ERA-NET Bioenergy Project
FutureBioTec

“Future low emission biomass combustion systems”

Final report

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Abstract

The ERA-NET Bioenergy project "FutureBioTec" aimed to provide a substantial contribution concerning the development of future low emission stoves and automated small- and medium-scale biomass combustion systems (<20 MW_{th}). The project focused on the further development of wood stoves towards significantly decreased CO, OGC and PM emissions by primary measures (air staging and air distribution, grate design and implementation of automated process control systems), the improvement of automated furnaces in the residential and the small to medium-scale (<20 MW_{th}) capacity range towards lower PM and NO_x emissions by primary measures (extremely staged combustion, utilisation of additives and fuel blending concerning new biomass fuels, development of a new combustion system for pulverized fuels), as well as the evaluation, development and optimisation of secondary measures for PM emission reduction for residential biomass combustion systems. According to the different working fields addressed, the project is structured into 4 work packages (WP):

WP1: Reduction of PM, CO and OGC emissions from wood stoves by primary measures.

WP2: Reduction of PM and NO_x emissions from automated boilers by primary measures.

WP3: PM emission reduction by secondary measures - evaluation of existing particle precipitation technologies for residential biomass combustion systems.

WP4: Development of a specially designed condensing heat exchanger for simultaneous heat recovery and efficient particle precipitation.

In order to reach the aims of the project, a consortium of 9 internationally recognised R&D partners as well as 2 industrial partners from 7 European countries has been formed. The project which has been coordinated by the Austrian Competence Centre BIOENERGY 2020+ GmbH has been started in October 2009 and completed in September 2012. In September 2012 the results of the project have been presented at an international workshop in Graz to interested stakeholders (in total 67 participants from 7 countries attended).

Within the scope of work package 1 country reports regarding "Operational influences of hand-charged wood stoves" have been compiled by the partners involved. These country reports have subsequently been summarized in a report prepared by TFZ. In addition, comprehensive tests have been conducted by TFZ, BE2020 and UEF. At TFZ two chimney stoves with exactly the same firebox geometry and volume but with and without grate have been examined. The results show that the presence of a grate can be beneficial regarding gaseous emissions. Furthermore, an universal retrofit air control unit was tested at two different stoves. The results showed that the emissions were not reduced by the device. It was concluded that such units can only perform efficiently if they are an integrated part of a certain stove technology and not just an add-on. At BE2020 different strategies regarding air staging as well as an automated control system were developed and tested. The development was accompanied and supported by CFD-simulations. The different measures applied led to a stepwise reduction of the emissions. Partner UEF, in cooperation with Warma-Uunit Ltd., performed combustion experiments using a hybrid masonry heater for both logwood and wood pellets. Finally a "Low emission operation manual for chimney stove users" and "Guidelines for low emission chimney stove design" have been elaborated based on the results gained within this work package.

Within the scope of work package 2 a summary report regarding the evaluation of existing data on air staging strategies has been compiled by BE2020, UEF and UmU. The report summarizes and evaluates available data regarding the influence of air staging on NO_x and PM emissions for fixed bed biomass combustion. Furthermore, systematic experimental studies have been conducted by BE2020, UEF and Teagasc at different grate furnace systems (nominal power output between 35 and 180 kW) utilizing different biomass fuels. The results show that the clearest and strongest dependence on NO_x emissions is given by the air ratio in the primary combustion chamber (PCC). The optimum regarding NO_x emissions seems not to be fuel dependent (for a given technology) but technology dependent to a certain extent. Consequently, the optimum conditions have to be determined for a given technology with dedicated test runs and the process control should be adjusted

accordingly. Moreover, NO_x emissions increase with decreasing residence time in the PCC. The temperature in the PCC does not seem to be a relevant influencing parameter on NO_x emissions within the range investigated (900 – 1,100 °C). PM_1 emissions decrease with increasing volume flow through the fuel bed most probably due to lower fuel bed temperatures at higher air flows. The temperature in the PCC is also of relevance for the fuel bed temperature and has an influence on PM_1 emissions which is more pronounced at low air ratios in the PCC. Based on the results design and operation concepts for low-emission biomass grate furnaces based on advanced air staging have been compiled.

Regarding the work performed on additives and fuel blending, a state-of-the-art report on "fuel additives and blending as primary measures for reduction of fine ash particle emissions" has been compiled in a first step. Furthermore, dedicated lab-scale (BE2020) and small-scale (Teagasc) test runs were performed using Kaolin additivation to softwood and straw as well as peat/miscanthus and peat/tall fescue fuel blends. The tests at BE2020 were accompanied by thermodynamic high-temperature equilibrium calculations. The results show that PM_1 emissions decrease with increasing amounts of Kaolin additivation (up to a certain additivation ratio) and that peat addition reduced slagging tendencies as well as PM_1 emissions for the fuels investigated. In addition, studies with small lab-reactors burning single-pellet samples have been performed by UmU and SP. In general, a somewhat higher release of K was seen in the single pellets tests compared to the K found in fine PM from the pellet burners. This is rather expected and presumably explained by "secondary" capture mechanisms in the fuel bed and also by losses on surfaces in the boiler/flue gas systems.

At IEn a new combustion technology for pulverized biomass fuels has been developed. In this respect investigations of fuel ignition and fuel combustion kinetics were performed using two drop tube furnaces and accompanying CFD simulations. In a next step a 5-15 kW and a 0.5 MW burner for pulverized biomass were developed and tested and subsequently the technology was upscaled to 20 MW. The results of the tests performed show that also in pulverized fuel systems air staging has a strong influence on NO_x as well as TSP emissions.

Within the scope of work package 3 a survey on the present state in Europe regarding particle precipitation devices for residential biomass combustion (nominal boiler capacity <50 kW_{th}) was compiled. Furthermore, a number of ESPs has been tested by the project partners, namely the chimney-mounted applications Ruff-Kat ESP (by TFZ), Oekotube ESP (by BE2020 and Teagasc) and the R_ESP (by SP) as well as the Al-top ESP (by Teagasc). Finally, the experiences made within the project group from the test runs have been summarized in the document "Guidelines for design and application of electrostatic precipitators for residential biomass combustion".

UEF has developed a condensing heat exchanger for efficient heat recovery with fine particle reduction. Within the scope of work package 4, a scrubber unit was developed to assist in keeping the heat exchanger inlet as well as walls clean. The aerosol behaviour was simulated with a computational model. Forces affecting the particles were computed under consideration of thermophoresis, diffusiophoresis and Brownian diffusion. Furthermore, test runs have been conducted which show that the condensing heat exchanger generated 32 % and 36 % lower fine particle emissions when compared to the reference boiler cases. The prototype which was tested, is compact in size and has a high heat recovery potential combined with a certain reduction in particulate emissions. The system is especially suitable for low-temperature heating systems (floor heating) and for use with moist fuels, for example wood chips.

Concluding, the project "FutureBioTec" resulted in a considerable know-how gain regarding future low-emission small- to medium-scale biomass combustion systems. To widely disseminate this knowledge all guidelines and state-of-the-art reports mentioned as well as additional publications generated within the project are publicly available on the webpage futurebiotec.bioenergy2020.eu.

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1 Introduction and objectives

The European Union and its member States aim at an increased use of renewable energy in order to avoid a further increase in atmospheric CO_2 concentrations and therefore, the European Commission actively supports the utilisation of biomass for energy production. However, this aim must be achieved without increasing other harmful emissions such as fine particulate matter ($PM_{2.5}$) nitric oxides (NO_x), carbon monoxide (CO) and organic compounds (OGC, PAH). Therefore, especially regarding the small and medium-scale heating sector, where a great potential for biomass utilisation all over Europe exists, the promotion of energy from biomass must be accompanied by further technology development towards low emission combustion systems.

The ERA-NET Bioenergy project "FutureBioTec" aimed to provide a substantial contribution concerning the development of future low emission stoves and automated small and medium-scale biomass combustion systems (<20 MW_{th}) and therefore has the following overall objectives, which have been defined under consideration of the different states of development of the different combustion technologies and capacity ranges addressed. The project focused on the **further development of wood stoves** towards **significantly decreased CO, OGC and PM emissions** by primary measures (air staging and air distribution, grate design and implementation of automated process control systems), the **improvement of automated furnaces in the residential and the small- to medium-scale (<20 MW_{th})** capacity range **towards lower PM and NO_x emissions** by primary measures (extremely staged combustion, utilisation of additives and fuel blending concerning new biomass fuels), as well as the **evaluation, development and optimisation of secondary measures for PM emission reduction in residential biomass combustion systems**. This technology development was accompanied by techno-economic evaluations in order to proof that the new technologies are also economically competitive.

