FINAL REPORT

CONTRACT N° : ERK6-CT-1999-00003

PROJECT N° : NNE5-1999-00114

ACRONYM : BIO-Aerosols

TITLE :

Aerosols in fixed-bed biomass combustion – formation, growth, chemical composition, deposition, precipitation and separation from flue gas

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REPORTING PERIOD: FROM 1st of March 2000 **TO** 28th of February 2003

PROJECT START DATE: 1st of March 2000 **DURATION :** 36 months

Date of issue of this report: April 2003

Project funded by the European Community under the 'Energy, Environment and Sustainable Development' Programme (1998-2002)

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1 Summary

The project focused on research into the formation and behaviour of aerosols and fly ashes formed during fixed-bed biomass combustion. Characteristics of aerosols, fly ashes and deposits were investigated considering different woody biomass fuels (bark, wood chips, waste wood). Test runs at a pilot-scale combustion plant and a large-scale CHP plant including fuel, aerosol, fly ash and deposit sampling with subsequent SEM and chemical analyses were performed to gain information about particle size distribution, shape and chemical composition of aerosols, fly ashes and deposits. Based on these data, the mechanisms of aerosol and fly ash formation were investigated using computer aided mathematical models. Additionally, CFD was used to describe the motion of aerosols and fly ashes in furnaces and boilers. This knowledge was summarised in a database and used as a basis for investigations of aerosol precipitation and reduction of corrosive deposits. The rotational particle separator (RPS), an innovative dust separator, was tested concerning its applicability to small-scale combustion units. Moreover, the influence of additives injected into the furnace on formation, growth and chemical composition of aerosols was investigated. Finally, the ecological and health risks of aerosol emissions from biomass combustion were evaluated.

Two test series at a pilot-scale combustion unit (nominal boiler capacity: 440 kW_{th}) and one test series at a large-scale CHP plant (40 MW_{th}) were performed. Bark, wood chips, fibre boards and waste wood were used as fuels. A huge amount of high quality measurement and analysis data concerning particle size distributions and the concentrations of aerosols and fly ashes in the flue gas at the boiler outlet as well as fuel, aerosol, fly ash and deposit analyses was gathered during these test runs and subsequently summarised in an appropriate database. In parallel, simulation codes for aerosol formation and growth as well as CFD models designed to describe temperature and flow distributions and to calculate particle trajectories in furnaces and boilers were set up, calibrated and checked with the results from the test runs. Different aerosol formation mechanisms which are mainly related to the chemical composition of the fuel used, were postulated as one important conclusion from this work.

A long-term test run at a large-scale waste wood fired combustion unit (40 MW_{th}) as well as test runs at a pilot-scale combustion unit were performed to investigate additive injection. The results of the long-term test have shown, that, by using an appropriate additive, it is generally possible to reduce the stickiness of deposits and to increase the cleaning intervals of the combustion plant. However, the results from the test runs at the pilot-scale combustion unit suggested that aerosol formation can only be marginally influenced by additive injection. Furthermore, it was not possible to identify clear mechanisms of how the additive used influenced deposit build-up.

The investigations of aerosol precipitation clearly indicated that proven and economically sound aerosol separation devices exist for medium- and small-scale applications (ESP, baghouse filters). Such technologies, however, are too expensive for small-scale application and cost effective aerosol separators are still lacking. Therefore, the applicability of the RPS for small-scale biomass combustion units was investigated. It has been shown that in general, the RPS can be used for aerosol precipitation, but several mechanical problems with the filter element do not allow safe long-term operation of the RPS in biomass combustion units at present.

Finally, first attempts were made to investigate the influence of aerosol emissions from biomass combustion on human health. The results of the studies indicated that the potential of aerosol emissions from biomass combustion is about the same as that from coal combustion plants.

2 Aims of the project

Compared with energy production from fossil fuels, one last weak point of biomass combustion are ash related problems, namely deposit formation and aerosol and fly ash emissions. The project therefore focused on the investigation of aerosol and fly ash formation and behaviour in fixed-bed combustion units using woody biofuels. Consequently, the main aims of the project were, firstly, to gain comprehensive knowledge about aerosol formation and behaviour and, secondly, to find solutions for problems caused by aerosols and fly ashes in biomass combustion units. Another important aim of the project was to develop primary and secondary measures to influence aerosol formation and to reduce the corrosive potential of aerosol layers on tube surfaces of biomass boilers. Based on the results achieved, aerosol precipitation in small, medium and large-scale biomass combustion plants was to be improved by appropriate dust precipitator designs. Finally, the project aimed at the investigation of health risks caused by aerosol emissions from biomass combustion units.

