

Simulations with the CFD software package Fluent have been performed on a staggered tube bundle configuration for which also experimental results on mean and fluctuating values of gas velocities are available. The optimal way to perform such simulations is based on the unsteady Reynolds-averaged Navier-Stokes equation (RANS) with the Reynolds Stress Model as turbulence model in a two dimensional geometry. Unsteady simulations are necessary since shedding of vortices of the same size as the tubes plays an important role and this cannot be captured with the $k-\varepsilon$ turbulence model. Moreover, close to the walls the flow is far from isotropy and this anisotropy has a large influence on particle behaviour. Hence, also for this reason the isotropic $k-\varepsilon$ model is not suitable for simulations of particle-laden flows. The small increase in accuracy over unsteady RANS simulations with the Reynolds Stress Model (RSM) does not outweigh the extra computational effort necessary for large-eddy simulation. Hence, unsteady RANS simulation with the RSM were performed in a 2D case study to investigate the influence of design and operating parameters on particle movement and impaction on superheater tube bundles in water tube and steam boilers.

Flow, heat transfer and particle movement simulations have been performed in typical heat exchanger configurations in biomass fired boilers (for example see Figure 10 for superheater-velocities). Two different geometries have been considered, each with two different values of the pitch in normal direction and in all configurations four simulations have been performed with different values of magnitude and direction of the incoming gas velocity. For all these simulations coarse fly ash particles with six different Stokes number between 0.2 and 30 have been tracked. The simulations were based on the unsteady Reynolds-averaged Navier-Stokes equation with the Reynolds Stress turbulence model. Particles are influenced by the gas flow through the action of the drag force, where the effect of turbulence is taken into account by the discrete random walk model. Interaction between particles and heat exchanger tubes has been taken into account by constant normal and tangential restitution coefficients.

It turned out that the fraction of mass and kinetic energy impacted on the tubes is a function of both Stokes and Reynolds number and depends to a great extent on the angle of incidence of the inlet gas velocity. However, the dependence on the Reynolds number is not very strong.

The interaction between particles and tube walls is an important issue. In the present simulations constant restitution coefficients in tangential and normal direction are used, which are based on (very scarce) literature. Moreover, it is assumed that particles do not stick to the walls. In reality, particles do stick to the walls and form a layer in such a way that the geometry of the tubes and consequently the flow around the tubes change. Additionally, this layer results in reduced heat transfer. Consequently, a thorough experimental study on interaction between particles and round tube walls is highly recommended as a necessary future work in order to determine the restitution coefficients and conditions for particle sticking.

Almost all simulations have been performed for isothermal conditions. In reality, the flow is highly non-isothermal and large temperature gradients occur especially near the tube walls. This could have a large influence on particle behaviour, not only due to the changes in the gas velocity and turbulence, but also because of the extra thermophoretic force, which drives particles towards the colder tube walls. Therefore, this work was extended to non-isothermal conditions.

First simulation with non-isothermal conditions showed, that the effect of thermophoretic forces can be neglected for the Stokes numbers considered since the impaction rates are almost identical when the thermophoretic forces are included or not. These simulations further showed, that also the influence of heat transfer on the particle impaction rates via changing flow conditions is relatively small. However, this is presently investigated in detail for different mean flow velocities and inflow angles for the superheater geometries considered within the BIOASH project (results will be orally presented at the conference "Deutscher Flammentag" in September 2007 [15]). Furthermore, the investigations will be extended for typical geometries of economisers. The results can be used to generate a look-up table of the impaction rates and particle kinetic energies as a function of the influence variables investigated for each tube row in order to link the deposit formation model under development with CFD based heat exchanger models. This would allow to predict ash deposit formation in the whole boiler including the convective section. In this context it is recommended to numerically investigate further relevant tube bundle types, e.g. in thermal-oil boilers and fire tube boilers, in order to achieve a wider applicability range of the deposit formation model under development.

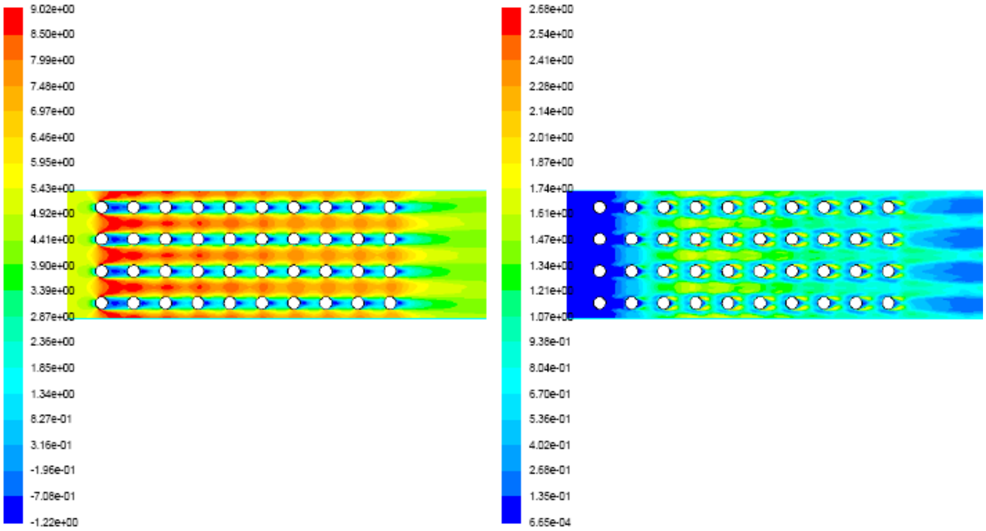


Figure 10: Mean streamwise velocity and its r.m.s. for non-isothermal flow in [m/s]

Explanations: r.m.s. … root mean square value
mean inflow velocity of flue gas 5 m/s, tube diameter: 38 mm; pitch: 100 mm; flue gas composition: 6.3 wt% O_2, 19.2 wt% CO_2. 6.8 wt% H_2O, 67.7 wt% N_2

Development of an advanced aerosol formation model considering turbulence and the release of ash forming compounds from the fuel

The objective of this task was the improvement of an existing aerosol formation model. The basic model, which had been developed by TUG and could be used for simulating aerosol formation during biomass combustion in flame tube boilers, was improved by extending the calculation capabilities to simulate aerosol formation in water tube boilers using more appropriate particle precipitation mechanisms. Furthermore, comprehensive test runs at different combustion units using a broad variety of fuels enabled the creation of detailed input parameters for aerosol formation simulations and allowed to compare the simulation results with extensive measurement results.

The basic aerosol formation model is a plug flow model including thermodynamic equilibrium calculations in order to determine the local gas composition and a kinetic approach for the determination of concentrations of gaseous sulphates. Furthermore, the particle formation mechanisms nucleation, condensation and coagulation are considered as well as the particle precipitation mechanisms settling, thermophoresis, diffusional deposition and turbophoresis.

With the basic aerosol formation code, aerosol formation was calculated for test runs performed at the MAWERA pilot plant in Jan. 2005 for three different biomass fuels (bark BM1, wood chips BM2, waste wood BM3). The required input data, which were profiles of flue gas temperature, flue gas velocity, flue gas residence time and geometric data of the combustion plant as well as PSDs and chemical composition of primary particles (particles released from the fuel bed to the flue gas) and the flue gas composition were determined by the evaluation of plant operating data and by mass balances for each of the test runs performed. The results of the simulations performed with these data showed that the PSDs as well as the chemical compositions of aerosol particles at boiler outlet could be reproduced well with the basic aerosol formation model. Aerosols from combustion of wood chips (spruce) consisted mainly of alkali sulphates and carbonates. During combustion of bark the amounts of Cl and Zn in the aerosol particles increased in comparison to wood chips while no alkali carbonates were formed. During waste wood combustion the high concentration of Zn in the fuel lead to the formation of such a high number of ZnO particles that further nucleation of sulphates and chlorides was suppressed and only condensation on these particles occurred. Also the contribution of Pb compounds to aerosol formation during waste wood combustion, as obtained from measurements, could be reproduced by the calculations.

In order to be able to simulate aerosol formation in water tube boilers the particle precipitation mechanism of inertial impaction was additionally implemented into the model. First modelling calculations with the adapted code were performed for aerosol formation at the Dolna Odra power station (Poland). Two test cases were considered, one for coal-sawdust co-firing and one for coal only. The input data for the Dolna Odra test cases were created according to the same procedure as described for the calculations for the MAWERA pilot plant. The calculation results (PSDs of aerosols at boiler outlet as well as chemical composition of particles) were strongly dominated by the entrained ash particles formed during the combustion of coal. The ash particles formed a third peak of the particle size distribution at 0.5 μm cut diameter (aerodynamic diameter, see Figure 11).

This peak, which lies between the main aerosol peak and the coarse fly ash peak formed due to fragmentation of different ash minerals, could not be modelled using the present aerosol formation model since the model uses an average particle composition. As a result of a literature study concerning the fragmentation of mineral inclusions in coal it could be found that mainly two types of minerals, namely calcite and pyrite, show fragmentation during thermal treatment. This behaviour could also be modelled according to literature by using a

Poisson distribution and determining the relevant parameters of the distribution function experimentally. It was concluded that this approach for the modelling of the particle fragmentation could not be implemented into the present aerosol formation model, since the particles in the model are treated with an average size and composition for each size section. In order to consider fragmentation, separate chemical particle classes would have to be implemented into the model, which is also recommended as a future work for the appropriate aerosol formation modelling of biomass-coal co-firing plants.

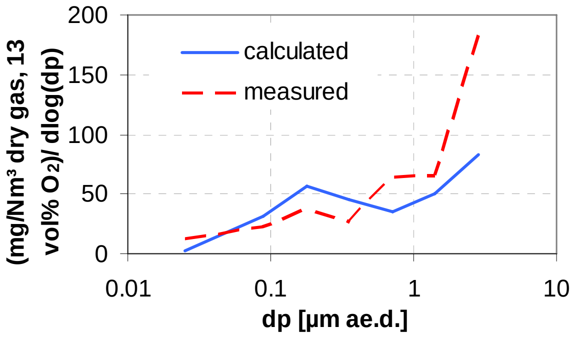


Figure 11: Measured and calculated particle size distributions of aerosols at boiler outlet during co-firing of sawdust and coal in the Dolna Odra power station

Explanations: ae.d.: aerodynamic diameter; sampling equipment at boiler outlet… BLPI; measurement point BLPI … boiler outlet (~300°C)

Furthermore, calculations were performed for aerosol formation during combustion of waste wood at the CHP plant Elsterwerda. The input data were created in the same manner as for the previous simulation calculations. The results showed a good match of measured and calculated PSDs (see Figure 12) as well as of the chemical compositions at boiler outlet. For the Elsterwerda test case measurements showed that ZnO particles dominate the aerosol fraction in the furnace, which could not be reproduced by the calculations. The reason was that the thermodynamic equilibrium calculations performed in order to determine the gas phase composition did not predict sufficient amounts of ZnO in the gas phase. Instead ZnO particles had to be inserted as entrained aerosol particles in order to gain the same particle formation pathway as obtained from measurements.