In detail the following objectives have been defined:

- Development of primary measures concerning PM, OGC, CO and NOx emission reduction for stoves (work package 1)
    - Investigation of new designs (grate and air staging) and new control concepts for wood stoves.
    - Development of guidelines for low emission wood stove design and control.
    - Development of a "low emission operation manual" for wood stove users.
- Development of primary measures for PM and NO_x emission reduction in automated furnaces (work package 2)
    - Systematic evaluation of effects of different air staging strategies and excess air ratios on the NO_x and PM emissions with a special focus on staged combustion. The influence of the following parameters have been systematically investigated during test runs at small-scale grate-fired biomass combustion plant: air staging (distribution between primary and secondary air), excess air ratio, furnace temperature and flue gas recirculation below and above the fuel bed
    - Development and test of a low emission burner for pulverised fuels.
    - Determination of the behaviour of the critical ash forming elements as a function of combustion conditions and fuel quality.
    - Elucidate and determine the potential and suitability of using different additives and fuel blending for low PM emission utilisation.
    - Compilation of a guideline for low emission combustion concepts

- Development of secondary measures for PM emission reduction in small-scale biomass combustion systems (work package 3)
    - Compilation of the European state-of-the-art concerning particle precipitation devices for residential biomass combustion systems.
    - Techno-economic evaluation of different particle precipitation devices for residential biomass combustion systems.
    - Compilation of design and application guidelines for particle precipitation devices for residential biomass combustion systems.
- Development of a new technology for a condensing heat exchanger as device for combined heat recovery and particle precipitation based on thermophoretic and diffusiophoretic effects (work package 4)

Figure 1 gives an overview over the work packages defined and the respective partners involved.

	Work package	start	end	BE2020	UEF	TFZ	Teagasc	IEn	UmU	LTU	SP	APP	Warma
1	Reduction of PM, CO, OGC and NO_x emissions from wood stoves by primary measures	1	36	x	x	x*			x		x		x
2	Reduction of PM and NO_x emissions from automated boilers by primary measures	1	36	x*	x		x	x	x	x	x		
3	PM emission reduction by secondary measures	1	36	x	x	x	x				x*	x	
4	Development of a specially designed condensing heat exchanger	1	36		x*								
5	Coordination and dissemination	1	36	x*	x	x	x	x	x	x	x		

Figure 1: Overview over the work packages defined and the respective partners involved

Explanations: x* … work package leader

In order to reach the aims of the project defined, a consortium of 9 internationally recognised R&D partners as well as 2 industrial partners from 7 European countries has been formed (see chapter 2). The project which has been coordinated by the Austrian Competence Centre Bioenergy 2020+ GmbH has been started in October 2009 and has been completed in September 2012. In September 2012 the results of the project have been presented at an international workshop in Graz. The proceedings of the workshop are available at futurebiotec.bioenergy2020.eu.

2 FutureBioTec project partners

Project coordinator

bioenergy2020+ process & particle engineering TU Graz Graz University of Technology	BIOENERGY 2020+ GmbH (BE2020) in cooperation with Graz University of Technology Institute for Process and Particle Engineering Graz, Austria

Project partners (R&D)

UNIVERSITY OF EASTERN FINLAND	University of Eastern Finland (UEF) Department of Environmental Sciences Fine Particle and Aerosol Technology Laboratory Kuopio, Finland
Technologie- und Förderzentrum	Technology and Support Centre of Renewable Raw Materials (TFZ) Straubing, Germany
UMEÅ UNIVERSITET	Umeå University (UmU) Energy Technology and Thermal Process Chemistry Umeå, Sweden
LULEÅ UNIVERSITY OF TECHNOLOGY	Luleå University of Technology (LTU) Division of Energy Engineering Luleå, Sweden
SP	SP Technical Research Institute of Sweden (SP) Division of Energy Technology Borås, Sweden
IEN	Institute of Power Engineering (IEn) Thermal Division Department Warsaw, Poland
Teagasc Agriculture and Food Development Authority	Teagasc, Crops Research Centre Carlow, Ireland

Industrial partners

Warma uunit	Warma-Uunit Ltd, Finland
APP	Applied Plasma Physics AS, Norway

3 Results

3.1 *Work package 1: Reduction of PM, CO and OGC emissions from wood stoves by primary measures*

3.1.1 General remarks

Stoves are one of the most common technologies for residential heating all over Europe. During the last few years stoves have not only been used for heating purposes, they are also seen as furniture accessories and therefore a broad range of different designs is nowadays available. However, the technical standard of different stove technologies varies significantly and thus there is a remarkable potential for the optimisation of these appliances. In work package 1 it was therefore the aim to provide knowledge and guidance for the reduction of PM, CO and OGC emissions from wood stoves. The focus was here set on primary measures.

As an initial step and support for the subsequent experimental work planned country reports regarding "Operational influences of hand-charged wood stoves" have been compiled by the partners involved. These country reports have subsequently been summarized in a report prepared by TFZ.

3.1.2 Selected results of test runs performed with different wood stoves

Several different user and fuel impacts on gaseous and particulate emissions were investigated using different chimney stoves and masonry heaters. Also technical stove features such as variations in combustion air flow, stove dimensions, control strategies or grate options were regarded. In addition, at BE2020 accompanying CFD simulations for wood stoves have been performed to evaluate the influence of relevant parameters in more detail. The major findings from selected test runs by different partners are summarized in the following.

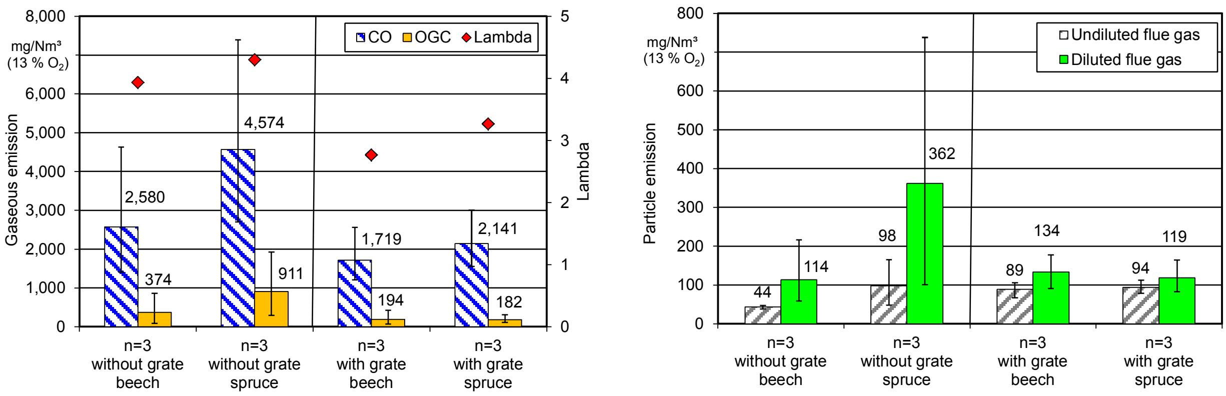


Figure 2: Influence of the presence of a grate in a chimney stove regarding gaseous and particle emission using beech and spruce wood without bark at nominal heat output.

Explanations: n = number of batches measured per trial (ignition batch excluded); emissions related to dry flue gas and 13 vol% O_2

At TFZ test runs were performed within the scope of the project but also data from a parallel project were particularly evaluated and discussed to provide answers to questions concerning operational impacts as required to derive proper recommendations for stoves user. These operational (user-) impacts on stove performance covered fuel mass variations, fuel moisture variations, the proper time of recharging, variable log sizes and numbers of wood logs recharged. Furthermore, two ignition modes were compared: ignition from the top and ignition from below (traditional).

Within the scope of the ERA-NET project “FutureBioTec” test runs were conducted using two chimney stoves having exactly the same firebox geometry and volume, but one of the stoves was equipped with a grate while the other wasn't. The results show that the presence of a grate can be beneficial regarding gaseous emissions while no clear influence was observed for PM emissions during nominal heat output (see Figure 2). During the ignition batch the grate influenced the emissions negatively (not shown here). In an average operation the grate seems to have advantages regarding emissions when aggregated over a whole set of several batches.

In order to prevent false operation of chimney stoves a universal retrofit air control unit was tested on two different stoves. The results obtained for one of the stoves are shown in Figure 3. It can be seen that the emissions were not reduced by the device; they were usually increased instead, especially at low load when using only one single log per batch. Therefore, it has been concluded that universal retrofit units at the given state of technology are not suitable for emission reduction if they are not specifically adapted to the respective stove and if they only apply the flue gas temperature as input parameter for the feed air flap.