3 Methodological approach

To reach the aims mentioned above, the project was structured into 5 work packages:
- Aerosol characterisation,
- Aerosol formation and behaviour modelling,
- Aerosol precipitation,
- Influencing aerosols,
- Ecological and health risks caused by aerosol emissions.

The overall methodological approach of the project was, besides the performance of literature studies, based on test runs at pilot-scale and real-scale combustion units, on mathematical modelling of the relevant processes in aerosol and fly ash formation, deposit formation and the melting behaviour of deposits and on lab-scale studies concerning health risks of aerosol emissions from biomass combustion. The basic idea behind this approach was to reach the objectives of the project by a extremely close cooperation and data exchange between the partners performing test runs and the partners specialised in the mathematical modelling.

4 Results

In the following, the work performed as well as the main results of the project are described work package per work package.

4.1 Workpackage 1: Aerosol characterisation

The aim of the work package was to gain all relevant data concerning characteristics and formation of aerosols, fly ashes and deposits during fixed-bed combustion of woody biomass as a basis for the work in the other work packages. Therefore, test runs at a pilot-scale combustion unit (440 kW_{th}) and a large-scale biomass combustion unit (40 MW_{th}) were performed. Chemically untreated wood chips (spruce and beech), bark, fibreboard and waste wood were used as fuels. The test runs comprised fuel, ash, aerosol, fly ash and deposit sampling as well as subsequent wet chemical and SEM/EDX analyses of the samples taken. Thereby, the particle size distributions, chemical compositions and concentrations of aerosols and fly ashes in the flue gas at the boiler outlet as well as the deposit build-up on boiler tubes and the chemical composition of these deposits were determined.

As the results of the measurements have shown, fly ash emissions from biomass combustion consist of two fractions, the aerosols (particles <1 µm) and coarse fly ashes (particles >1 µm). The typical bimodal particles size distribution of fly ashes formed during biomass combustion is shown in Figure 4.1-1.

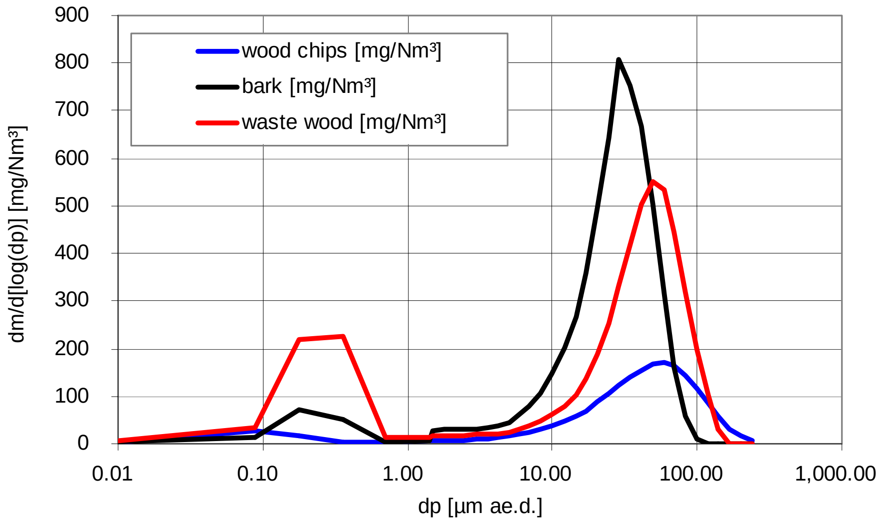

Figure 4.1-1: Particle size distribution of fly ash emissions from biomass combustion units

Explanations: dp … particle diameter; ae.d. … aerodynamic diameter; results from test runs at the pilot-scale combustion unit at partner MAHOL; all data related to dry flue gas and 13 vol.% O_2

The results from the measurements have shown, that fly ash concentrations at the boiler outlet can vary between about 100 mg/Nm³ and about 1,000 mg/Nm³ (related to dry flue gas and 13 vol.% O_2). The particle size distribution of the coarse fly ashes was normal logarithmic with a peak diameter in the range between 30 and 70 µm (aerodynamic diameter). Usually, coarse fly ash particles in the size range between some µm up to about 300 µm were found. From the measurement data was derived that the fly ash emissions increase with increasing ash content of the fuel and with increasing load of the combustion unit.