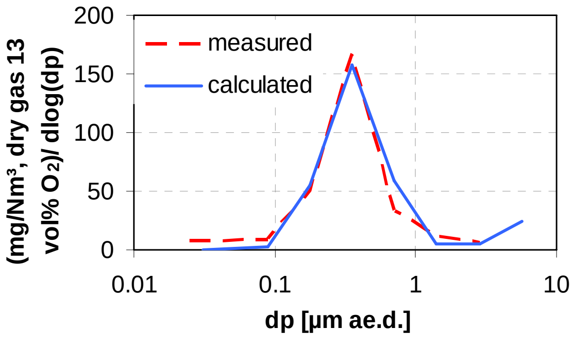


Figure 12: Measured and calculated particle size distributions of aerosols at boiler outlet during combustion of waste wood in the Elsterwerda CHP plant

Explanations: ae.d.: aerodynamic diameter; sampling equipment at boiler outlet… BLPI; measurement point BLPI … boiler outlet (~170°C)

In addition, calculations of aerosol formation during co-combustion of straw and natural gas in the Elean power station were performed and compared with experimental data. The predicted particle size distribution was similar to the mean PSD obtained from measurements, having the peak on the 4th impactor stage with a cut diameter of 0.5 µm (aerodynamic diameter). Also the chemical compositions of measured and predicted aerosols were similar. In both cases the particle composition was dominated by KCl. Furthermore, the total mass of aerosols was comparable to the measured mass. But as in the case of Elsterwerda, entrained aerosol particles in the size range between 10 and 100 nm, in this case composed of SiO_2, had to be considered as first seed particles for condensation in the particle size distribution of the entrained particles. Otherwise the PSD did not match very well.

Generally, the results from modelling aerosol formation with the model developed showed good results regarding the chemical composition and the PSD of aerosol particles, which confirmed the applicability of the further developed model. Moreover, the quality of the results was strongly dependent on the quality of the input data, which confirmed the approach of improving the modelling quality by detailed input data preparation for different biomass fuels.

The work performed within the project on aerosol formation modelling has already been presented at the Conference "Impacts of Fuel Quality on Power Production" in Snowbird, Utah (USA) in November 2006. The conference paper [3] was subsequently submitted by the conference chairs to the Journal "Fuel Processing Technology".

Development of sub-models for transport and adhesion of ash species (gases, aerosols and coarse mode fly ashes), deposit build-up, heat transfer through deposits and shedding of deposits

DTU delivered documented sub-models for ash transport, adhesion, deposit consolidation and material property data which were implemented into the CFD deposit- and aerosol formation code developed within the BIOASH project.

An important mechanism to understand is the transport of heat through deposits, since that will in time control the surface temperature of the deposit. Thus an outline of mechanisms of heat transfer through deposits has been worked out, with special focus on the estimation of an effective thermal conductivity in the deposit as a function of porosity, temperature and chemical composition of the deposit. Furthermore, fit functions for radiative emissivities of deposit surfaces have been supplied be DTU. In addition, a significant amount of pure component data for use in e.g. heat transfer models has been supplied.

A separate model for the formation of ash in PF-fired boilers, based on analysis of CCSEM-data has been delivered. The model proved to be very useful on coal-straw co-fired systems in Denmark, when tested.

Finally, an outline of a model for shedding by gravitational effects has been documented and delivered. Moreover, a review paper on erosion modelling, which was taken as basis for erosion model implementation within the BIOASH project, was provided by DTU.

Integration of aerosol and deposit formation models into a CFD-code

A basic CFD model for the prediction of deposit formation in biomass fired boilers has been developed as efficient design tool by partner TUG. Before the start of the BIOASH project, the effects of condensation of ash forming vapours and the precipitation of silica rich coarse fly ash particles in the furnace and the radiation section of the boiler were considered in the CFD modelling approach. In the framework of the BIOASH project, the CFD based model has been further developed to a comprehensive engineering tool and has also been validated. This model has a high flexibility concerning the fuel fired and operating conditions at reasonable calculation times which also enables the application for the simulation of co-firing systems. In the new version of the deposit formation model developed within the BIOASH project, the following processes are considered: condensation of ash forming vapours, deposition of silica-rich coarse fly ash particles, erosion and time dependent deposit build-up as a function of several influencing parameters such as heat transfer and deposit emissivity.

Moreover, a CFD based aerosol formation model has been developed. The aim of the aerosol formation model is to consider the basic aerosol formation and deposition processes, which may occur in furnaces and boilers of biomass combustion plants and may have considerable influence on ash deposit formation and on ash deposit properties. However, within the timeframe of the BIOASH project, the aerosol formation model could not be fully but only partly linked with the deposit formation model. Hence, this work will be conducted as next important modelling step. In the current state of model development the formation of ash particles from the vapour phase is implemented, whereas the implementation of modelling the particle size distribution requires further work. Thus, the particle formation mechanisms of nucleation and condensation are considered, but aerosols are treated as having one single particle size, which includes, that modelling particle coagulation is not implemented yet. Furthermore, thermophoresis and gravitational settling were considered for modelling particle precipitation.

Test calculations of aerosol formation during combustion of waste wood (see Figure 13) performed with the CFD based aerosol formation model show qualitatively good and quantitatively reasonable results regarding aerosols formed. Issues for further work are the implementation of modelling the particle size distribution and subsequently the modelling of particle coagulation as well as improving the quality of the description of parameters relevant for particle formation such as material property data (diffusion coefficient of the vapour, material density, surface tension of nucleating compounds, thermal conductivity of condensing compounds) and of the particle deposition processes. By these measures the quality of the whole deposit formation model should be noticeably improved as well as a more accurate prediction of fine particulate emissions from biomass combustion plants should be possible.

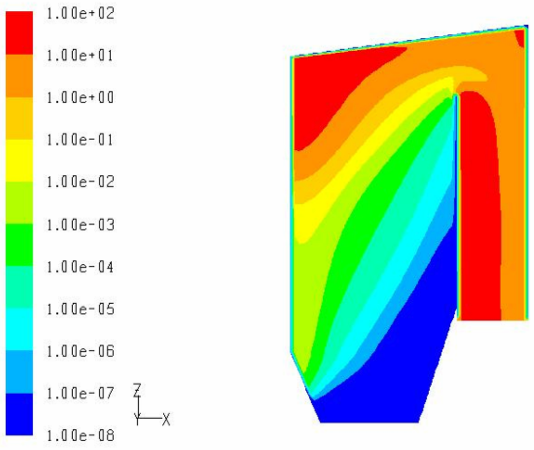


Figure 13: Calculated amount of aerosols formed by gas to particle conversion of K_2SO_4 during combustion of waste wood in the radiation section of the Elsterwerda CHP plant

Explanations: mg/Nm^3 related to dry flue gas and 13 vol% O_2; plant view … symmetry plane of the first and second duct of the Elsterwerda CHP plant

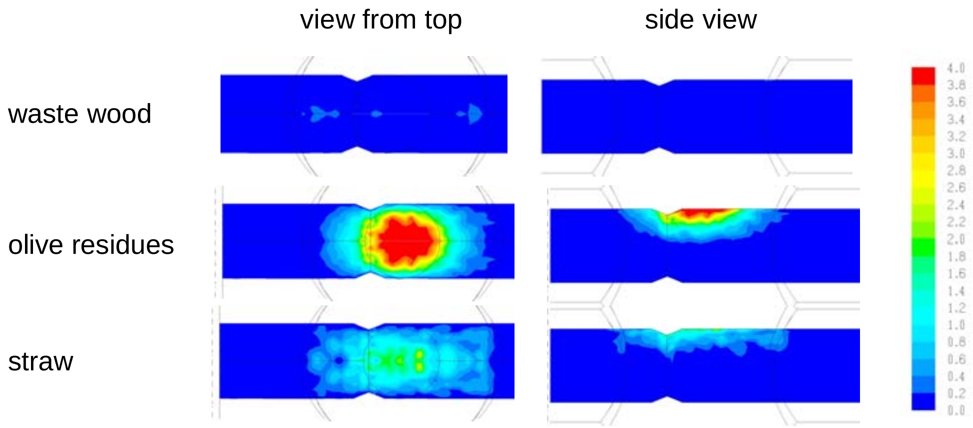
The results of first simulations of deposit formation in biomass grate furnaces and boilers, showed that regarding the deposit formation mechanisms included (deposition of coarse fly ash particles and condensation of ash vapours) the deposition of coarse fly ash particles is dominating. These results could also be observed by on-site observations of real-scale biomass combustion units. Moreover, the simulations showed that the prediction of the stickiness of coarse fly ash particles is very sensitive to the reference viscosity, which is a model parameter of the stickiness approach applied for silica rich particles. In order to achieve a quantitatively improved prediction of ash deposit formation, a new correlation for the reference viscosity as a function of the kinetic energy was derived. The data base for this newly developed function were literature data regarding deposit probe measurements using glass particles as synthetic ash. In order to extend this data base and to validate the stickiness approach within this project, additional deposit probe experiments with glass particles as synthetic ashes were performed by ECN. Simulations of these experiments showed significant deviations of the particle capture efficiencies from the experimental results. It was concluded that additional sub-models describing the particle stickiness are needed in order to describe the capture efficiency of particles under the operating conditions of biomass combustion plants. While for lower particle viscosities the influence of surface tensions has to be taken into consideration, for high particle viscosities the stickiness should be determined based on deformations of the impacting particles.

Moreover, since the validation experiments showed that erosion can considerably influence deposit build-up especially for conditions where silica rich ashes play an important role, an erosion model for brittle erosion of the target material was applied. The deposit formation experiments with glass particles were taken as a rough estimation for comparison with the simulation results, since they only supplied integral deposition rates which are influenced by erosion generally but showed no impaction angle dependent values of erosion rates. By applying the erosion model, the agreement of both simulations and experiments could be qualitatively improved and the calculated capture efficiency showed a stronger increase with temperature than before, which results in a better agreement with the experimental data. On the other hand, the temperature range, where a significant increase of particle stickiness was predicted, was shifted towards higher values. Hence, a sufficient quantitative agreement between measurements and simulations could not be achieved by tuning the erosion constant. As already discussed, this might be due to limited reliability of the stickiness approach. In order to demonstrate this, the reference viscosity was modified, whereby a reasonable quantitative agreement with the experiments could be achieved. However, it is not recommended to use the modified reference viscosity, since more deposition experiments are necessary in order to achieve reliable data as a sufficient basis for improving the stickiness model. Furthermore, also comprehensive erosion experiments with a set-up allowing the investigation of erosion as a function of relevant influencing parameters should be performed (necessary for future work).