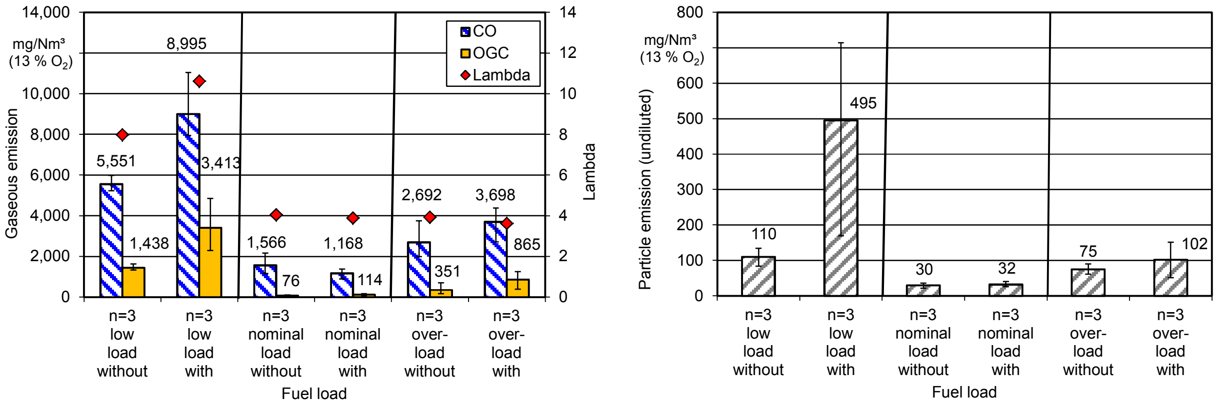


Figure 3: Influence of the retrofit air control unit on gaseous and particle emissions using beech wood without bark while loading different masses per batch

Explanations: Measurements "with" and "without" retrofit air control unit applied on the same chimney stove (modern 7 kW stove with central combustion air socket)

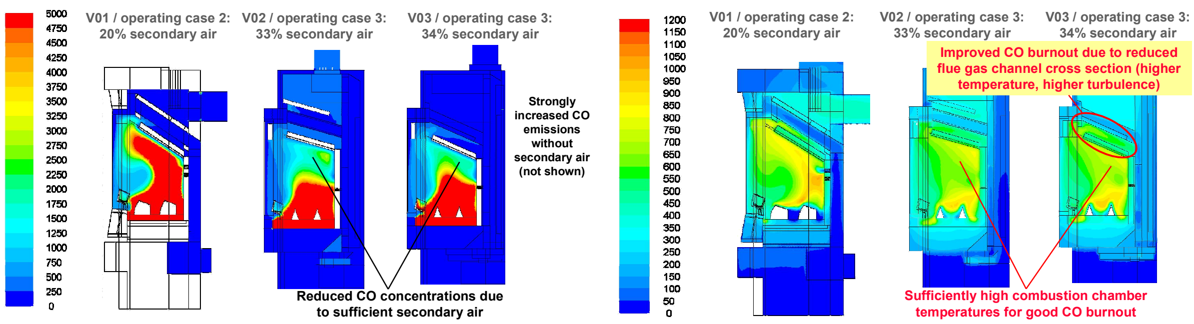


Figure 4: Results from CFD-simulations - iso-surfaces of CO concentrations [ppmv] in the flue gas in the vertical symmetry plane of the stove (left) and iso-surfaces of air, flue gas and stove temperatures [°C] in the vertical symmetry plane of the stove (right)

At BE2020 different strategies regarding air staging as well as an automated control system were developed and tested as primary measures for emission reduction from chimney stoves. In a first step secondary air injection through nozzles placed at the backwall of the main combustion chamber was implemented and optimised at a state-of-the-art chimney stove. Different numbers of nozzles as well as nozzle positions were tested. These investigations were accompanied and supported by CFD-simulations in order to pre-optimise the secondary air injection and to reduce the number of test runs needed. In Figure 4 an example for the CFD-simulations performed is presented. It shows the influence of the amount of secondary air injected into the flue gas and its influence on CO emissions (burnout quality).

Moreover, an automated control system based on combustion air control in dependence of the furnace control was implemented to optimise the overall air supply over the whole batch. Finally, a better isolation of the burning chamber was applied to further enhance the gas phase burnout. The different measures led to a stepwise reduction of the emissions (see Figure 5) by 60% for CO, 86% for OGC and 55% for PM.

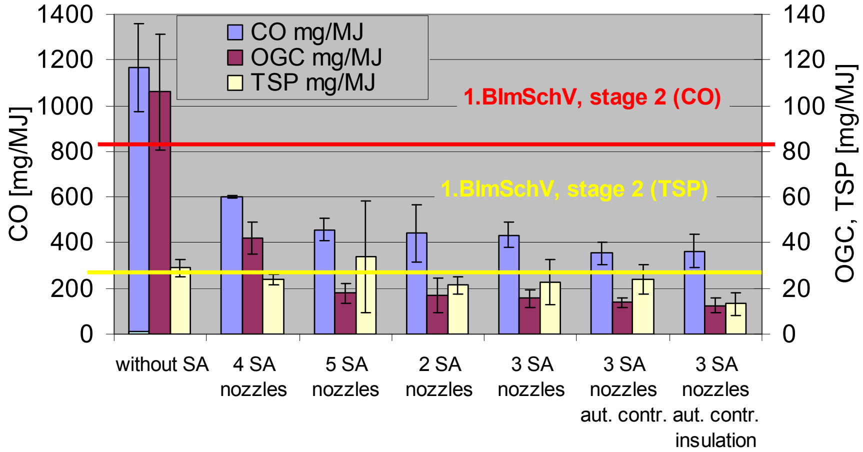


Figure 5: Emission reduction of a state-of-the-art stove by implementing secondary air injection, an automated control system as well as a better isolation of the burning chamber

Explanations: BImSchV … limit values according to the German BImSchV; SA … secondary air; aut. Contr. … with automated control system

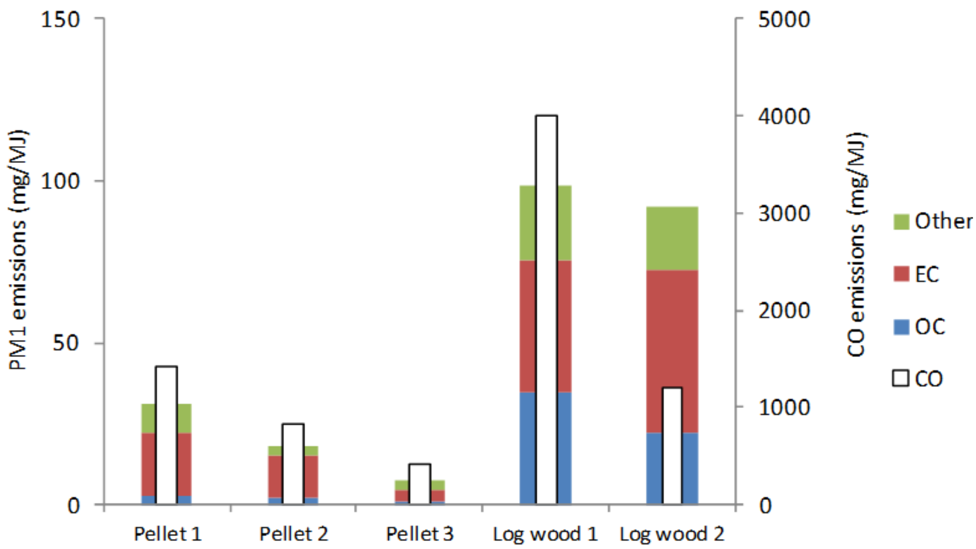


Figure 6: Emissions from a hybrid stove during pellet combustion and log wood combustion highlighting the effect of improvements on fine particle and gaseous emissions achieved during the project.

Explanations: Values are average values over the combustion cycle; Pellet 1, 2, 3 … 3 test runs with pellet operation; log wood 1, 2 … test runs with log wood operation (ignition batch + 2 batches each); other: inorganic species

In cooperation with Warma-Uunit Ltd. Partner UEF performed combustion experiments using a hybrid masonry heater for both log wood and wood pellets. This possibility gives flexibility for this type of appliance, in which log wood has been used as only fuel up to now. A different grate system is needed for pellet use but no additional changes are required. In pellet operation, the stove is used in one-batch principle. Air-staging, grate design, operational practises and combustion chamber materials were improved during the project and their effect on emissions has been verified by measurements.

The operational practices proofed to have the largest effect on emissions for log wood stoves, even though some air-staging strategies were introduced during the project. In pellet combustion, the improvement of the control of combustion air supply resulted in a more stable operation at lower excess oxygen in the flue gas. Changes in grate design improved mixing of combustible gases and secondary air. All of the changes that were made in the pellet combustion system resulted in total in a 3.4-fold decrease in CO emissions and a 4.2-fold decrease in PM_1 emissions (see Figure 6). The decrease in PM_1 emission was mostly due to more efficient burnout. The improvements in log wood combustion resulted in a 3-fold decrease in CO emissions and 7% decrease in PM_1 emissions. In comparison, pellet combustion generated 3-times less CO emissions and 13-times less PM_1 emissions compared to log wood combustion. Pellet combustion produced similar PM_1 emissions to automated appliances.