The aerosol emissions (particles <1 µm) at the boiler outlet varied, depending on the fuel used, between 20 mg/Nm³ for spruce up to about 380 mg/Nm³ for waste wood (all concentrations related to dry flue gas and 13 vol.% O_2). The result of the test runs also indicated that operation parameters as the excess air ratio, the combustion temperature and flue gas recirculation do not significantly influence aerosol formation. The evaluation of the chemical analyses of aerosols revealed that the chemical composition of the fuel is the main influencing parameter concerning the mass of aerosols formed. During the combustion of fuels with rather low contents of typical aerosol forming elements such as K, Na, Zn and Pb, lower masses of aerosols are formed than during the combustion of fuels which contain high concentrations of these elements. Consequently, the aerosol concentration in the flue gas increases from spruce combustion to beech combustion (higher K content) and bark combustion (increased K, Zn and Pb content) to waste wood combustion (extremely high heavy metal contents as well as higher Na contents). The particle size distribution of aerosols in all cases is unimodal and represents approximately a logarithmic normal distribution. The peak diameter of the PSD increases with increasing aerosol concentration, which indicates that the number concentration of aerosols formed during the combustion of different biomass fuels in a certain combustion unit is approximately constant.

Based on the overall evaluation of the test runs and the analyses performed, three different aerosol formation processes for the combustion of different types of woody biomass were identified (Figure 1.2-2).

- The first process comprises the combustion of chemically untreated wood chips as well as fibre boards. The aerosol fraction in this case mainly consists of K and S with smaller amounts of Cl, and therefore, nucleation of KCl and K_2SO_4 particles and subsequent condensation of these species on the particles formed is assumed to be the most important mechanism.

- Aerosols formed during the combustion of bark mainly consist of K, Cl and S but also of considerable amounts of Ca (in the submicron mode) and heavy metals such as Zn and Pb. As regards Ca, it must be mentioned that a release of Ca to the vapour phase is not possible according to the thermodynamic data of Ca. Consequently, it must be assumed that very small Ca particles already exist in the flue gas right after the flue gas leaves the fuel bed. In the following, KCl and K_2SO_4, will form new particles by nucleation but will also condense on the surfaces of the existing Ca nuclei. Later on, also heavy metal compounds (mainly Zn and Pb-compounds) will condense on these particles.
- During waste wood combustion Zn is released from the fuel bed to the gaseous phase and subsequently reacts with oxygen. The vapour pressure of the resulting ZnO is very high, resulting in an immediate supersaturation followed by nucleation of ZnO. Other volatile species (e.g.: alkali chlorides, lead compounds) condense on the surfaces of these ZnO particles with decreasing temperature of the flue gas. Due to the high number of ZnO-particles, nucleation of other compounds is assumed to be nearly totally suppressed by surface condensation.