The time dependent deposit build-up is taken into account by a quasi-stationary time step calculation. The heat conductivity of a deposit layer is determined by its composition, temperature, porosity and structure. Within this project, a multi-component model for the temperature dependent heat conductivity of the solid phase was introduced based on a model recommendation by DTU. For the effective heat conductivity of the porous deposit layer, two versions of the Rayleigh model for sintered and for non-sintered deposit layers were implemented in addition to the model of Richards. A comparison of the models with experimental data from literature for sintered and non-sintered ash samples showed that in case of non-sintered deposit layers the model of Richards (as in the case of deposit probe experiments performed by ECN) and in case of sintered deposit probes the Rayleigh model (version for sintered layers) is closest to the experiments. Therefore, for furnace and boiler simulations, it is recommended to choose a suitable model (Richards or Rayleigh) based on e.g. deposit temperatures and growth times of the deposit layers as criterion, if the deposit layer considered is un-sintered or sintered. However, the data available are not sufficient for a final choice and validation of the heat conductivity model and therefore more experimental data are needed in the future.

Furthermore, radiation plays an important role in heat transfer processes in combustion plants. An empirical correlation for surface emissivity as a function of temperature has been implemented in the deposit formation model. However, the calculated emissivity can only be considered as an estimation since data from experiments showed large variations and therefore a need for further experiments on emissivity of ash deposit samples exists.

The extended deposit formation model (without the aerosol formation model) was finally applied for a simulation of deposit probe experiments performed by ECN. The test runs were performed with three selected biomass fuels (waste wood BM3, olive residues BM5 and straw BM6) for the purpose of a model validation under conditions prevailing in a biomass fired boiler (see Figure 14). Rosin-Rammler size functions were applied for modelling coarse fly ash particle size distributions and were derived by approximating ECN impactor measurement data, whereas the measured particle size distributions were refined from two to three size sections in the size range between 13.5 and 400 µm.



fuel	**experimental results** thickness [mm]	**numerical results** thickness [mm]
waste wood BM3	0.0	0.3
olive residues BM5	1.3	4.0
straw BM6	1.3	1.5

Figure 14: Iso-surfaces of simulated deposit layer thickness on the deposit probe for different fuels (top) as well as comparison of measurement and simulation concerning averaged deposit layer thickness (below)

The experiments showed that in the case of waste wood only a small deposit layer formed, while the highest amount of deposited mass was determined in case of straw. While simulated and calculated results of deposited mass are in relatively good agreement for waste wood, the deviations were larger for straw (predicted values are smaller) and especially for olive residues (predicted values are larger). An important reason for these differences can be found in the measured particle size distribution and its resolution, which is too coarse for the CFD simulations, since the impaction rates are strongly influenced by the particle size and its inertia, respectively. Moreover, the particle diameter strongly influences the temperature and the velocity of the particle and, according to the viscosity approach, also the stickiness of the particle. Therefore, a higher resolution of the measured and simulated particle size distributions is necessary for a model validation in the future. In general, CFD based sensitivity analyses on the influence of the particle size distribution on the deposition rates in real-scale plants shall be performed in the future, in order to optimise the resolution of the particle size distribution for the CFD simulations under the aspects of prediction accuracy and computation time.

Furthermore, for olive residues it was shown, that nearly all particles impacting on the deposit probe, where sticky. Since comparisons of viscosity measurements with model predictions showed larger deviations for this fuel, the viscosity approach seems not to be suitable for olive residues which produce salt-rich and silicon-lean ashes. Therefore, the melt fraction approach, which is already being applied for deposit layers from condensing ash vapours, will also be applied as stickiness model for silicon-lean and salt-rich ash particles in the future.

Deviations between measurements and simulations concerning the deposited mass may partly be a result of the release factors applied to describe the release of ash vapours from the fuel which influence the mass fluxes of the coarse fly ash particles and the ash forming vapours. While calculations and measurements concerning the average deposit layer thickness (see Figure 14) are in relatively good agreement for waste wood and also for straw, the deviations are much larger for olive residues (predicted values are larger). Since for straw the agreement concerning the deposit layer thickness is much better than the agreement concerning the deposited mass and worse for olive residues, larger uncertainties in the calculation of the porosity and the density of the deposit layer, respectively, have to be considered. As already explained, more accurate models for porosity calculations including sintering are needed in the future. In this context, more detailed information on the particle density itself, which was set constant to an average value, is necessary as a basis for improved models.

The calculated chemical composition of the deposit layer is in good agreement with measurements for olive residues, in reasonable agreement for waste wood and also in reasonable agreement for straw but with larger quantitative deviations especially concerning the mass fraction of SiO_2 (measured value is higher than predicted value). While for olive residues, the chemical composition is nearly independent from the particle size class, in the cases of waste wood and straw the coarse representation of the particle size distributions as well as uncertainties concerning the ash release to the gas phase are possible reasons for larger deviations.

Furthermore, while for straw a good agreement of measurements and simulations regarding the fouling factor (average thermal resistance) of the deposit layer was found, the numerical results for waste wood and olive residues deviate stronger from the experimental data. For waste wood, these deviations can be explained by the low mass of ash deposited and, following, by enhanced measurement uncertainties. The deviations occurring especially for olive residues can be explained by the reasons leading also to deviations between measurements and simulations regarding deposited mass and average deposit layer thickness.

In general, a good qualitative and reasonable quantitative agreement between measurements and simulations concerning mass, average thickness, chemical composition as well as average thermal resistance was found. Concluding, even at the present state of development, the model can be applied for the support of plant designs by providing qualitative information. The influence of the fuel fired and operation conditions on the deposit formation processes can be investigated already in the design phase of the plant allowing for appropriate measures in order to reduce as deposit formation. However, the model validation has shown that further work is necessary in order to be able to achieve a more accurate prediction of aerosol and ash deposit formation. For further information see [4].

1.3.5 WP 4: Test runs at real-scale application

The objective of WP 4 was to perform test runs at pilot-scale and real-scale applications to gather data concerning aerosol and deposit formation as well as to gain real-scale data concerning the release of ash forming elements from the fuel. Furthermore, test runs at biomass and coal co-firing applications aim at the identification of potential problems related to fuel selection, increased deposit formation and boiler tube corrosion. In addition, it was an important objective to use the results and experiences from the test runs to verify the models developed and to apply them for the further development and optimisation of furnace and boiler designs as well as process control strategies.

Figure 15 gives an overview of the 4 plants where in total 7 test runs with different fuels have been performed. The test runs focused on the following main objectives:

- Fuel sampling and subsequent analyses of the fuels.
- Aerosol and fly ash sampling with low-pressure cascade impactors and total dust sampling in the flue gas downstream the boiler.
- Deposit sampling with conventional deposit probes as well as with long-term deposit probes developed within WP2.
- Aerosol sampling in the hot furnace applying the newly developed high temperature low-pressure impactor (developed and manufactured within WP 2).
- Flue gas measurements concerning CO, CO_2, O_2, SO_2 and HCl.
- Sample taking from all relevant ash fractions (bottom ash, furnace fly ash, cyclone fly ash, filter fly ash) and subsequent analyses of the samples taken.
- Recording of all relevant operation parameters (furnace temperatures, load, combustion air supply etc.).
- Calculation of mass and element balances over the respective plant.

Name	Mawera pilot-scale combustion plant	Dolna Odra power station	Elsterwerda CHP plant	Elean power station
Location	Hard, Austria	Nowy Czarnowo, Poland	Elsterwerda, Germany	Ely, United Kingdom
Fuels	wood chips BM2, bark BM1, waste wood BM3	co-firing of coal C1 and sawdust BM4, coal C1	waste wood	wheat straw BM6
Nominal capacity	0.44 MW$_{th}$	1,742 MW$_{el}$	44 MW$_{th}$, 12.6 MW$_{el}$	38 MW$_{el}$
Combustion system	grate-fired	pulverised fuel combustion	grate-fired	grate-fired
Date of test runs	January 2005	April 2005	August 2005	November 2005

Figure 15: Plants where test runs were performed within the BIOASH-project

Explanations: picture sources: 1) http://www.stadtwerk-elsterwerda.de
2) http://www.bartonwillmore.co.uk

Comparing the list of measurements performed and samples taken with the objectives concerning measurements and sampling mentioned above it can be stated, that the testing programme has been carried out as initially planned. In total more than 300 measurements (total dust, BLPI, HT-LPI, suction pyrometer, HCl, SO_x) have been conducted and almost 400 fuel and ash samples have been taken during the test runs within the BIOASH project. Approximately 5,600 parameters have been measured wet chemically in the TUG laboratory and more that 34 different samples have been investigated by means of SEM-EDX. Moreover, a total of 55 deposit samples taken by AAU and IEn have been analysed by means of SEM-EDX and compiled in a database by AAU.

Consequently a comprehensive data set concerning real-scale test runs is available. The information gained from the test runs has been used for the validation of models developed within the project (see WP 3), as well as for the comparison with lab-scale results of release investigations in fixed-bed and pf-fired systems (see also WP 1).

For all test runs mass and element balances over the respective plant, which have been calculated based on the measurement and analyses data as well as plant operation data, are available. Based on these balances the release of ash forming elements from the fuel has been evaluated and compared with results achieved from DTU and ECN during lab-scale test runs. Summarising, the comparison of results from mass balance calculations concerning the release of volatile ash forming elements from the fuel bed from the MAWERA test runs with results of fixed-bed release experiments (DTU) delivered a good correlation for most elements investigated (see WP 1, Figure 3). Also the release rates calculated for the test run at Elean power station (straw) matched well with results achieved from lab-scale test at DTU. Moreover, the results achieved during lab-scale (ECN) and real-scale test runs under pf-conditions were well comparable for almost all elements investigated.

In addition, a comparison of the concentration of particle bound aerosol forming species in the flue gas downstream the boiler and in the furnace (particle sampling with the newly developed high-temperature low-pressure impactor HT-LPI) has been performed. These investigations provide exciting information concerning the aerosol formation process. Figure 16 shows results for the test run performed at the Elsterwerda CHP plant where measurements at 4 sampling points along the flue gas path through the steam boiler were conducted. By comparing the results of HT-LPI measurements in the first duct and the second duct of the boiler, downstream the first superheater as well as BLPI measurements downstream the economiser, the particle formation process can be followed. It has for instance been shown, that about 67 wt% of the aerosol emission measured at boiler outlet, already exists in the first duct. This share increases up to 77 wt.% downstream the superheater (results calculated without consideration of the amount of aerosols condensed at boiler walls and boiler tubes).