3.1.3 Low emission operation manual for chimney stove users

At the beginning of the project the knowledge regarding wood stove design and operation already available at the partners and in literature has been gathered by the consortium. The test runs performed within *FutureBioTec* (section 3.1.2) lead to a significant improvement of this knowledge. Finally, the results and experiences from the test runs and simulations performed as well as the pre-existing knowledge were summarised and intensively discussed within the consortium. Based on that, a *low emission operation manual for chimney stove users* was compiled. The aim of this manual is to provide comprehensive information regarding an appropriate low emission operation of chimney stoves.

The manual addresses two different target groups. First off all interested stove owners who want to improve the performance of their appliances can make use of the manual. The second target group are stove manufacturers as well as public and non-public organisations who promote low-emission heating systems. In contrast with many other already existing information brochures and flyers on low emission heating the *FutureBioTec*-manual is very comprehensive and tackles all aspects of stove operation. Therefore, also excerpts of the manual could be used by stove manufacturers to improve their operation manuals and from public and non-public organisations to be used in their information material on low emission heating. To enable this further utilisation of the manual, it is made available on the project webpage as download.

As mentioned the manual provides information regarding all relevant aspects of low emission stove operation leading from the fuel selection and fuel handling to the combustion process. Also other issues such as appropriate stove dimensioning (in terms of heating demand) as well as stove positioning and maintenance aspects are discussed. Pictures and diagrams were used to make the explanations easily understandable also for technically not educated persons, such as typical stove users are. In detail the following aspects are discussed:

- **Wood as fuel**: General aspects of wood logs such as fuel standards, log wood dimensions, energy content, density, moisture content and their impact on the fuel quality are discussed. Moreover, information about permissible and non permissible fuels for stoves and regarding appropriate ignition material is provided.
  Major recommendations given are that only fuel with a moisture content between 8 and 20 wt% should be applied and that the utilisation of technically dried wood (below 8 %) and wet wood shall both be avoided.
  Moreover it is pointed out that preferably hardwood (e.g.: beech) should be used. Wood briquettes are also well suitable for combustion in chimney stoves. However, briquettes made of pure bark should be avoided due to smouldering conditions causing high emissions.

- **Log wood drying, storage and quality control**: In this section comprehensive information on the influence of storage on the moisture content is provided.
- **Stove technology:** Design and function of stoves are explained to the reader and information about the correct selection of the heating power with respect to the building/room to be heated is provided. Different aspects which help the user to distinguish between a high quality and a low quality product are highlighted. Moreover, the reader is informed about the correct positioning of a stove in a room.
- **Stove operation:** Valuable information on the stove operation is provided. One major advise is that stove ignition should be performed from the top (i.e. the ignition block is placed on top of a single layer of wood logs; then the ignition block is covered with the kindling and ignited). This ignition method has the potential to decrease the CO emissions already during the start-up batch by about 60% in comparison to traditional methods and is therefore a key issue to be communicated to users but also to manufacturers.
  Moreover, the correct recharging (regarding time, fuel mass and log positioning) is explained. The major messages are that recharging should preferably be done at the extinction of bright yellow flames and that the fuel load per batch should be adjusted to the instructions of the manufacturer (using single logs as well as overloading the stove lead to a drastic increase of emissions and should therefore be avoided).
  The final part of this section is dedicated to ash handling as well as aspects regarding maintenance and troubleshooting.

3.1.4 Guidelines for an improved design of wood stoves

The pre-existing knowledge as well as the results from test runs performed and of the CFD simulations have also been discussed with respect to proposals for improved stove design. The results of these discussions have formed the basis for the “Guidelines for low emission stove design” (see Figure 7) which were compiled to support stove manufacturers in optimising their products. These guidelines are also available on the project webpage for download.

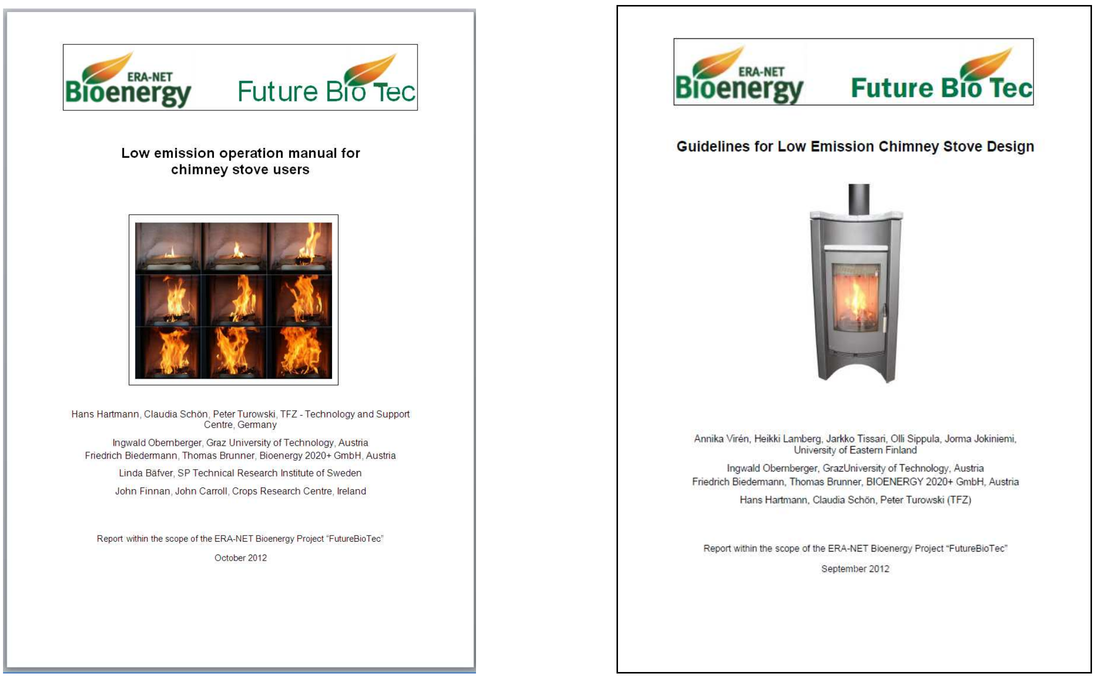
The main aspects covered by this guideline are:

- **Basic definitions:** To gain a common language, especially regarding the different relevant components of a stove (main combustion chamber, post combustion chamber, etc.) and different combustion air flows that can be applied (primary air, secondary air, window purge air) and to avoid misinterpretation, at the beginning a section describing these basic definitions is given. This is of particular relevance since different stove manufacturers use different terms, especially for the air streams supplied to the stove.
- **Parameters affecting emissions of stoves:** In this section relevant parameters responsible for emission formation (CO, OGC, TSP, PM_1) are briefly described to provide to manufacturers a better understanding for the following sections.
- **General requirements for low emission chimney stoves** are then defined which mainly focus on stove geometries, construction related issues (materials to be applied, reduction of false air intake, etc.) as well as the implementation of air staging strategies in general.
- **Geometric design concepts** are then discussed mainly focusing on the design of the main combustion chamber and its isolation (to achieve high temperatures to improve burnout), on the post combustion chamber design as well as on grate designs. Recommendations how to optimise these parts of a stove are provided.
- **Air supply and air staging** is an issue of outstanding importance for low-emission stove concepts and therefore, these aspects are discussed in a separate section. The

relevance of different air streams (primary, secondary and window purge air) are discussed and recommendations how to implement an optimised injection of these air streams are given. Generally it is proposed to apply at least primary and window purge air however, the application of secondary air to improve burnout is strongly recommended. The chapter also includes recommendations regarding air preheating.

- **Automatic combustion control** is gaining rising relevance also in stoves. As the project has clearly shown, user induced errors can be almost excluded by the application of intelligent automated control systems. Therefore, the basic working principles of automated control systems and recommendation regarding their setup and implementation are provided.
- **CFD-aided design of wood stoves** provides a tool which can make the development and optimisation work more target oriented and thereby helps to safe time for costly prototype reconstructions. Moreover, CFD simulations provide a visualisation of the combustion process and therefore deeper insights how the variation of certain parameters (geometries, air staging strategies) influences emissions. Therefore, the possibilities of this design tool are presented to the manufacturers.

It has to be pointed out that due to the high number of stove manufacturers in Europe and due to the manifold different design options the recommendations provided are rather general. The guideline tries to explain which measures influence emissions from a stove and which strategies for emission reduction can be applied. It is up to stove manufacturers to finally utilise this knowledge and implement the proposed measures in their specific stove concepts.