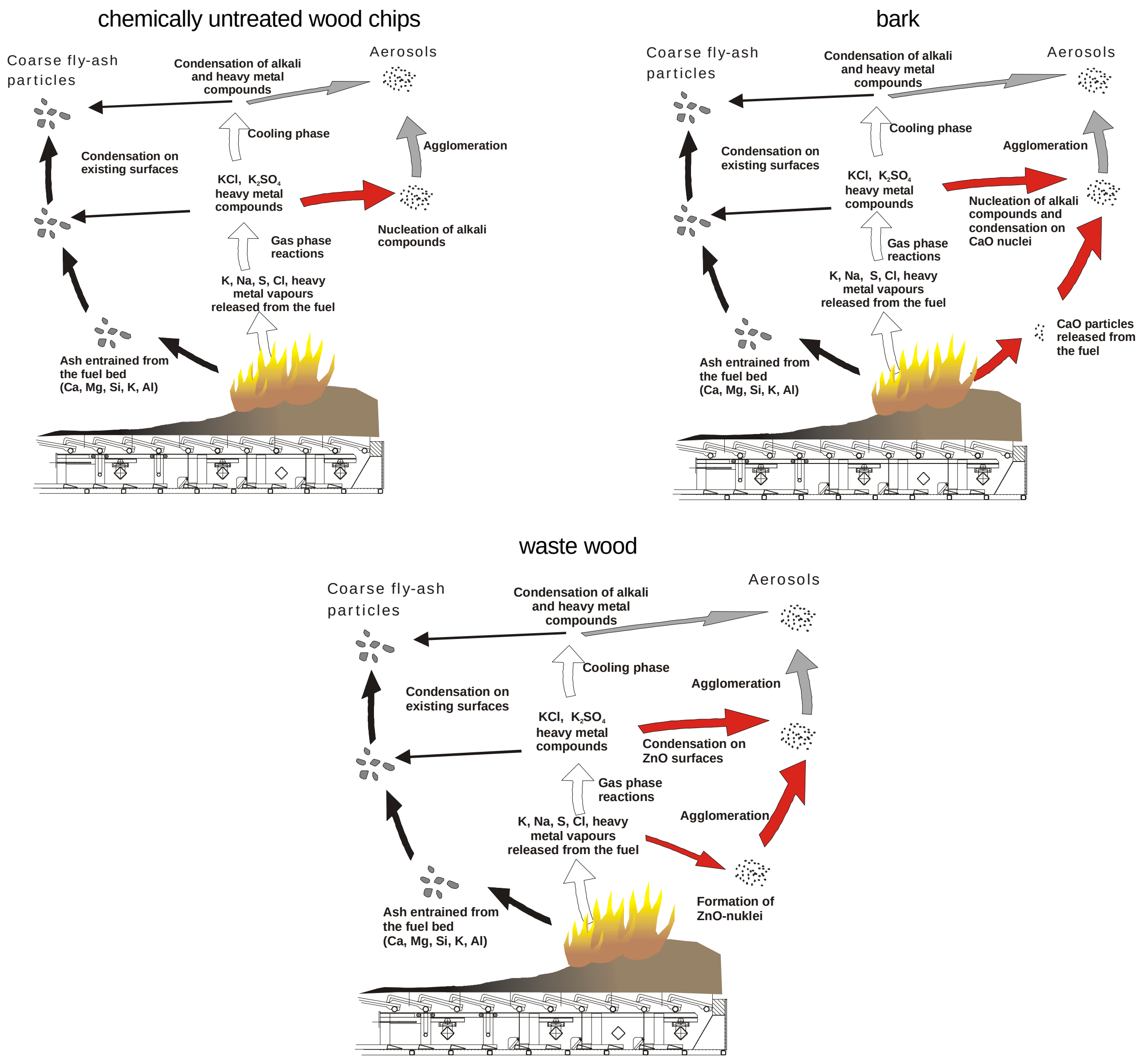

Figure 4.1-2: Aerosol formation mechanisms during fixed-bed combustion of chemically untreated wood chips, bark and waste wood

Regarding deposit build-up, deposit probe sampling at tube surface temperatures between 230 and 650°C was performed. The deposit samples were subsequently analysed by SEM/EDX. During these measurements the deposit rate of build up (RBU) varied between some $g/m^2/h$ and about 10 $g/m^2/h$ for chemically untreated biomass fuels. During waste wood combustion RBUs from 10 $g/m^2/h$ to 50 $g/m^2/h$ were determined.

In general, the results concerning deposit build-up gained from the evaluation of the analyses and the test runs can be compressed to the following four conclusions:

- The rate of deposit formation was partly coupled to the fuel used during the test runs. Therefore, fuel characterisation is important in predicting ash-related problems.
- Different types of waste-wood gave rise to higher rates of deposit formation than chemically untreated wood and bark.
- This might be due to the higher levels of Na, Zn, Pb, S and Cl in these fuel types. The results gained imply high deposition rates of these elements on the probes.
- Compounds of Na, Zn, Pb, S and Cl lower the melting point of the ash, and low temperature melts in deposits will promote the corrosion of tube material.

4.2 Workpackage 2: Aerosol formation and behaviour modelling

In close cooperation with the Aerosol Laboratory at DTH.DCE, a PC-based code, the Plug Flow Aerosol Condenser (PFAC), has been established and made applicable. The code can predict formation of K-, S-, and Cl-rich aerosols in a flue gas from combustion of biomass on a grate.

PFAC is a mathematical model for simulation of the formation and evolution of a multi-component aerosol during cooling of a flue gas with a certain content of condensible vapours. The model has until now been used for simulation of fine particle formation, and change of gas composition, during cooling of flue gases from the combustion of straw. The model equations include homogeneous nucleation of pure substances, growth by multi-component gas-to-particle conversion, and coagulation of spherical particles (taking into account Brownian motions, turbulent shear, and gravitational settling). The local gas phase composition is determined from a gas phase chemical equilibrium calculation combined with a finite reaction rate kinetics for slower reactions.