Moreover, the application of SEM-EDX analyses of the samples gained from the impactors provides the possibility to analyse aerosol formation on an elemental basis. It has for instance been shown that during the combustion of waste wood at Elsterwerda Zn, K, Na, S and Pb are the most relevant constituents of the aerosols sampled in the first duct. ZnO particles are the first to be formed and thus Zn plays a relevant role concerning aerosol formation for waste wood. Later on, during the cooling of the flue gas in the radiative and the convective path of the plant, alkaline metal sulphates and chlorides as well as $PbSO_4$ and $PbCl_2$ undergo gas to particle conversion processes. A detailed evaluation of the aerosol formation pathways during test runs at the Elsterwerda CHP plant is given in [2].

During test runs with coal as well as during co-firing sawdust and coal, besides spherical aluminium silicate particles mainly $CaSO_4$ particles have been identified as relevant aerosol forming components.

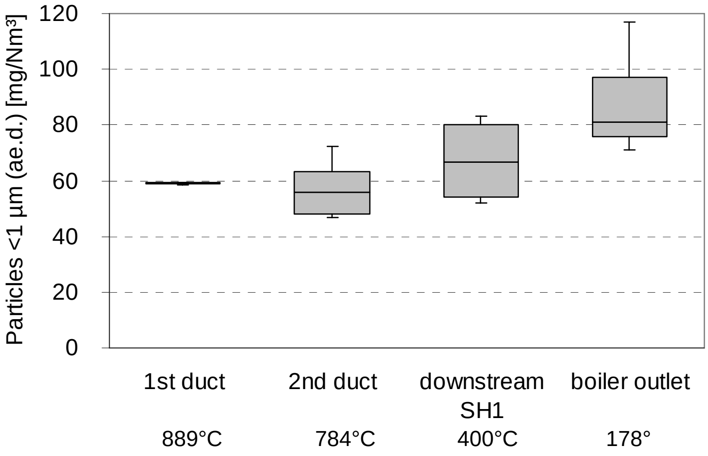


Figure 16: Concentrations of aerosols at 4 different sampling points for the combustion of waste wood at Elsterwerda CHP plant

Explanation: all concentrations related to dry flue gas and 13 vol.% O_2; ae.d.: aerodynamic diameter; the boxes indicate the quartiles 25% to 75%, the line in the box displays the median value, furthermore maximum and minimum values are indicated; number of measurements performed: 1st duct: 2; 2nd duct: 5; downstream SH1: 4; boiler outlet: 6

A further interesting finding achieved from SEM-EDX analyses is shown in Figure 17. It indicates that Si-particles occur in very small size ranges at high temperatures during the combustion of straw. Small amounts of Si in small size ranges were also found for the woody biomass fuels wood chips, bark and waste wood. However, Si-particles were not as clearly identified as for straw combustion.

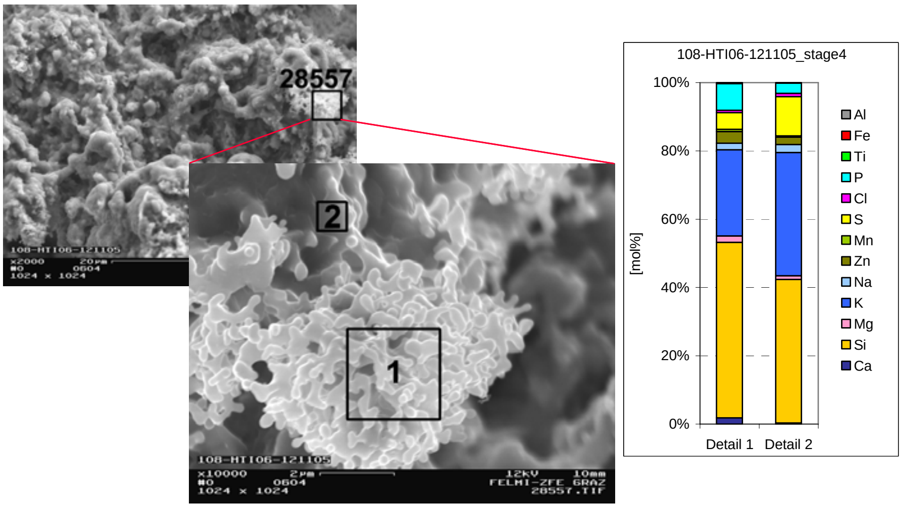


Figure 17: SEM-images and results of EDX-analyses of aerosols sampled at high temperatures directly in the furnace during straw combustion at Elean power station

Explanations: Sample No.: 108-HTI06-121105, stage 4 (stokes diameter 0.22 µm); measurement performed at temperatures at the sampling point between 1,000°C and 1,050°C;
bar charts show the result of EDX-analysis performed for details 1 and 2;
results normalised to 100% except O, Pt (material of sampling foil), Cr (component of the alloy of stainless steel 1.4841) and C (used for coating of the sample)

During the evaluation of deposit measurements performed at Elean power station AAU detected a decrease of Si in the deposits with increasing exposure time. This indicates small sticky Si-containing particles released directly from the fuel due to fragmentation from organically bound Si, which is in line with the results TUG achieved from HTI-measurements. Moreover, this assumption is strengthened by results of impactor measurements under pf-conditions performed by partner ECN with straw BM6. ECN reported that in the impactor stages with the lowest cut diameter inorganic matter was observed as submicron size particles, many of which still embedded in a carbonaceous matrix (residence time in the furnace 20 ms). EDX analyses confirmed that these are Si and/or Ca rich particles. In addition, EDX analyses of particles found on the surface of the ashed straw fuel (performed by DTU and AAU) revealed that the elements present in the highest amounts are silicon and potassium, followed by calcium and smaller amounts of chlorine and sulphur. Potassium was found combined mainly with silicon, possibly as K-silicate but also with sulphur and chlorine. Since the presence of significant amounts of K decreases the melting point of Si, it can be assumed that the K-silicate particles shown in Figure 17 originally were embedded in the surface structure of the straw, entrained and molten during the combustion. Therefore, it can be concluded that Si plays a significant role for the formation of aerosols during the combustion of straw most probably through fragmentation.

During all real-scale test runs deposit measurements have been performed by AAU and partly by IEn. All results have been listed in a deposit database. The database contains the deposit build-up rates and the compositions of the deposits analysed (analyses at 3 positions of each deposition ring). Additionally fuel and ash data related to the deposit probe measurements are mentioned. A total of 55 deposit samples (165 analyses) are listed in the database. In order to enlarge the database also data from an earlier project (EU-BIOAEROSOLS), where solely wood fuels were investigated, have been included.

In Figure 18 deposit build-up rates (RBU) as determined during pilot-scale test runs at partner MAW are shown. No significant dependence on the exposure time could be noticed. However, the tests showed a slight difference between the fuels, and the fuels can be ranked in an increasing fouling tendency as follows – wood chips < bark < waste wood.

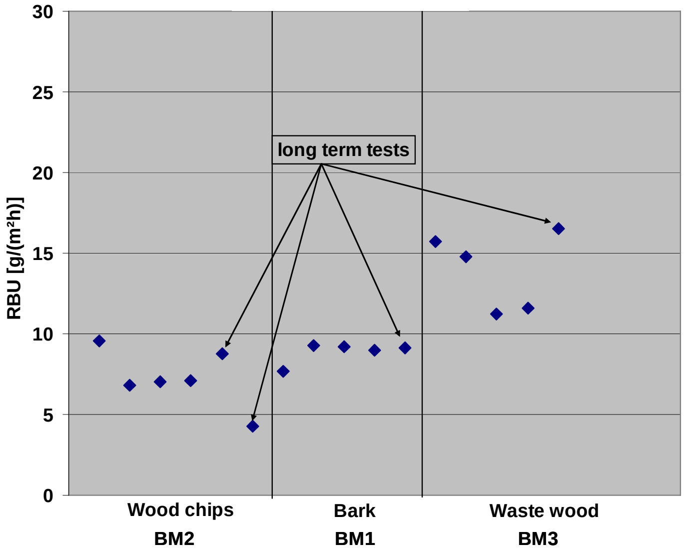


Figure 18: Rates of deposit build-up determined during test runs at the pilot-scale combustion unit of partner MAW

Explanations: RBU … rate of build-up; ring temperatures 330 – 550°C;
flue gas temperatures BM1: app. 800°C, BM2: app. 1,000°C, BM3: app. 950°C

1.3.6 WP 5 Aerosol precipitation in small-scale biomass combustion units

In medium and large-scale biomass combustion plants electrostatic precipitators (ESP) as well as baghouse filters are applied for particulate emission control. These technologies however are due to economic reasons presently not applicable for small-scale biomass combustion plants and therefore, currently no commercially attractive aerosol precipitation techniques for this capacity range are available. The aim of this WP was to investigate the possibility to reduce aerosol emissions in small-scale biomass combustion plants by stimulating condensation of aerosol forming vapours on heat exchanger surfaces (which is contrary to the goal of current heat exchanger designs) and thus to combine heat exchange and aerosol condensation in one unit, the so called aerosol condenser heat exchanger.

An analytical approach which incorporates heterogeneous- and wall condensation was derived to investigate whether there is a physical basis for condensation of aerosol forming elements on heat exchanger walls by preference. Consequently, stimulating wall condensation results in fine particulate emission reductions to the atmosphere. Continuum diffusion of molecules towards already present nuclei in the flue gas in combination with a correction factor for diffusion outside the continuum limit is used in the approach. This approach indicates a significant reduction of aerosol emissions by preference of wall condensation when sufficient heat exchanging area is provided, the distance to the wall in each cross section is in the millimetre range and the flow regime is laminar.

This approach has been tested at a MAWERA pilot-scale biomass combustion plant. A slip stream was extracted from the secondary combustion zone and fed to appropriate test heat exchangers. Two tubular water cooled heat exchangers and one triangular shaped gas to gas heat exchanger, both exhibiting typical equivalent tube diameters in the millimetre regime and Reynolds numbers up to 1,000 were applied. The trend derived from the calculations is a conservative one and showed a good agreement with the measurement results. The test runs have shown that a reduction in the particulate emission related to common boiler designs of more than 70% could be achieved using a gas to gas heat exchanger with an equivalent diameter of 2.22 mm (see Figure 19). In Figure 19 results of test runs with the heat exchangers are compared with the theoretical particulate emission reductions calculated in dependence on the tube diameters. The measurements confirm the trend obtained by the theoretical approach. Decreasing the equivalent tube diameter in the millimetre range results in a significant decrease of the particulate emissions.

Besides surface condensation of ash forming vapours also other particle and vapour deposition mechanisms (e.g.: thermophoresis) neglected within the modelling approach might influence particle precipitation in the aerosol condenser heat exchanger. Their effects on the precipitation efficiency are of second order and they are therefore not relevant for providing guidelines regarding the design of the heat exchanger. However, the influence of thermophoresis on particle precipitation is still a topic of further investigation.