ERA-NET Bioenergy Future Bio Tec
Low emission operation manual for chimney stove users
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Ingwald Obernberger, Graz University of Technology, Austria
Friedrich Biedermann, Thomas Brunner, Bioenergy 2020+ GmbH, Austria
Linda Bäfver, SP Technical Research Institute of Sweden
John Finnan, John Carroll, Crops Research Centre, Ireland
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Guidelines for Low Emission Chimney Stove Design
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Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec"
September 2012

Figure 7: Two guidelines, one for stove operation (for users) and one for stove design (for manufacturers) have been elaborated within the scope of WP1 (see www.futurebiotec.bioenergy2020.eu).

3.1.5 Relevant literature

SCHÖN, C., HARTMANN, H. (2012): Combustion behaviour of wood briquettes in stoves. In: Proceedings 20th European Biomass Conference & Exhibition - From Research to Industry and Markets. Milano, Italy, 18-22 June 2012. ETA Renewable Energies (Eds.), Florence, Italy, pp. 1286-1292

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3.2 Work package 2: Reduction of PM and NO_x emissions from automated boilers by primary measures

Within the scope of work package 2 comprehensive tests and evaluations regarding reduction of PM and NO_x emissions from automated boilers by primary measures have been performed. An important focus within the scope of work package 2 has been the performance of test runs and systematic investigations of the effect of air staging as an efficient primary measure to reduce NO_x and PM emissions at different fixed bed combustion systems (see chapter 3.2.1). Based on the results of these investigations design and operation concepts for low-emission biomass grate furnaces based on advanced air staging have been elaborated (see chapter 3.2.2).

Furthermore, the application of additives and fuel blending as measures for an improved operation and emission reduction have been extensively examined (see chapter 3.2.3) and an improved method for the characterisation of the combustion behaviour by single pellets reactor tests has been applied (see chapter 3.2.4). In addition, a new combustion technology for pulverized biomass fuels has been developed by partner IEn (see chapter 3.2.5).

3.2.1 Air staging as an efficient primary measure to reduce NO_x and PM emissions in fixed bed systems

In a first step a summary report regarding the evaluation of existing data on air staging strategies has been compiled by BE2020, UEF and UmU. The report summarizes and evaluates available data regarding the influence of air staging on NO_x and PM emissions for fixed bed biomass combustion. In total, data from 9 different automated boiler technologies with a nominal boiler capacity between 5 kW_{th} und 9 MW_{th} have been considered. The results showed that no reliable data had been available regarding comprehensive and systematic studies on air staging strategies before the start of this project.

Test runs performed at BE2020

At BE2020 test runs have been performed at a pilot-scale combustion plant with a nominal boiler capacity of 180kW (see Figure 8). The furnace is equipped with moving grate technology and the combustion chamber is geometrically separated into a primary combustion chamber (PCC) and a secondary combustion chamber. Secondary air can be induced at two different positions into the furnace in order to vary the residence time of the flue gas in the PCC. The plant is equipped with flue gas recirculation, whereby the recirculated flue gas can be induced above or below the grate. False air (air leakages) in the furnace especially in the PCC through the fuel feeding system and the ash discharging system has been minimised in order to guarantee an effective air staging (false air amounted to max. 15% of the total combustion air supply after sealing). In this respect, it is important that the fuel feeding, the ash discharge channel and the furnace doors are tight and that there are no open holes in the furnace. During the test runs performed all combustion air flows, flue gas and flue gas recirculation flows as well as the gaseous emissions (CO, CO_2, O_2, NO, NO_2) at boiler outlet have been continuously measured. In addition, all relevant plant operation parameters such as load, temperatures, etc. have been recorded. The PM_1 emissions have been measured with a Berner type low pressure impactor und the TSP emissions with equipment according to VDI 2066.

In a first comprehensive test series, the combustion behaviour of chipboard has been examined. Chipboard from the same production patch and no chipboard residues has been used for the entire test series in order to ensure uniform fuel quality and composition. Subsequently the combustion behaviour of woodchips has been examined within a second test series. Only spruce with bark from one region with similar water contents has been used in order to ensure uniform fuel quality. Within the last test series performed short rotation coppice (willow) has been utilized. For all fuels the dependency of the CO emissions on the total air ratio for the fuels used has been determined. The results show that for total air ratios between 1.3 and 1.6 the average CO emissions measured were below 200 mg/Nm³ (dry flue gas, 13% O_2) which proves that no relevant effect of the burnout quality on NO_x and PM_1 emissions can be expected.

Within the scope of the test runs performed the following influencing parameters on NO_x and PM_1 emissions have been investigated for all fuels:

- air ratio in the PCC: (range: 0.4 – 1.4)
- residence time in the PCC: (large or small PCC)
- temperature in the PCC: (900°C, 1,000°C, 1,100°C)
- type of flue gas recirculation: (above or below the grate)

Only one parameter per test run has been varied. Test runs have been performed at 150 kW boiler load (approx. full load). The total excess air ratio (λ_{tot}) was about 1.4 for all test runs performed.

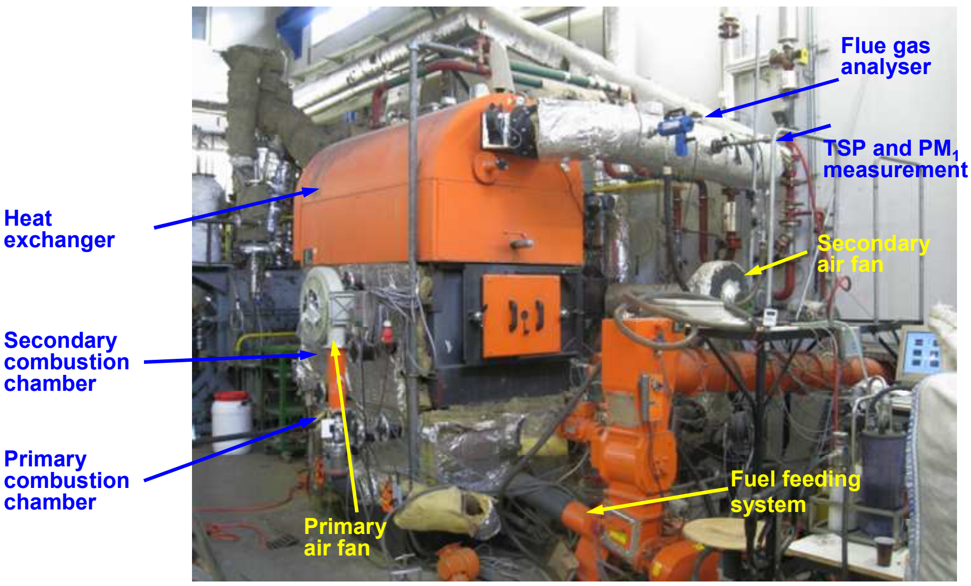


Figure 8: 180 kW moving grate plant – picture of the plant

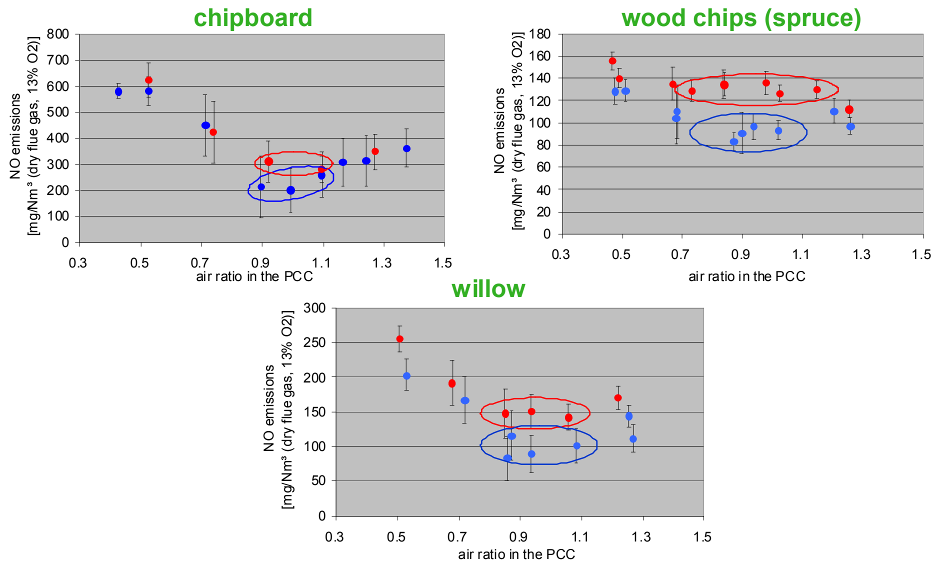


Figure 9: Air ratio in the PCC versus NO emissions for varying residence time
Explanations: Blue: Rec above grate, T_{PCC}=1,000°C, full load, **large PCC**; Red: Rec above grate, T_{PCC}=1,000°C, full load, **small PCC**; PCC … primary combustion chamber; minimum NO_x emission ranges marked

Figure 9 shows the air ratio in the PCC versus NO emissions for varying residence time. The results show that the air ratio in the PCC has the strongest influence on NO_x emissions. An optimum can be observed at an air ratio in the PCC between 0.9 and 1.0 for all three fuels used. Figure 9 also indicates that the residence time in the PCC (volume of the PCC) has an influence on NO_x emissions (besides the air ratio in the PCC the 2^{nd} relevant parameter). NO_x emissions increase with decreasing residence time. The type of flue gas recirculation seems to also have a slight effect on NO_x emissions (not shown here). Flue gas recirculation above the grate seems to be more efficient regarding NO_x reduction than flue gas recirculation below the grate. Furthermore, the tests performed show that the temperature in the PCC seems to have no relevant influence on NO_x emissions within the range investigated (not shown here).