In the original version of PFAC, an unstable equilibrium module was used. Thus, as part of this project, a significant amount of time was used to implement a fast, reliable and very robust global equilibrium module applying linear programming for an initial estimate of the equilibrium composition, refining the initial estimate by use of multiplier penalty functions and then finding the final solution by Lagrange-Newton iteration.

An important part of the project has been to evaluate the effect of operational parameters and fuel chemistry on the physics and the chemical composition of the aerosols generated during oxidative thermal utilization of wood fuels. Thus, a parametric study has been conducted, simulating aerosol formation in a grate-boiler fired with a washed wheat straw, i.e. a bio-fuel with a content of K, Cl and S, comparable to woody types of biomass. Four conditions were considered:

- Increased entrainment of ash, assuming constant number concentration of ash particles in the flue gas. This condition corresponds to a situation where a constant number of particles – with increasing diameters - per volume flue gas are entrained from the fuel bed.
- Instead of a constant number density, the mass of ash particles entrained could be constant. This is considered in the second case.
- The effect of the SO_2 kinetics was investigated by changing the activation energy of the sulfation reaction in the range 50, 100, 150, 200, 250 kJ/mole. The pre-exponential factor was kept constant at 1,238 s^{-1} in all simulations.

- Finally, the effect of fuel chemistry was investigated by artificially changing the Cl:2S ratio in the range {10:90, 30:70, 50:50, 70:30, 90:10}, assuming constant SO_2 kinetics, i.e. E_A = 200 kJ/mole and k_e = 1238 s^{-1}.

The parametric study revealed that particularly the distribution between Cl and S in the feedstock mixture influences the aerosol chemistry and size distribution significantly. Thus, the chemical composition of the feedstock mixture is a major controlling factor, when judging the corrosive potential of aerosols formed during wood-firing on a grate.

Aerosol formation when firing wood chips (beech, spruce, fibre board), bark and waste wood in the 400 kW_{th} pilot-scale combustion unit at MAHOL was simulated by PFAC. For the wood chip fuels, PFAC predicted an aerosol mass loading (mg aerosol/Nm^3 flue gas) almost twice as high as measured at the plant. This is most likely due to one of two reasons:

- the fact that no condensation of gaseous K-species on external heat transfer surfaces was implemented in PFAC at present, or
- the fact that the simulations are made assuming complete release (100%) of K, S and Cl from the grate during combustion.

The lack of external condensation may be a significant problem, since a considerable condensation within the first 20-30 cm of the fire tubes in the MAHOL boiler, when a hot flue gas (800°C) is brought into contact with the relatively cold inner surfaces of the fire tubes (150°C), is expected. Concerning the release of K, S and Cl, a mass balance conducted at the MAHOL test-facility when firing beech indicated release of 35 % K, 85 % S and 100 % Cl, on a mass base.

Thus, partner TUEIN developed a CFD-based model in order to quantify the deposition of K_2SO_4 and KCl on the inner side of the tubes in the boiler section of the MAHOL test facility. The simulations indicated deposition of 10-15% on a mass base of the K_2SO_4/KCl. This result was implemented in PFAC together with the reduced release of K, S, and Cl, based on the beech mass balance and the simulations were re-runed for all the wood-type fuels (beech, fibreboards and spruce). The new simulations indicated a particularly strong effect of the reduced release on the aerosol mass loading and chemistry. Thus, based on these simulations it was concluded that reliable release data are crucial to a correct prediction of aerosol mass loadings and chemistries.

For bark and waste wood, the PFAC simulations indicated that the presence of a huge amount of small aerosol-like particles rich in CaO (for bark) and in ZnO (for waste wood) will suppress any secondary nucleation of gaseous K_2SO_4/KCl being released from the grate. For bark, this is in contradiction to the observations made by partner TUGRAZ during the evaluation of the test runs performed within work package 1, which indicate, that there is also nucleation of K_2SO_4/KCl going on, even though a significant loading of small primary particles of ZnO/CaO is present.