For the future it is expected that the emission limits for particulate emissions from small-scale biomass combustion plants will be further decreased. Consequently, the demand for cost efficient aerosol precipitation techniques will gain rising relevance. With the concept of the aerosol condenser heat exchanger a start is made towards a simple and cheap aerosol precipitation technique. The concept realised with the gas to gas heat exchanger presented is an efficient approach in terms of precipitation efficiency, but is due to its complex geometry expensive to produce. Therefore, the concept has been simplified and adapted for flue gas to water heat exchange to make it applicable for small-scale biomass boilers.

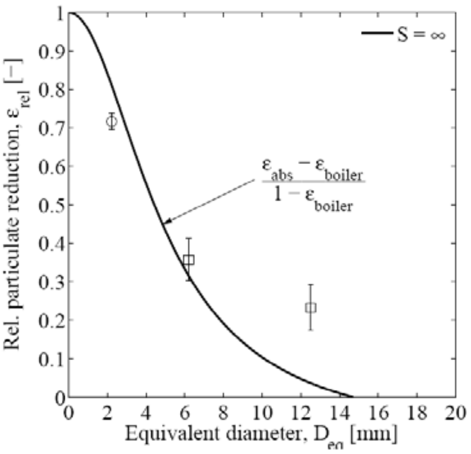


Figure 19: Comparison of theoretical and measured particulate emission reductions

Explanations: Theoretical (continuous line) and measured (○ = gas to gas heat exchanger, □ = water cooled heat exchanger) particulate emission reductions compared with emissions of plants with an ordinary boiler design (ε_{boiler} = 10%).

Using the model developed and the experience gained from the test runs, a fin-tube design with a fin spacing of 2 mm was selected. An appropriate heat exchanger has been designed by TUE, manufactured by MAWERA and tested at a MAWERA pilot-scale combustion plant in the same manner as the previous prototypes to have comparable process conditions. The thermal performance of the heat exchanger was as expected and an aerosol reduction of 65% compared to the emissions of the ordinary boiler could be achieved which also met the expectations. The condensed ash vapours formed a powdery layer on the heat exchanger surfaces that could easily be removed by pressurised air or a knocking system. Consequently, this design will be used for further optimisation in order to commercialise the new technology.

A paper which provides detailed information concerning the modelling and testing of the aerosol condenser heat exchanger has been submitted for publication to the Energy & Fuels-journal [14].

1.3.7 WP 6: Health effects of aerosols

The determination of the effect of particulate emissions from biomass firing and co-firing sources on the particulate imissions by performing exhaust gas distribution calculations and the evaluation of the main influencing parameters on the short-term toxicity of particulate emissions from biomass combustion and co-firing were the main objectives of WP 6.

Moreover, the estimation of effects of particulate emissions from biomass combustion and co-firing on the human health as well as the comparison with the risks caused by other particulate emission sources (e.g.: coal combustion, traffic) was another important goal.

Case studies concerning pollutant distribution calculations

The work performed by TUG focused on the determination of the effect of particulate emissions from biomass combustion on the ambient air quality, the evaluation of the particulate imission reduction caused by the substitution of single domestic heating appliances by a biomass CHP plant (combined heat and power plant) and the comparison of the contributions of traffic and heating to air quality regarding PM_{10}.

The dispersion of air pollutants is caused by local air flows and turbulences. For near-ground sources, these are dependent on the general meteorological conditions, the area structure and the land use facts. For all simulations, the prognostic dispersion model GRAL (Graz Lagrange model) served as a basis.

Several calculations have been conducted considering

- 2 different Austrian regions
  (urban: city A – 100,000 inhabitants, rural: city B – 25,000 inhabitants),
- different combustion plant capacities (44 MW_{th} at city A as well as 12 MW_{th} at City B),
- different scenarios concerning the PM emissions,
  - normal operation (emission data based on the test runs results; 1.1 mg/Nm³ measured at the Elsterwerda plant and 12.4 mg/Nm³ measured at a plant equipped with a wet ESP for city A and B),
  - lower filter efficiency for plant A (emission of 12.4 mg/Nm³),
  - emissions according to the PM emission limit of 50 mg/Nm³
    (all emission data related to dry flue gas and 13 vol% O_2), and
- 2 different weather scenarios (winter, summer).

Concerning the emission calculation for domestic heating the emission inventory for domestic heating from year 2004 was used for both cities. Moreover, households which already use a pipe-bound heat supply (e.g. natural gas) have been excluded from the calculation. Therefore, only domestic heating emissions caused by solid fuels and heating oil were taken into consideration for the calculation.

An example of the results achieved from these calculations is given in Figure 20 where the PM emission dispersion from plant A is compared with the PM caused by traffic and domestic heating. The simulations (at CHP plant emissions of 1.1 mg/Nm³) showed a very low additional PM_{10} burden caused by the biomass combustion plant not exceeding 0.04 µg/m³ (one year mean value). Due to bad dispersion conditions and higher heat demand during the winter period, a higher PM concentration level is detected for this period. Therefore, the mean additional burden of PM_{10} for the winter mean value (December, January and February) amounts to a maximum of 0.1 µg/m³ (see left image in Figure 20). As it can also be seen from Figure 20, these PM concentrations are almost neglectable compared to those caused by domestic heating and traffic.

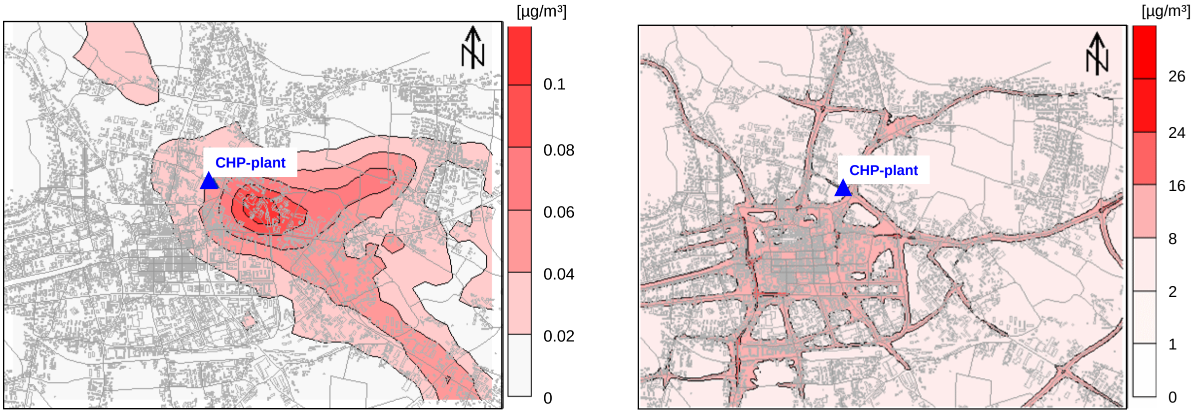


Figure 20: Additional PM_{10} burden caused by the biomass CHP-plant – calculated winter mean concentration values (left) and PM_{10} caused by domestic heating and traffic (right)

Explanations: CHP-plant: large scale waste wood fired unit (44 MW_{th}), normal operation with max. PM_{10} emission freights of 0.13 kg/h

In order to underline the different effects of additional burdens caused by the biomass CHP plants (which depend on the local climate and wind systems) two representative points per area have been chosen for detailed comparisons. Point 1 has been placed near the CHP plant to represent concentration values that are under significant influence of the exhaust flow trail, whereas point 2 has been placed offside the sphere of exhaust flow. The results for city A are outlined in Table 4. A local degradation of the air quality at point 1 occurs when assuming a PM emission of the CHP-plant of 50 mg/Nm³ (actual emission limit). However, it can be seen, that a significant improvement of the air quality can be reached by the application of appropriate filter technologies.

Concerning the influence of traffic it can be stated that offside main roads the effects of traffic on local air pollution are of minor influence (50% domestic heating – 50% local traffic volume). Along main roads a maximum burden of 26 µg/m³ (84% local traffic volume) has been calculated (right image in Figure 20). This means that along main roads and in the city centre the positive effect on the air quality by substitution of domestic heating by a biomass CHP plant is much lower than offside main roads.

Concluding, it can be stated that for both cities a significant contribution of domestic heating to the reduced air quality concerning PM_{10} was identified. If these households are connected to the biomass CHP plant through a district heating system, a notable improvement of the air quality situation can be achieved.

Table 4: Evaluation of different effects of additional burden on local air pollution levels of PM_{10} for City A

Explanations: CHP-plant: large scale waste wood fired unit (44 MW_{th}), point 1 represents concentration values that are under significant influence of the exhaust flow trail, point 2 represents concentration values offside the sphere of exhaust flow

City A	Point	CHP-plant	Domestic heating	Air quality
		Annual average concentration value [µg/m³]		
normal operation	1	0.03	2.14	-0.94
	2	0.01	2.26	-1.02
lower filter efficiency	1	0.36	2.14	-0.61
	2	0.11	2.26	-0.92
legally allowed limiting value	1	1.57	2.14	0.60
	2	0.47	2.26	-0.56
		Winter average concentration value [µg/m³]		
normal operation	1	0.07	4.21	-1.84
	2	0.02	4.47	-2.01
lower filter efficiency	1	0.73	4.21	-1.18
	2	0.20	4.47	-1.83
legally allowed limiting value	1	3.16	4.21	1.24
	2	0.86	4.47	-1.17

In-vivo and in-vitro tests with PM from biomass combustion and biomass co-firing and evaluation of parameters influencing the toxicity of PM from biomass combustion and co-firing

Health effects of 6 different fly ash samples from biomass combustion and co-firing plants were investigated in a 28-day nose-only inhalation study with Wistar WU rats. Respirable fractions of carbon black (Printex 90) and of titanium dioxide (Bayertitan T) were used as reference materials for positive and negative controls.

The fly ash samples BM1 (bark) and BM3 (waste wood) have been sampled during the pilot-scale test runs at MAWERA downstream multi-cyclone by applying a sampling device consisting of a cyclone and a fabric filter. Fly ash sample BM6 (straw) was sampled directly from the filter fly ash at Elean power station, whereas the fly ash samples C1 (Polish coal) and C1+BM4 (co-firing of coal and sawdust) were sampled at the last precipitation stage of the ESP. Since it was not possible to take a representative fly ash sample during the test run with wood chips (BM2), the fly ash sample BM2 was later collected at partner TUG during combustion tests at a comparable pilot-scale combustion plant with a comparable wood chips fuel and applying a more efficient sampling device.

To separate coarse fly ash particles which could occasionally have passed the cyclone upstream the particle sampling, all samples mentioned were subsequently sieved at 40 µm (smallest analytical sieve available). By comparing results from wet chemical analyses of the ash samples finally utilised for the in-vivo study with results of wet chemical analyses of the sub-micron fractions of impactor samples taken during the same test runs it was assured, that for all in-vivo tests the same amount of sub-micron particles was redispersed.