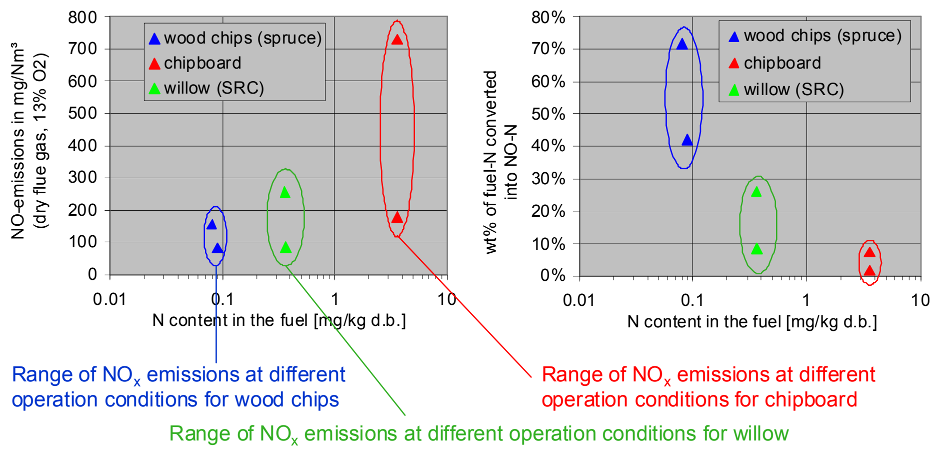


Figure 10: NO_x emissions and N conversion versus N in the fuel

Figure 10 (left diagram) also shows the wide variation of NO_x emissions measured during the test runs performed and demonstrates that low NO_x emissions are also achievable for fuels with high N contents by efficiently applying primary measures. Furthermore, the NO_x reduction potential is much higher for fuels with a high N content (chipboard) compared to fuels with low N contents (woodchips). Consequently, an efficient air staging concept has rising importance for these fuels. Figure 10 (right diagram) shows that depending on the operational conditions between 1.5% and 7.4% of the fuel-N are converted into N in NO_x

emissions for chipboard and between 43% and 72% for woodchips (spruce). For willow the respective values are 9 to 27%. This figure shows that the N conversion depends on the N content of the fuel. The conversion of the fuel-N into N in NO_x increases considerably with decreasing N content. However, although the conversion rate of the fuel-N is lower for fuels with high N content, the total NO_x emissions are higher.

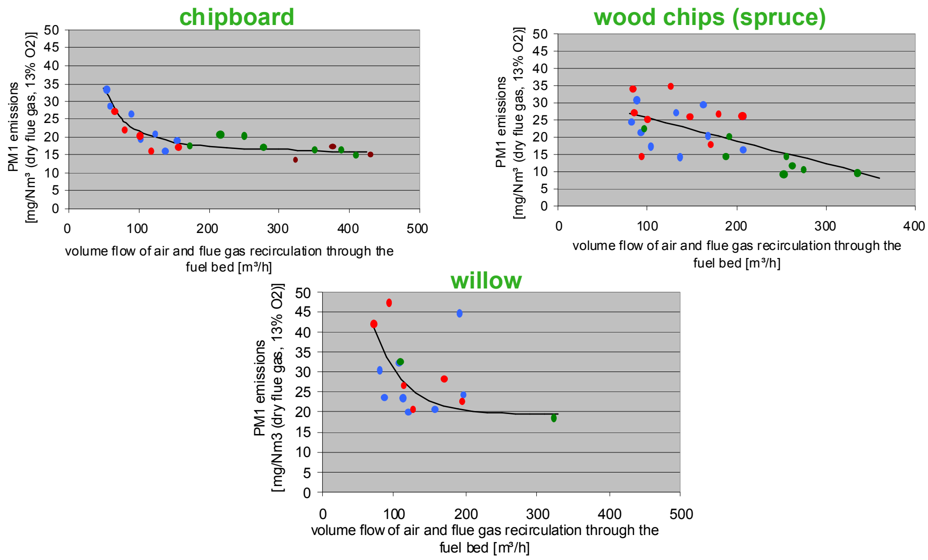


Figure 11: Influence of volume flow of air and flue gas recirculation through the fuel bed on PM_1 emissions

Explanations: Blue: Rec above grate, large PCC, full load, TPCC=1,000°C; Green: Rec below grate, large PCC, full load, TPCC=1,000°C; Red: Rec above grate, small PCC, full load, TPCC=1,000°C; Brown: Rec below grate, small PCC, full load, TPCC=1,000°CLine: regression for PM1 emissions at 1,000°C; the correlations calculated are statistically highly significant

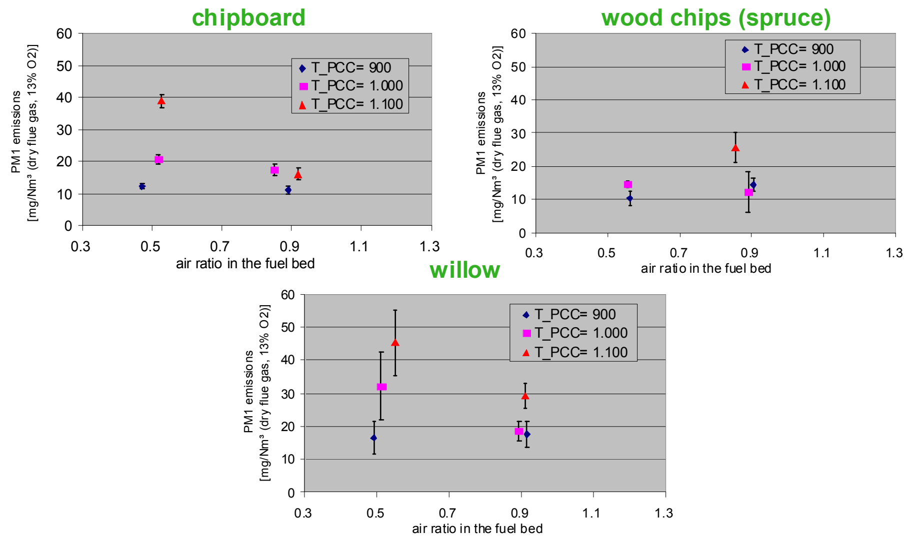


Figure 12: Influence of the temperature in the PCC and in the fuel bed on PM_1 emissions

Explanations: only test runs with flue gas recirculation below grate considered; for wood chips the point T_{PCC} =1,100 °C at an air ratio in the fuel bed of 0.5 could not be tested since the moisture content of the fuel was too high

Regarding PM_1 emissions, two relevant influencing parameters could be identified based on the results of the tests performed. One relevant influencing parameter is the volume flow of the gas through the fuel bed (sum of primary air and flue gas recirculation below the grate, see Figure 11). A statistically highly significant correlation could be identified that with rising gas flow through the fuel bed PM_1 emissions decrease. This is due to the fact that the gas flow causes a cooling effect as not the whole oxygen supplied is consumed in the bed which is confirmed by CFD simulations of packed biomass fuel beds. The effect gets the more pronounced the lower the gas flow is. A second relevant influencing parameter is the temperature in the PCC (see Figure 12). As higher gas temperatures cause higher radiation, they also influence the bed temperature. This effect gets the more pronounced the lower the gas flow through the grate is (the lower the air ratio in the fuel bed is).

Regarding TSP emissions, no clear dependency of the volume flow through the fuel bed on the TSP emissions has been found.

Test runs performed at University of Eastern Finland

Within the scope of test runs performed by UEF a novel grate combustion reactor with a nominal boiler capacity of 40 kW was used (see Figure 13). The combustion chamber is geometrically separated into a PCC and a secondary combustion chamber. No flue gas recirculation is applied. Wood chips, wood pellets and a mixture of wood chip (78 wt%) and reed canary grass (22 wt%) have been used as fuel. Test runs have been performed at full load with temperatures at the end of the PCC ranging between 800 to 1,000°C. The total excess air ratio (λ_{tot}) was set to 1.8 to 2.0. The false air in the PCC amounted to approx. 11% of the total amount of combustion air supplied. During the test runs relevant operating parameters have been recorded and gaseous emissions (O_2, CO, NO_x) as well as TSP and PM_1 emissions have been measured.