Regarding the deposit behaviour of coarse fly ashes and aerosols in the furnace and the boiler several studies using CFD (computational fluid dynamics) were performed by partner TUEIN. Firstly, the applicability of Eulerian (Turbulent Diffusion and Probability Density Function) models and Langrangian (Direct Numerical Simulation and Large Eddy Simulation) models for turbulence modelling in biomass furnaces and boilers was studied. Then, based on the data gained from the test runs and on geometry data provided by the partners MAHOL and STALEFA, the flow and temperature profiles at the pilot-scale combustion unit at MAHOL and the large-scale CHP plant manufactured by STALEFA were calculated. The resulting velocity and temperature profiles were forwarded to the aerosol formation modelling mentioned above. Furthermore, the deposition probability of aerosols and coarse fly ashes in the furnaces was calculated. It was shown, that only particles with an aerodynamic diameter >5 µm build up deposits by inertial impaction, while smaller particles generally follow the streamlines of the flue gas. Fine particle deposition due to thermophoresis or diffusion effects was evaluated to be of less importance. Finally, it was worked out, that direct wall condensation of ash forming vapours at the surfaces of heat exchangers is the most important mechanism for deposition of aerosol forming species in boilers.

One additional important output of the flow calculations were guidelines, how the results from the measurements with the deposit probe performed during the test runs (gas flow around a cylinder/tube) can be applied to predict deposit behaviour in a fire tube boiler (axial flow of flue gas in a tube).

4.3 Workpackage 3: Aerosol precipitation

Work package 3 was structured into two main parts, namely aerosol precipitation in medium and large-scale combustion units as well as aerosol precipitation in small-scale combustion units.

As a basis for the evaluation of dust precipitation devices, at first the data from the test runs performed within work package 1 were summarised in an aerosol and fly ash database comprising data concerning particle size distributions, chemical compositions and concentrations of aerosols and fly ashes formed during the combustion of different woody biofuels as well as relevant plant operation data recorded during the respective test runs. To evaluate state-of-the-art devices for aerosol precipitation in medium and large-scale biomass combustion units, the design data of ESP and baghouse filters as well as measurement results from test runs at those types of filters were compared with the raw gas data from the aerosol and fly ash database. Furthermore, current dust emission limits in several European countries were evaluated and compared with these results. The study revealed, that for all relevant medium and large-scale applications firing different types of woody biomass (chemically untreated wood, bark, waste wood) appropriate and economically sound filter technologies are available. However, it was concluded that based on the data from the aerosol and fly ash database an even more fuel specific design of dust precipitators will be possible, and therefore, investment and operation costs could be reduced at a constant level of precipitation efficiency.

The study also clearly indicated that, due to economic restrictions, for small-scale biomass combustion units only cyclones and multi-cyclones are applicable. Since these devices can separate coarse fly ash particles while aerosols are not precipitated, it was concluded, that no efficient and cost effective aerosol precipitation device for small-scale biomass combustion units exists at the moment. Therefore, the rotational particle separator (RPS), a dust separation device which already has proven its applicability in several types of processes, was further developed to be applied in biomass combustion processes. The RPS consists of three main parts, a static body designed like a cyclone, a filter element consisting of a large number of narrow parallel channels rotating around the vertical axis of the RPS, and a cleaning system designed to remove the particles precipitated on the walls of the filter element. The flue gas first flows through the cyclone part, where coarse particles are separated and then through the filter element, at which, due to the high rotation speed of the element, aerosols are precipitated.

A test RPS was designed, manufactured and applied to the pilot-scale combustion unit at partner MAHOL. First test runs have shown, that, in general, the RPS concept is applicable for aerosol precipitation in biomass combustion units using chemically untreated wood chips as fuels. Precipitation efficiencies for aerosols in the range between 40 and 60% were achieved. On the other side it turned out, that some optimisations were needed to reduce the investment and operation costs. Therefore, mathematical simulations of the RPS mainly focusing on the design of the sealing impeller were performed by TUEIN. The sealing impeller is mounted at the filter element and is used, to avoid the flow of uncleaned flue gas through the area between the filter element and cyclone body. An overdesign of this impeller leads to an increased pressure loss over the RPS and to an increased electricity demand for driving the filter element. Additionally, optimisation work concerning of the shaft seals, the cleaning system, and the bearings of the filter element was initiated. After about half a year of operation of the RPS at the MAHOL pilot-scale combustion plant, some problems with the cleaning system occurred, thus the filter element had to be removed and to be cleaned manually. When inspecting the filter element, some damages of the braze between the filter channels became obvious. In the following, the rotation stability of the filter element was not given any longer. As the reasons for this an insufficient brazing quality of the filter element was seen. During the remaining time of the project this problem was discussed between TUEIN and the manufacturer of the filter element, but no solution was found. Therefore, taking the actual stage concerning the brazing of the filter element into consideration, it must be stated, that due to the fact that a stable long-term operation cannot be guaranteed, a market introduction of the RPS is not possible, even if the tests have shown, that concerning its separation efficiency, the RPS would be a suitable aerosol precipitator for small-scale biomass combustion units.