The health effects of other relevant ambient air particles like diesel exhaust particles (DEP) have been investigated in the last decades in various studies including animal studies, in-vitro cell tests, epidemiological studies and controlled short term human exposures. These studies have shown two major endpoints, the induction of lung tumours and the cardiovascular effect in a sensitive subpopulation of humans. For both endpoints inflammatory effects in the lungs were considered as early indicators in short term studies. Therefore, the investigation of the aerosols from biomass combustion and coal and biomass co-firing in the present study focused predominantly on the analysis of inflammatory effects in the lungs of rats by bronchoalveolar lavage (BAL) and histopathology.

The MMAD (mean mass aerodynamic diameter) of all fly ash samples and reference materials was in a similar range between 1.5 and 3 µm. Therefore, the deposition of these particles in the respiratory system was similar for all samples.

For different parameters (percentage of polymorphonuclear neutrophils (PMN), Interleucin-8 and interstitial inflammatory cell infiltration in the lung tissue) indicating inflammatory effects in the lung, a significant increase was observed for groups exposed to carbon black, C1 and C1+BM4 fly ashes (see all results in Table 5). Additionally, for the same groups a significant increase of cell proliferation in the lung epithelium was detected. These effects which were observed already after 4 weeks of exposure could be early indicators for the development of lung tumours. In a 2 year inhalation study with rats using a similar exposure concentration as in the present study for carbon black as well as for diesel exhaust particles lung tumours were detected.

The common characteristic of carbon black, C1 and C1+BM4 is the high content of insoluble particles whereas the other biomass fly ash samples BM1, BM2, BM3 and BM6 mainly consist of soluble salts. After inhalative exposure these salts are dissolved very fast and cleared from the lung by the blood stream. Therefore, the concentration of soluble fly ash particles is very low in the lung after long term inhalation whereas insoluble particles accumulate in the lung. For the insoluble particle samples C1 and C1+BM4 the effects on inflammation and cell proliferation in the lung were similar or slightly lower than for the carcinogenic carbon black or diesel exhaust particles. For the soluble fly ash samples no adverse health effects were detected in the present study.

This means, in this in-vivo study the percentage of insoluble particles in the fly ash samples was the important parameter which influences the potency for the induction of adverse health effects.

It has to be taken into account that the particle samples used in this study originated from state-of-the-art biomass combustion plants respectively from real-scale coal as well as biomass and coal co-firing power plants. In these installations combustion technology and combustion control are highly advanced and therefore, the gas phase burnout is almost complete and the TOC concentrations in the total ashes are <5 wt% d.b. As a consequence only minor amounts of TOC emissions (<2 mg/Nm^3) could be determined and therefore, the fine particulate emissions almost exclusively consist of inorganic salts. Moreover, particle precipitation devices such as baghouse filters or ESPs are applied in order to reduce particulate emissions. In old biomass residential heating systems on the other side, TOC emissions and consequently also soot and organic aerosol emissions can be significantly higher. In this case, the health effects caused by the fine particulate emissions might be more comparable with those of the carbon black samples applied in this study than with the samples from well controlled biomass combustion.

However, an important aim for future research on this topic should be to investigate the influence of the combustion quality on the health effects of the particulate emissions with special respect to biomass based residential heating systems.

Table 5: Summary of results from the in-vivo study

Explanations: data in % of the control sample, BAL … Bronchoalveolar Lavage; PMN … polymorphonuclear neutrophils; LDH … lactic dehydrogenase; GSH … reduced glutathione; statistics: comparison to control group by Dunnett's test: * p<5%; ** p<1%; a … Values are shown as percental incidence of lesion

Parameter	Control	BM1	BM2	BM6	BM3	C1+ BM4	C1	TiO_2	Carbon black
Lung weight	100	105	100	102	98	103	101	100	**120
Lung function									
Dynamic compliance	100	97	100	110	97	112	95	98	122
Lung resistance	100	85	85	78	92	91	98	84	106
BAL results									
PMN	100	73	138	188	120	**1,099	**1672	68	**6,203
LDH	100	86	84	88	110	151	161	88	**396
Total Protein	100	103	106	97	99	**143	**148	95	**218
GSH	100	93	94	76	126	*136	121	94	128
Interleucin-8	100	87	104	84	111	**311	**517	87	**1,383
Histopathology									
Lung inflammatory cell infiltration[a]	17	50	67	67	50	67	*83	17	**100
Interstitial fibrosis[a]	0	0	0	0	0	17	33	0	**100
Cell proliferation lung parenchyma	100	98	102	121	96	*137	**172	86	**155

Within the in-vitro study the same test and reference items were investigated by exposure to human alveolar epithelial cells (cell line A549) to see if effects to human lung cells are comparable to rat lung cells.

In this in-vitro study inflammatory effects were induced by the biomass fly ash samples BM3, BM1 and C1+BM4. The highest effect was observed for the BM3 sample which contained the highest percentage of heavy metals (Zn and Pb). In contrast to the 4 week inhalative exposure, in the short term in-vitro test the soluble salts of the biomass fly ash samples BM3, BM1, BM2 and BM6 cannot be cleared from the exposure system. It was estimated that the concentration of the soluble material per area of exposed cells was approximately 4 orders of magnitude higher in the in-vitro test compared to the in-vivo study.

Therefore, the relevance of the in-vitro results using soluble fly ash samples is low regarding long term exposure effects of humans by inhalation.

Merging of data from pollutant distribution calculations and the results from investigations of aerosols on health effects

When merging the results from pollutant distribution calculations and results achieved from in-vivo and in-vitro studies it must be stated that the local traffic volume contributes considerably to the total PM_{10} burden. Since diesel soot is comparable with the carbon black reference sample used in this study, it can be stated that PM_{10} emissions caused by traffic have a considerably higher potential for causing health effects than emissions caused by a modern biomass CHP plant equipped with appropriate filter technology.

Concerning the toxic effects of heavy metals it has to be stated that, in principle, the dissolution of salts containing heavy metals could cause health effects especially for PM_{10} from combustion units firing waste wood.

The fly ash sample from the waste wood combustion plant investigated in this project contained 8.2 wt% (d.b.) Pb and 12.2 wt% (d.b.) Zn. Inorganic Pb has been classified by IARC in category 2B (possibly carcinogenic for man). In Germany, according to TA Luft (Technical Instructions on Air Quality Control, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany, July 24, 2002) the permissible maximum ambient concentration for Pb in airborne dust is 2 µg/m³. Consequently, the ambient PM concentration caused by the waste wood fired CHP plant investigated in this study has to be below 24 µg/m³. Even in the worst case (winter, PM_{10} emission of 50 mg/Nm³) the calculated mean concentration of PM_{10} is approximately 4 orders of magnitude lower than this value.

Compared to Pb, the lower limit of the toxic concentration for Zn is significantly higher. Zn is an essential trace element for humans. Daily ingestion of 15 mg Zn by food is supposed to be harmless. The inhaled air volume is approx. 12 m³ per day for humans. Therefore, for fly ash samples containing 12.2 wt.% (d.b.) Zn the uptake of Zn by inhalation of a total dust concentration of even 50 µg/m³ (EU limit for PM_{10}) will be 0.07 mg/day, which is more than two magnitudes below the 15-mg limit.

The concentration of heavy metals in other biomass fuels like wood chips, bark, straw, saw dust and olive residues is much lower than for waste wood (see also the composition of BIOASH-fuels in Table 2) and consequently also the concentration of heavy metals in aerosols formed during the combustion of these fuels is lower. Therefore, PM_{10} emissions of biomass combustion units firing fuels with low heavy metal concentrations can be evaluated as not health relevant from this point of view.

In conclusion it can be stated that modern medium and large-scale biomass combustion plants ensure an almost complete burn-out and apply appropriate PM emission control. Therefore, the PM emissions of these plants are comparably low and are dominated by water soluble alkaline salts. It has been shown, that these particles have low health relevance. On the other hand PM emissions from residential heating, especially from old installations with bad burn-out qualities, can contain considerable amounts of organic aerosols. Consequently, the health relevance of these emissions has to be evaluated higher (confirmed by the results of the in-vivo results regarding carbon black). The substitution of old residential heating systems by biomass fired district heating plants is therefore very efficient in reducing health risks caused by PM emissions.

Moreover, PM_{10} emissions caused by traffic are dominated by organic species, and thus, as outlined in this study, are of high health relevance for humans. The health effects of insoluble diesel soot can be directly compared with those obtained for carbon black used in this study. Therefore, the reduction of PM emissions from traffic should in any case be an important aim, especially since particulate emissions from traffic contribute considerably to the total PM burden.

For future research it is suggested to focus on the investigation of the influence of different concentrations of organic carbon and soot in aerosol emissions from residential wood combustion (different burn-out qualities) on health effects. This field is presently almost unexplored but of high relevance, since these emissions significantly contribute to the ambient air quality situation in many European regions.

1.4 Summary, concluding remarks and potential for future R&D work

Summarising, it can be stated that all milestones and deliverables defined have been successfully reached. The work performed and the results achieved represent an important step forward in the research field of ash and aerosol related problems in biomass combustion and co-firing.

The release behaviour of easily volatile elements from the fuel has been investigated in detail and comprehensive knowledge about it is now available. In order to obtain reliable quantitative data on the release of inorganic elements during combustion under grate-fired or pf conditions it is recommended to perform lab-scale combustion tests on the actual fuel. To support the interpretation of the lab-scale release data, advanced fuel characterisation by use of STA-analyses and chemical fractionation (CF), as well as global equilibrium analyses (GEA) of thermal fuel conversion systems, provide valuable additional information on the release of inorganic elements. If carefully adapted to fuel and combustion conditions, especially GEA can be very valuable for modelling the release behaviour. Therefore, GEA should be combined with lab-scale release measurements for the purpose of modelling ash or aerosol formation during biomass combustion. In addition, pilot-scale mass balance tests are very useful for obtaining a complete picture of the combustion behaviour of a fuel and as a basis for the appropriate design of a large-scale plant.

The results of extensive DTG/DSC studies were applied to improve a thermodynamic melting model for alkali salt mixtures containing Pb and Zn. The data set combined both gas phase species, solid and liquid compounds and solid and liquid solutions. The improvements made to existing data bases make it the most comprehensive and reliable model available at present for calculations related to metal release, gas phase speciation, fine particle speciation and estimated composition for coarse ash fractions. Furthermore, it can be used to estimate the melting behaviour of various ash fractions, based either on predicted or analysed elemental composition and gaseous conditions. This melting model will also act as an important tool in the course of the further development of CFD-based deposit formation models for biomass combustion and co-firing plants.

The high-temperature viscosity of ash systems has been successfully measured over a range of compositions, relevant in biomass (co-)combustion processes. An extensive dataset has been established, which can be used as a basis to model the deposition by impaction of ash particles, or the behaviour of molten slags in general. The results of these tests match well with literature data and have provided valuable input for modelling tasks of the project and for biomass combustion and co-firing in general.