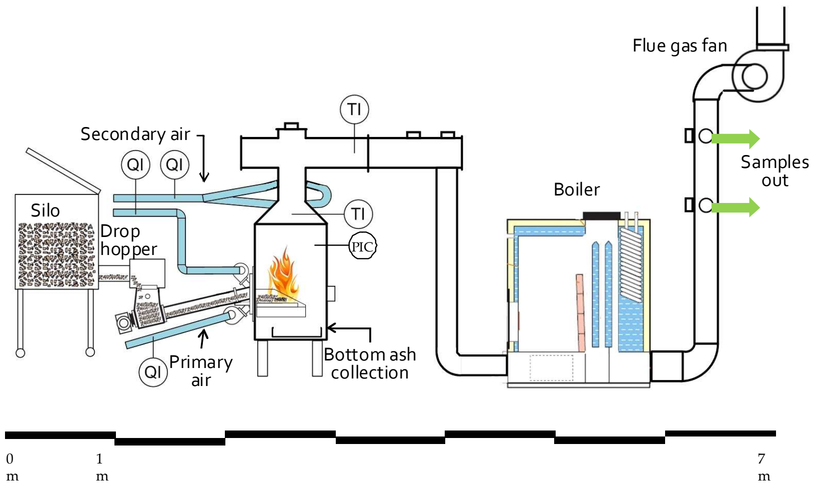


Figure 13: Scheme of the novel grate combustion reactor with a nominal boiler capacity of 40 kW

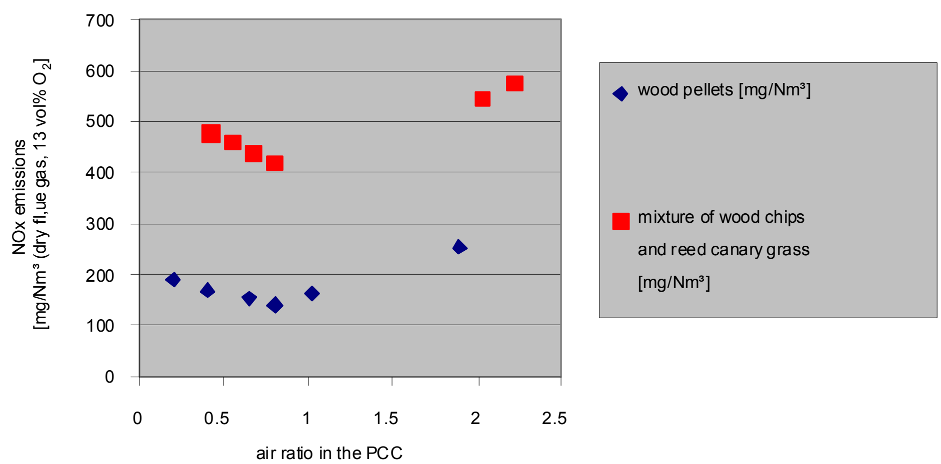


Figure 14: Air ratio in the PCC versus NO_x emissions for different fuels examined

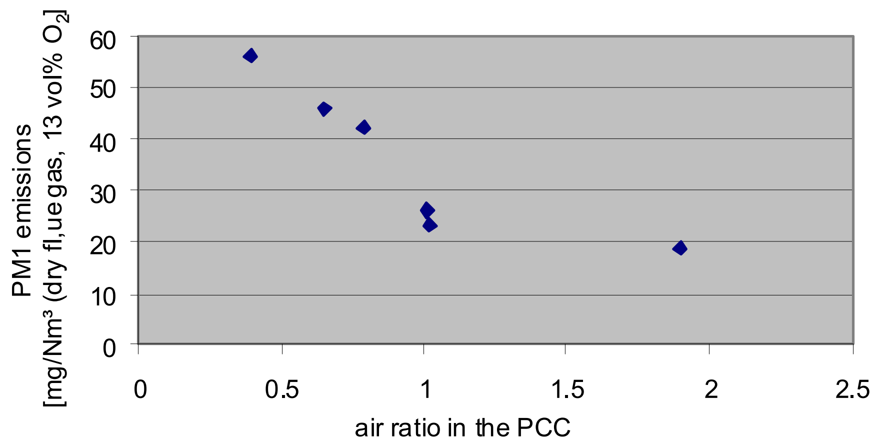


Figure 15: Air ratio in the PCC versus PM emissions for wood pellets

Figure 14 shows the air ratio in the PCC versus NO_x emissions for different fuels examined. The results show that, similar to the tests performed by BE2020, the air ratio in the PCC has a strong influence on NO_x emissions. An optimum can be identified at air ratios in the PCC around 0.8. Regarding PM_1 emissions, Figure 15 shows that the air ratio in the PCC and correspondingly the volume flow through the fuel bed has a strong influence on PM_1 emissions. PM_1 emissions decrease at increasing air ratio in the PCC.

Test runs performed at Teagasc, Ireland

Test runs at Teagasc have been performed with a tilting grate boiler (nominal boiler capacity: 35 kW, see Figure 16). The combustion chamber is geometrically separated into a PCC and a secondary combustion chamber and flue gas recirculation can be induced below the grate. Within the cope of the tests performed the following fuels have been used:

- Wood (N content: 0.16 wt% d.b.)
- Miscanthus (N content: 0.30 wt% d.b.)
- Cocksfoot (N content: 0.63 wt% d.b.)
- Tall Fescue (N content: 0.70 wt% d.b.)

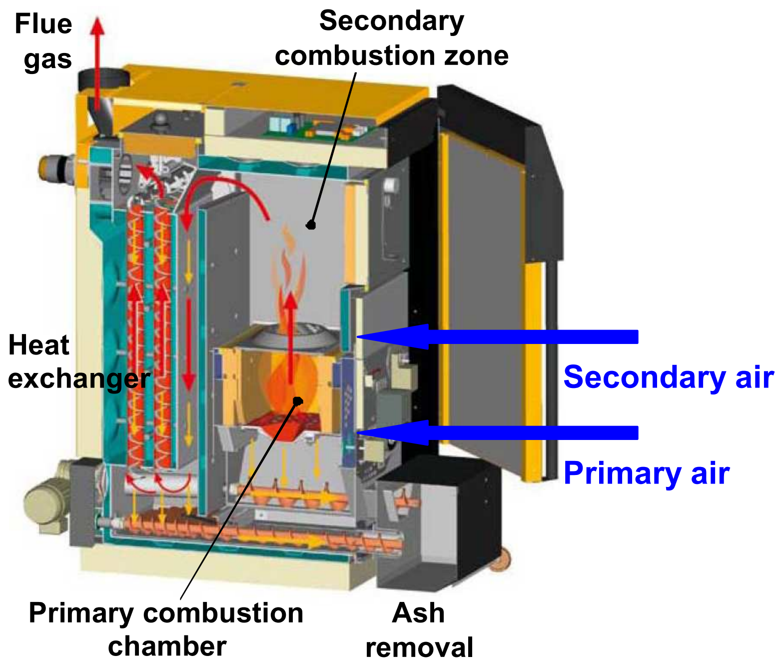


Figure 16: 35 kW tilting grate boiler at Teagasc

Temperatures have been measured in the primary combustion chamber, in the secondary combustion chamber and in the flue gas downstream the boiler. Furthermore, the volume flows of the primary and secondary air as well as of the flue gas recirculation have been determined. In addition gaseous (CO, NO_x, O_2, CO_2) and particulate (TSP and PM_1) emissions have been measured. The false air amounted to approx. 12% of the total amount of combustion air supplied and was reduced to approx. 5% after sealing.

Figure 17 shows exemplary results of the air ratio in the PCC versus NO_x emissions for different fuels examined. Again a clear dependency of the NO_x emissions on the air ratio in the PCC can be observed. Furthermore, NO_x emissions increase with increasing N content in the fuel. The results also indicate that PM_1 emissions decrease with reduced temperatures in the primary combustion chamber (not shown here).