4.4 Workpackage 4: Influencing aerosols

The aim of work package 4 was the development of additives for biomass combustion units in order to reduce aerosol and deposit formation. Tests have shown that additives developed for coal fired plants or for oil fired boilers or motors are not applicable in biomass fired applications, which resulted in the necessity to develop additives especially for biomass combustion.

During the first year of the project, pre-tests with an additive developed by ERC were performed at the 40 MW_{th} waste wood fired CHP plant manufactured by partner STALEFA. Long-term experiments with additive injection (about two months) were performed and additional test runs including fuel, particle and deposit sampling and subsequent chemical and SEM/EDX analyses of the samples were carried out by partners TUGRAZ and UFS. The results of the long-term pre-test led to the conclusion that the additive used caused the deposits to be less sticky and more porous. The deposits could be removed more easily from the boiler tubes than the deposits formed during operation without additive injection. Moreover, the increase of the furnace temperature over the test period, which is a suitable indicator for the growth of deposits, was less marked during the period of additive injection than before. Therefore, in principle, it can be said that the additive worked well regarding the reduction of hard deposit formation, but on the other side, the evaluation of the results of short term deposit probe measurements performed did not show measurable effects of the additive on deposit formation and on deposit chemistry.

Within a second testing campaign, a further developed additive (based on Mg and Si-compounds) was injected into the pilot-scale combustion unit at MAHOL. Extensive measurements concerning deposit formation, particle size distributions and concentrations of aerosols and fly ashes in the flue gas at the boiler outlet were performed. Additionally, wet chemical analyses of the fuels used as well as of all the ash fractions produced, were performed in order to facilitate a correct mass and element balancing over the combustion unit as a basis for the evaluation of the test runs.

One aim of these test runs was to study, if the injection of a high amount of additive particles into the furnace could provide such a high surface area, that nucleation of aerosol forming compounds is suppressed due to condensation of these compounds on the additive particles. The amount of additive needed for a suppression of nucleation was calculated with the AFB code developed within work package 2. The results have shown, that the main mass peak of the additive particles was situated in the particle diameter range >1 µm, whereas the location of the aerosol peak remained unchanged. These results may also lead to the conclusion that the additive particles were too big to significantly affect aerosol mass size distribution. Electrical Low Pressure Impactor (ELPI) measurements showed changes in the PSD only in size ranges below 0.1 µm which confirms that the additive cannot be used for the suppression of aerosol nucleation as theoretically predicted.

The effect of additive injection on the formation of deposits was investigated by UFS. 21 deposit probe samples were taken during the test runs and examined with SEM/EDX. The results of multiple linear regression analyses performed by UFS corresponded with the results obtained for the other test runs within work package 1 in terms of the influence of fuel composition and temperatures on the RBU. Concerning the influence of the additive on deposit build-up, a slight decrease of the deposit build-up rate was observed. However, based on the results of the chemical analyses of the deposit samples taken, this reduction of the RBU could not directly be related to the additive. A similar tendency was also found during the tests at the large-scale CHP plant.

The results from the test runs indicate, that there obviously exists a slight long-term effect of additive injection on deposit formation. However, the exact mechanism for that could not be identified by the evaluation of the short term measurements during the testing campaigns and therefore, additional research within this field will be needed.

4.5 Workpackage 5: Health effects of aerosol emissions

During the last years particulate immissions have become a topic of major relevance in public discussions concerning ambient air pollution. A considerable number of studies has already been performed on this topic and the most relevant results can be summarised as follows:

- It has been shown, that there is a correlation between respiratory problems such as asthma, chronic obstructive pulmonary diseases, pneumonia and lung cancer and the concentration of particulate matter in the ambient air. Furthermore, it was revealed, that gaseous pollutants do not have a significant impact on these respiratory problems.
- Moreover, in-vivo studies as well as semi empirical modelling have revealed, that, the smaller the particles inhaled are, the deeper they can penetrate the human lungs. While rather big particles (about 5µm) are precipitated in the mouth, nose and throat, submicron particles are deposited in the inner parts of the lungs, the alveoli.
- Due to the fact that smaller particles have larger specific surface areas, the reactivity of particles increases with decreasing particle size. It has been shown, that therefore, smaller particles also cause higher health risks.