The potential of ash deposits for corrosion as a function of deposit composition and exposure time has been determined for waste wood conditions. The results indicate that the presence of metal chlorides in deposits strongly enhances the corrosion attack, by chlorine-induced corrosion. A straightforward relationship between the deposit composition and the corrosion rate was not found, but the results indicate that the formation of a melt (probably containing K, Zn, S and Cl) may have an influence on the corrosion rate (melt-induced corrosion). The exact corrosion mechanisms could however not be identified in this study, because of the lack of phase diagrams for the chemical systems involved and because of the complexity of the system, due to possible interactions between the deposit and the flue gas (containing HCl and SO_2). Further work is needed and recommended to investigate these issues in detail.

An existing basic model for simulating aerosol formation during biomass combustion was improved in order to contribute to a better understanding of aerosol formation and behaviour. Subsequently the model was applied for several test cases (test runs performed within the BIOASH project) in order to compare and evaluate modelling and measurement results. Generally, the quality of the results was strongly dependent on the quality of the input data, which confirmed the approach of improving the modelling quality by the preparation of detailed input data sets for the biomass fuels investigated. Furthermore, good results regarding the chemical compositions and the particle size distributions of aerosol particles were achieved, which confirmed the applicability of the model. Moreover, the formation pathways of the aerosol particles during the combustion of the different fuels investigated at different combustion plants could be reproduced well.

Advanced aerosol formation models and deposit formation models have been coupled with CFD-codes. Moreover, the CFD deposit formation model developed has been validated with deposit probe experiments performed within the project. In general, a good qualitative and reasonable quantitative agreement between measurements and simulations concerning mass, average thickness, chemical composition as well as average thermal resistance was found. Concluding, even at the present state of development, the model can be applied for the support of plant designs by providing qualitative information. The influence of the fuel fired and operation conditions on the deposit formation processes can be investigated already in the design phase of the plant allowing to set appropriate measures in order to reduce ash deposit formation. However, the model validation has shown that further work in the fields of aerosol modelling (particle size distribution modelling) as well as of ash deposit formation modelling (modelling of particle stickiness; interaction with aerosol formation and deposit growth under consideration of erosion and shedding as well as interaction with heat transfer; link of deposit formation model with heat exchanger models) is necessary in order to move a step further towards a more accurate prediction of aerosol and ash deposit formation in the whole biomass combustion plant including the convective section of the boiler.

In order to gain real-scale data concerning the release of ash forming species from the fuel as well as aerosol formation and deposit build-up test runs at pilot-scale as well as real-scale grate-fired biomass combustion plants firing wood chips, bark, waste wood and straw as well as at a power station co-firing sawdust and coal have been performed. The data achieved from these test runs acted as a basis for the validation and calibration of the models developed within the project. Moreover, the comparison of the real-scale data concerning the release of ash forming elements from the fuel with the results from the lab-scale experiments showed that in comparable temperature ranges comparable release ratios could be achieved. Generally, it can be concluded that pilot-scale test runs are very useful for the characterisation of the combustion behaviour of "new biomass fuels" (fuels not well known yet, e.g. herbaceous biomass fuels) as a basis for plant design.

Currently, no commercially attractive aerosol precipitation techniques for small-scale biomass combustion plants are available. Thus within this project the possibility to reduce aerosol emissions by stimulating condensation of aerosol forming vapours on heat exchanger surfaces should be investigated. A simple model in order to calculate the fine particulate emission reduction for such applications was derived. To verify the trends predicted by the model, measurements with specially designed test heat exchangers connected to a grate fired biomass combustion unit have been performed. Regarding the emission reduction versus the heat exchanger tube diameter, the results of test runs confirmed the modelling results. Aerosol emission reductions compared with conventional boiler designs of approximately 70% could be achieved. Concluding, it can be stated that the initial assumption that a heat exchanger can be designed which makes an efficient aerosol emission reduction possible was proven. These findings represent an interesting basis for practical application in small-scale biomass combustion plants.

The effect of particulate emissions from biomass combustion and co-firing on the air quality has been determined by performing exhaust gas distribution calculations. Several case studies considering 2 different Austrian regions (urban/rural), 2 combustion plants, 3 different scenarios concerning the PM emissions and 2 different weather scenarios (winter/summer) have thereby been performed. In conclusion it can be stated that for both regions, a significant contribution of PM_{10} to the annual mean value was noted from residential heating systems using solid fuels. By connecting these households to a biomass CHP plant through district heating, the areas could significantly reduce their pollution burden. Moreover, a significant improvement of the air quality could be reached by the application of a highly efficient particulate emission control technologies. In addition it can be stated that a considerable fraction of the total PM_{10} burden is caused by traffic. However, the effect of traffic on local air pollution is of much higher influence along main roads and in the city centre than offside main roads. Consequently, also the positive effect on the air quality by substitution of domestic heating by a biomass CHP plant is much lower along main roads than offside main roads.

Comprehensive test series (in-vitro as well as in-vivo) were carried out concerning the assessment of health effects by PM emissions from biomass firing and co-firing. Results of in-vivo tests e.g. showed that for different parameters indicating inflammatory effects in the lung, a significant increase was observed for groups exposed to carbon black (positive control sample), fly ash sample C1 (coal) and fly ash sample C1+BM4 (co-firing of coal and sawdust) which all contain poorly soluble particles. In contrast, the biomass fly ash samples predominantly consist of salts which are characterised by high water solubility. Therefore, after inhalation exposure most of the fly ash material is cleared from the lung by dissolution and transportation by the blood stream. Thus the concentration of these fly ash samples in the lung in a long-term study (which is also the normal situation for human exposure) is very low. This explains why the fly ash samples from biomass fuels showed no effects in the lung of exposed animals. In principle, the dissolved elements could induce systemic toxicity in other organs, which could be true for heavy metals. However, under consideration of the low concentrations of heavy metals in the fly ash samples investigated, most presumably no relevant health effects will be induced by dissolved heavy metals. Even for the waste wood fly ash sample the calculated ambient concentrations for Pb and Zn are by far lower than legally allowed.

The long-term in-vivo exposure tests have shown that especially particle fractions with low water solubility as well as particle fractions with high organic or elemental carbon contents can cause health effects. The latter is especially of relevance for particulate emissions from small-scale biomass combustion plants, where, compared with medium- and large-scale applications, considerable amounts of carbonaceous species can be contained in the aerosols due to incomplete gas phase burnout. This topic however, is presently almost unexplored and should be addressed by future research projects.

As it can be seen from the sections above the project has been concluded successfully. However, to identify issues which are still not solved/answered satisfactorily and which request further R&D work (especially with respect to potential follow-up projects within FP7), a final evaluation and discussion concerning the work and the results achieved within each work package took place at the project co-ordination meeting in Eindhoven in February 2007. The outcomes of this discussion are summarised below.

- A demand for future R&D work is given in the field of fluidised bed combustion of biomass, as for this technology the release of ash forming elements is not well defined.
- The appliance of “new” biomass fuels (especially agricultural fuels or agro-industrial residues) for combustion and co-firing, which are expected to cause problems concerning fouling and deposit build-up, should be additionally investigated in future as for these fuels very rare information is existing so far.
- Another very important and interesting issue for future work is the investigation of the influence of fuel blending as well as of the utilisation of additives on the release as well as on the deposit and melt formation behaviour.
- Further work concerning the corrosive potential of aerosols and fly ashes is needed in order to identify the exact corrosion mechanisms induced and their influencing variables.
- The further improvement of the developed CFD-based deposit formation model is a relevant future task. Besides comprehensive experiments for the further development and validation of the models (e.g. erosion, radiative emissivity), further evaluation and development of sub-models is needed (e.g. stickiness, shedding). Moreover, it is recommended to consider also plain walls in future work (wall fouling). Concerning advanced aerosol formation modelling it was supposed that the formation of aerosols immediately above the fuel bed may have a very large impact on the resulting particle size distribution. Therefore, the focus for future R&D work should consider this issue.
- The principle of the aerosol condenser developed within the project has shown its applicability for aerosol precipitation in small-scale biomass combustion plants. As a basis for a market introduction further developments concerning an adaptation to practical needs as well as concerning the implementation of an automatic cleaning system are needed. Moreover, subsequent long-term testing of the aerosol condenser is necessary.
- Concerning the assessment of health effects it is recommended to investigate especially small-scale biomass combustion systems in future. In contrast to the large-scale biomass combustion units investigated within the BIOASH project, samples from e.g. old domestic heating systems can contain large amounts of organic or elemental carbon due to incomplete burn-out. Moreover, multiple dose studies should be performed in the future in order to determine the NOAEL (no adverse effect level) and thus to secure and check the toxicological results achieved so far and to extend them to small-scale systems.
- Therefore, as already mentioned earlier, the investigation of the influence of the combustion quality on the health effects caused by particulate emissions with special respect to residential biomass heating systems is an important topic for future research.

2 DISSEMINATION AND USE

Exploitable knowledge and its use

Comprehensive fuel-specific data concerning ash formation, ash deposition and the release of volatile elements from the fuel for fixed bed as well as pf systems are available for all BIOASH-fuels (fixed bed release only for bark BM1, wood chips BM2, waste wood BM3 and straw BM6). The data have already been used within the project as valuable input data for the modelling tasks and will also serve in future as relevant basis data for an appropriate furnace and boiler design.

Moreover, ECN will use this information to enhance and support industrial co-firing activities by means of active participation and consultation. Using the data, ECN develops predictive tools which can be applied in fuel selection or process optimisation, both aiming to reduce ash-related problems in biomass co-firing.

Results of investigations of secondary reactions in the system K-Ca-Si as well as of the quantification of surface chemistry by TOF-SIMS again provide valuable information for the modelling of deposit and aerosol formation processes.

The new thermodynamic database gained from the project can be used for both oxidising and reducing conditions and takes into consideration reactions between gas and condensed phases (release) and melting behaviour of Pb- and Zn-containing salts. The improvements made to existing data bases make it the most comprehensive and reliable one for calculations related to metal release, gas phase speciation, fine particle speciation and estimated compositions for coarse ash fractions. Furthermore, it can be used to estimate the melting behaviour of various ash fractions, based either on predicted or analysed elemental composition and gas phase conditions. The database was subsequently used to calculate the ash reactions during combustion of the BIOASH-fuels. The results are given as GEA-Atlas (Global Equilibrium Analysis Atlas) that can be used to determine which chemical ash compounds are stable in different conditions. The GEA is a powerful tool for the first analysis of ash reactions in combustion systems. The very simplified estimation of the combustion device to be a well mixed plug flow reactor with a temperature gradient provides useful information for both, design and operation of biomass combustion units.

The full-scale deposit measurements provide a relevant database for fuel and deposit characterisation (deposit rate of build up, elemental compositions of the deposits, fuel analyses results) which is highly relevant for the development and validation of empirical models.

IEN and AAU have designed and manufactured new types of probes for the determination of deposit build-up in biomass combustion and biomass and coal co-firing applications. In contrast to common techniques, the application of the new probes also provides information about heat flux as well as the possibility of an optical control of deposit build up. At IEN a PhD study dealing with the development and application of these new probes will be finalised soon. Moreover, the probes have already been successfully applied during the test runs within the BIOASH project to gain new and valuable data concerning deposit formation. These data will serve as an important basis for the further development of deposit formation prediction tools.

Furthermore, AAU and IEn will use the new probes in future within their activities concerning deposit formation measurements at commercial installations. The results gained from these measurements will help the operators to reduce deposit formation problems in the boiler and the convective heat exchanger sections in order to increase the efficiencies and the availabilities of their plants.

The newly developed high-temperature low-pressure impactor (HT-LPI) provides the possibility of aerosol sampling in high temperature environments (about 1,000°C). The data gained from measurements with the HT-LPI give new and valuable insights into aerosol formation processes and therefore contribute to a better understanding of the mechanisms involved. Furthermore, these data can also be used as a basis for deposit formation modelling in combustion processes. The HT-LPI has already been successfully applied within the project during the real-scale test runs.

Future applications of the HT-LPI are seen in R&D programs which deal with fine particle related issues during combustion processes. Therefore, TUG aims at a broad application of this unique device within future research projects and also expects a strong interest of furnace and boiler manufacturers regarding measurement campaigns with the HT-LPI.

During the test runs at different real-scale biomass combustion and biomass and coal co-firing plants, comprehensive data concerning ash and aerosol formation have been gained. Furthermore, data and experiences concerning the interactions between fuel composition, plant operation and ash and aerosol formation result from this work. TUG will use these data and experiences as a basis for the solution of ash related problems within other research projects as well as for the development and optimisation of industrial plants.

An already existing computer code for the simulation of aerosol formation in fixed-bed biomass combustion systems was substantially improved within the BIOASH project. Moreover, the aerosol formation model was extended to an application for pulverised fuel systems as well as water tube steam boilers. As a result more precise predictions of aerosol formation in biomass combustion and co-firing units should be possible in future. TUG will use this model for the prediction of aerosol formation in combustion units which is a relevant issue concerning deposit formation and emission control and will also support industrial furnace and boiler developments with this model in the future.

In order to minimise problems related to ash deposit formation in biomass combustion plants, a CFD model for the prediction of ash deposit formation was developed as a flexible engineering tool for plant design. Before the start of the BIOASH project the effects of condensation of ash forming vapours and the precipitation of silicon rich coarse fly ash particles in the furnace and the radiation section of the boiler were considered in the modelling approach. In the framework of this project, this model was considerably extended and validated. New sub-models for aerosol formation (single particle diameter), particle adhesion, deposit erosion as well as time dependent deposit build-up and heat transfer through deposits were implemented. TUG intends to apply this model as engineering and analysis tool for biomass combustion plants. Moreover, TUG intends in collaborations with other scientific partners to further develop the model regarding the issues discussed in section 1.4.

Moreover, the results achieved during real-scale test runs as well as the application of the models developed provide valuable input for the improvement of furnace and boiler designs. The participation of the industrial partners (MB, SKG, MAW) will ensure, that the innovations, experiences and the results gained from the project are directly applied to real-scale applications.

Guidelines for the design of a so-called aerosol condenser heat exchanger, which is a device for combined heat exchange and fine particle emission control for small-scale biomass furnaces, have been developed by TUe in cooperation with TUG. Based on these guidelines prototypes of the aerosol condenser heat exchanger have been designed, manufactured and tested. The results achieved are promising concerning the applicability of this new and innovative device for small-scale biomass combustion units. A patent application for this aerosol condenser heat exchanger has been made.

Within the BIOASH project investigations concerning the health effects of aerosols have been conducted. These new and first results concerning health effects of PM emissions from medium and large-scale biomass combustion and co-firing plants will act as an important basis for advanced future R&D work on this subject. Relevant and important information concerning appropriate emission control strategies and the toxicological effects of aerosols from biomass combustion and co-firing were achieved.

Dissemination of knowledge

In order to make the project, its objectives and its outcomes visible in the public the following activities have already been performed.

On the 18th of March 2005 the international Workshop “Aerosols in biomass combustion” took place in Graz, which was jointly organised by the project coordinator TUG in close cooperation with IEA Bioenergy, Task 32, “Biomass combustion and co-firing”. This seminar has also been used to introduce the BIOASH project to a considerable number of international experts from 10 European countries. ECN, DTU, AAU, TUe and TUG gave presentations linked to the work within BIOASH at this seminar (see [9], [10], [11], [12] and [13]). Not only technicians, but also experts from medicine and people from public authorities have participated in the seminar. The proceedings of the seminar are published in the following book:

- OBERNBERGER Ingwald (ed), BRUNNER Thomas (ed), 2005: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series "Thermal Biomass Utilization", Volume 6, ISBN 3-9501980-2-4, published from BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

In the frame of the World Energy 2006 conference in Jönkoping (Sweden) a Biomass FP6 Project Contractors’ Meeting has been held on May 31st, 2006. An overview of actual results achieved during the project has been presented by the co-ordinator in the frame of this meeting.

From October 29th to November 3rd, 2006 a conference focusing on the “Impacts of Fuel Quality on Power Production” was held in Snowbird, Utah, USA. 8 papers (see [1], [2], [3], [4], [5], [6], [7] and [8]) dealing with results achieved within Workpackages 1, 2, 3, 4 and 6 were published in a special session which was dedicated to the work within the BIOASH project. The session named “Ash & Aerosol Formation – European Experience” took place on the 2nd November 2006. For at least 2 of these papers ([3], [7]) it is already known that they are accepted for a special issue of the international journal “Fuel Processing Technology”.

Moreover, several publications dealing with the results of the BIOASH project are in the pipeline and will be presented within this and the next year at conferences as well as in scientific journals.

3 REFERENCES

[1] BRINK Anders, LAURÉN Tor, YRJAS Patrick, HUPA Mikko, FRIESENBICHLER Joachim, 2007: Development and evaluation of a long-term deposit probe for on-line monitoring of deposit growth. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.7-40 to 7-60, EPRI (Ed.), Palo Alto, CA; USA

[2] BRUNNER Thomas, FRIESENBICHLER Joachim, OBERNBERGER Ingwald, BERNER Axel, 2007: Development, test and application of a new low-pressure impactor for particle sampling at high temperatures up to about 1,000°C. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.7-61 to 7-76, EPRI (Ed.), Palo Alto, CA; USA

[3] JOELLER Markus, BRUNNER Thomas, OBERNBERGER Ingwald, 2007: Modeling of aerosol formation during biomass combustion for various furnace and boiler types. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.7-78 to 7-94, EPRI (Ed.), Palo Alto, CA; USA

[4] SCHULZE Kai, HOFMEISTER Georg, JÖLLER Markus, SCHARLER Robert, OBERNBERGER Ingwald, KORBEE Rob, CIEPLIK Mariusz, 2007: Development and evaluation of a flexible model for CFD simulation of ash deposit formation in biomass fired boilers. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.7-95 to 7-113, EPRI (Ed.), Palo Alto, CA; USA

[5] BELLMANN Bernd, CREUTZENBERG Otto, KNEBEL Jan, RITTER Detlef, POHLMANN Gerhard, 2007: Health effects of aerosols from biomass combustion plants - first results. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.8-3 to 8-15, EPRI (Ed.), Palo Alto, CA; USA

[6] KORBEE Rob, CIEPLIK Mariusz, 2007: Ash formation from biofuels and coal in pf systems. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, EPRI report No. 1014551 (2007), pp.8-29 to 8-43, EPRI (Ed.), Palo Alto, CA; USA

[7] FRANDSEN Flemming, VAN LITH Simone, KORBEE Rob, BACKMAN Rainer, YRJAS Patrick, OBERNBERGER Ingwald, BRUNNER Thomas, JÖLLER Markus, 2007: Quantification of the Release of Inorganic Elements from Biofuels. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, pp.9-66 to 9-90, EPRI report No. 1014551 (2007), EPRI (Ed.), Palo Alto, CA; USA

[8] FRANDSEN Flemming, MOIRAGHI Laura, VAN LITH Simone, LIN Weigang, 2007: Residual Ash Formation during Oxidative Thermal Conversion of Spruce and Bark under Lab-Scale Fixed-Bed Conditions. In: Proc of the Int. Conf. “Impacts of Fuel Quality on Power Production”, pp.6-47 to 6-69, EPRI report No. 1014551 (2007), EPRI (Ed.), Palo Alto, CA; USA

[9] KORBEE Rob, CIEPLIK Mariusz, KIEL Jacob, 2005 Release of aerosol forming species during combustion in pulverised fuel systems. In: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series "Thermal Biomass Utilization", Graz University of Technology, Vol. 6, pp. 55 to 64, ISBN 3-9501980-2-4, Graz, Austria

[10] FRANDSEN Flemming, MOIRAGHI Laura, VAN LITH Simone, JENSEN Peter, GLARBORG Peter, 2005: Release of metals, sulphur and chlorine and residual ash formation during biomass combustion on a grate. In: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series "Thermal Biomass Utilization", Graz University of Technology, Vol. 6, pp. 65 to 78, ISBN 3-9501980-2-4, Graz, Austria

[11] JÖLLER Markus, BRUNNER Thomas, OBERNBERGER Ingwald, 2005: Modelling of aerosol formation. In: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series "Thermal Biomass Utilization", Graz University of Technology, Vol. 6, pp. 79 to 106, ISBN 3-9501980-2-4, Graz, Austria

[12] VAN KEMENADE Erik, 2005: Aerosol and particle transport in biomass furnaces. In: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series

"Thermal Biomass Utilization", Graz University of Technology, Vol. 6, pp. 107 to 118, ISBN 3-9501980-2-4, Graz, Austria

[13] BACKMANN Rainer, SKRIFVARS Bengt-Johan, YRJAS Patrik, 2005: The influence of aerosol particles on the melting behaviour of ash deposits in biomass fired boilers. In: Aerosols in Biomass Combustion – Formation, Characterisation, Behaviour, Analysis, Emissions, Health Effects, book series "Thermal Biomass Utilization", Graz University of Technology, Vol. 6, pp. 119 to 132, ISBN 3-9501980-2-4, Graz, Austria

[14] DE BEST Carlo .J.J.M., VAN KEMENADE Erik, BRUNNER Thomas, OBERNBERGER Ingwald, 2007: Particulate emission reduction in small-scale biomass combustion plants by a condensing heat exchanger. to be published in Journal “Energy & Fuels”

[15] SCHARLER Robert, KUERTEN Hans, SCHULZE Kai, OBERNBERGER Ingwald, 2007: Numerical simulation of ash particle impaction in tube bundles - A case study as a basis for a CFD based ash deposit formation model in convective heat exchangers. to be presented at the Int. Conf. “Deutscher Flammentag”