Common methods to determine the effects of particulate matter on an organism are in-vivo tests with mice or rats and in-vitro exposure tests with mice or rat lung cells. Such kinds of tests were performed within the project using aerosols and fly ashes sampled during work package 1 as well as particles sampled within another project at the pilot-scale combustion unit at partner MAHOL as well as at a real-scale combustion unit which is, concerning the combustion conditions, comparable with the MAHOL pilot-scale combustion unit.

For the in-vivo tests a measured increase in lung permeability is one indicator of potential lung damage. An increase of permeability of the lung tissue can facilitate the transfer of particles or particle constituents to other organs of the body (i.e. the heart). During a first set of tests, in-vivo tests with ash from bark combustion were performed and compared with results from in-vivo test with ash from coal combustion. As far as the lung permeability is concerned, the results from these tests suggest that potential lung injury from inhalation of bark ash is no greater than that from inhalation of pulverized coal ash. This is in sharp contrast to previous results from co-combustion of MSS (municipal sewage sludge)/coal, which caused much greater increases in lung permeability (and consequently greater incipient lung injury) than did coal ash alone. On the other hand, lung functions such as static and dynamic compliance did deteriorate in comparison to exposure tests to coal ash. Summing up the results from these in-vivo studies, ash from bark combustion turned out to cause about the same level of health effect as ash from coal combustion.

A second set of in-vivo studies was performed with ash samples from the combustion of chemically untreated wood and waste wood. Ash from chemically untreated wood caused a decrease in lung permeability. The decrease in lung permeability suggests an inflammatory response after the exposure to these ash particles. Analysis of the blood for inflammatory cytokine TNF-α substantiated the lung permeability results. Furthermore, these ash particles appeared to change two pulmonary functions, namely lung compliance and pulmonary resistance. Exposure to ash particles from waste wood combustion appears to cause small fluctuations in lung permeability which were not statistically significant. Therefore, comparing the lung permeability response to these ash particles, the data suggest that ash particles from the combustion of wood are more distressing than the ash particles from waste wood combustion. However, the level of lung injury detected during the tests with aerosols and fly ashes from chemically untreated wood and waste wood was in about the same range as for ashes from bark combustion, and is therefore comparable with lung injury caused by ashes from coal combustion.

In vitro studies were used to evaluate the impact of exposure of aerosols from the combustion of different woody biofuels to rat lung epithelial type II cells (RLE-6TN). Individual types of aerosols were suspended in culture media and delivered directly to cell cultures. The cellular response was quantified through measurements of the impact of PM on the cell cultures. The primary metric employed is the inhibition of cell metabolism due to PM exposure.

In general, the aerosol samples tested induce a lower level of cellular response (toxicity) than that obtained from exposure of RLE cells to ashes from combustion of coals. The cellular responses follow a logical dose response relationship. Ash particle dosages of 0.1 to 0.25 mg/ml yield a small impact on cellular metabolism. At 0.5 mg/ml and higher, sizeable differences between PM types becomes apparent. The results of the tests have revealed that the particle size as well as the fuel used influence the toxicity of the aerosol and fly ash particles formed. The most toxic particles were found for ashes from bark, waste wood and beech combustion, the less toxic for combustion of spruce and of a mixture of sawdust and wood chips. No correlation between the cellular responses and the metal contents of the particles (Zn and Pb) were detected.

Summing up, the results indicate, that the effects on the pulmonary system caused by aerosol and fly ash emissions from the combustion of woody biomass are comparable with those of coal combustion and therefore, are lower than for particulate emissions from e.g. oil combustion. However, the study was based on in vivo tests with three ash samples and therefore, additional test will be needed to gain statistical security. Furthermore, it has been shown, that the results of the in vitro test might have been influenced by the very low masses of aerosols available for the tests due to the small amounts of aerosols which can be sampled with Berner-type impactors. Also in this case additional tests should be performed to ensure and verify the data achieved.