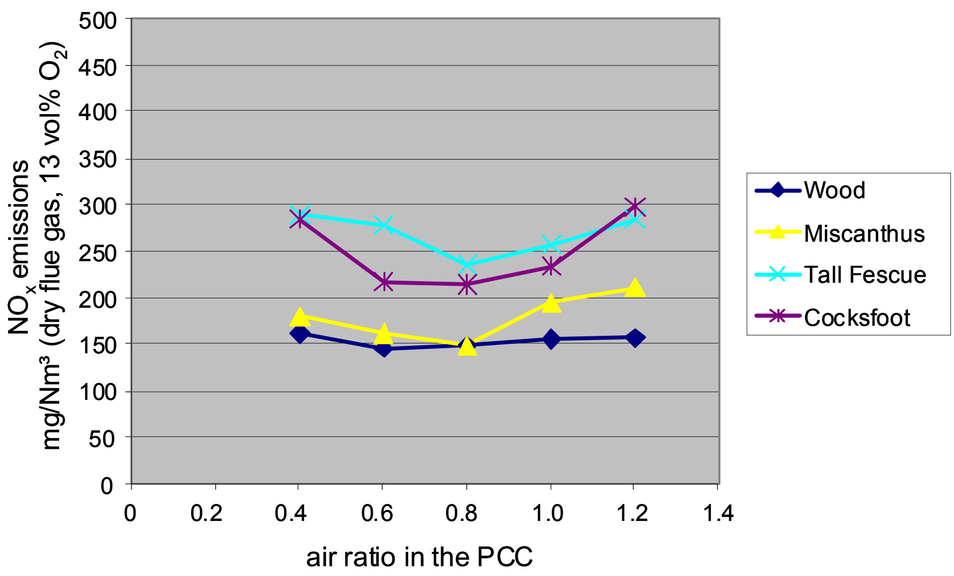


Figure 17: Air ratio in the PCC versus NO_x emissions for different fuels examined
Explanations: Test runs performed at full load; total excess air ratio (λ_{tot}): 1.6; temperatures in the PCC were kept constant with flue gas recirculation: 1,000°C for wood; 900°C for miscanthus, tall fescue and cocksfoot

Conclusions derived from all test runs performed:

Figure 18 shows a comparison of the results of the test runs performed by the three partners. The clearest and strongest dependence on NO_x emissions is given by the air ratio in the PCC, with lowest NO_x emissions at an air ratio below 1.0. The optimum regarding NO_x emissions seems not to be fuel dependent (for a given technology). However, the optimum regarding NO_x emissions seems to be technology dependent to a certain extent (see Figure 18). Consequently, the optimum has to be determined for a given technology with dedicated test runs and the process control should be adjusted accordingly.

NO_x emissions increase with decreasing residence time in the PCC. This effect seems to have rising importance the smaller the residence time available in the PCC is. Moreover, it seems to be more pronounced at air ratios in the PCC close to the optimum. The temperature in the PCC within the investigated range of 900°C to 1,100°C does not seem to be a relevant influencing parameter on NO_x emissions. Flue gas recirculation above the grate seems to be slightly more efficient regarding NO_x reduction than flue gas recirculation below the grate (at same temperature conditions) most likely due to a better mixing. The minimisation of false air in the PCC seems to be of great importance for an efficient air staging technology because it is not controllable and typically changes with varying load (should be lower than 15% of the total air supply). The comparison of the test results shows that the reduction potential regarding NO_x emissions increases considerably with increasing N content in the fuel. In general, the results show that the potential to reduce NO_x emissions by primary measures is considerable.

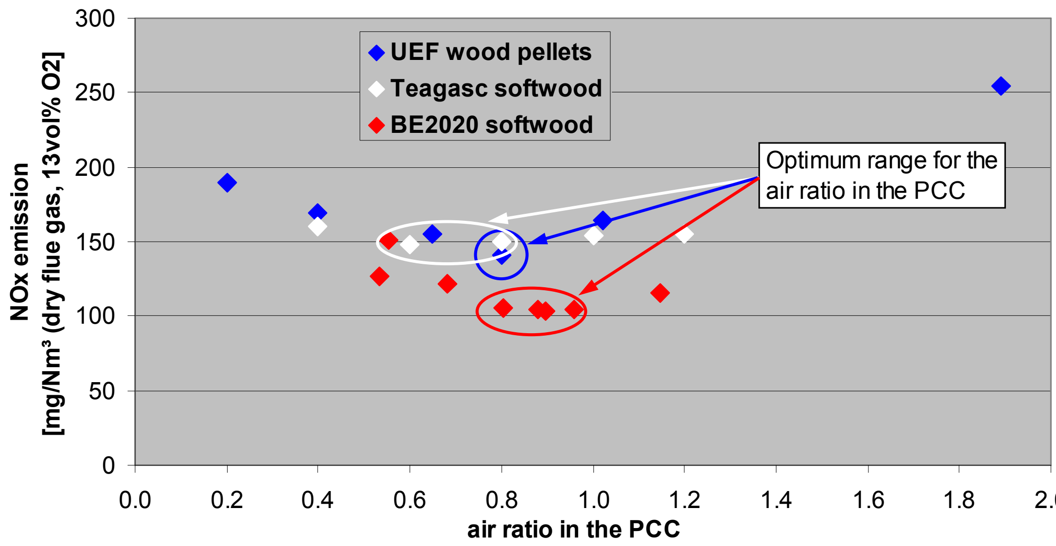


Figure 18: Comparison of the test runs performed at different combustion plants
Explanations: Test runs performed at full load; total excess air ratio (λtot): BE2020: 1.4; Teagasc: 1.6; UEF: 1.8 - 2.0; temperatures in the PCC: around 1,000°C; Fuel-N contents: BE2020: 0.08 wt% db; Teagasc: 0.16 wt% db; UEF: 0.04 wt% db

PM_1 emissions decrease with increasing volume flow through the fuel bed due to most probably lower fuel bed temperatures at higher air flows. The temperature in the PCC is also of relevance for the fuel bed temperature and has an influence on PM_1 emissions. However, this influence decreases with increasing air ratios in the primary combustion chamber. No clear dependency of the volume flow through the fuel bed on the TSP emissions has been found.

In order to reduce both, NO_x and PM_1 emissions

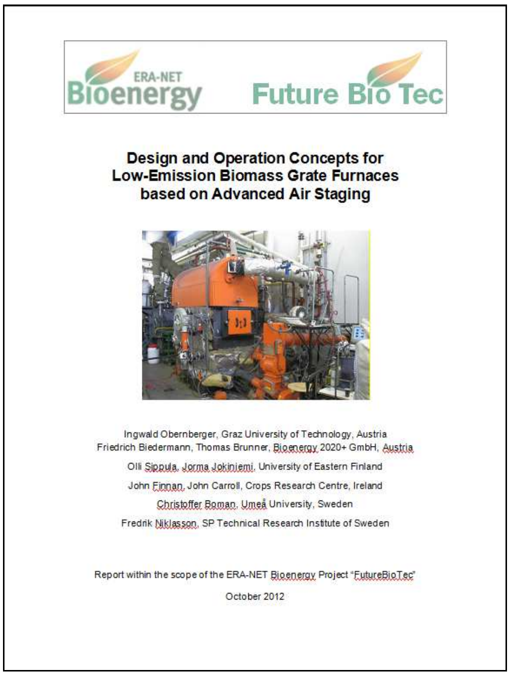
- the air ratio in the PCC should be kept slightly below 1.0 (the optimum value of the air ratio in the PCC is technology specific but not fuel specific and has to be determined within the scope of measurements),
- the mean residence time in the PCC should be reasonably high (above ~0.5 s),
- flue gas recirculation should be mainly applied below the grate to avoid slagging when fuels with low ash melting temperatures are utilised. Moreover, flue gas recirculation below the grate provides the possibility to cool the fuel bed in order to reduce the release of ash forming vapours and thus to reduce PM_1 emissions,
- flue gas recirculation into the PCC should also be applied to improve the mixing of the flue gases (reduce streak formation) and to control the temperature in the PCC,
- the flue gas temperature in the PCC should be kept moderate (900 – 1,000°C).

3.2.2 Design and operation concepts for low-emission biomass grate furnaces based on advanced air staging

Based on the results of the test runs performed by BE2020, UEF and Teagasc as well as on data from literature, design and operation concepts for low-emission biomass grate furnaces based on advanced air staging have been compiled (see Figure 19). This guideline includes information and recommendations for furnace and boiler manufacturers regarding the following topics:

- Basic remarks regarding the influence of air staging on NO_x and PM_1 emissions
- Design and operation concepts of staged combustion systems

  - o furnace geometry
  - o air supply strategies and flue gas recirculation
  - o recommendations regarding process control strategies to be implemented for advanced air staging
  - o requirements regarding sensors applied for process control
- Recommended settings for an efficient air staging


ERA-NET Bioenergy Future Bio Tec

Design and Operation Concepts for Low-Emission Biomass Grate Furnaces based on Advanced Air Staging

Ingwald Obernberger, Graz University of Technology, Austria
Friedrich Biedermann, Thomas Brunner, Bioenergy 2020+ GmbH, Austria
Olli Sippula, Jorma Jokiniemi, University of Eastern Finland
John Finnan, John Carroll, Crops Research Centre, Ireland
Christoffer Boman, Umeå University, Sweden
Fredrik Niklasson, SP Technical Research Institute of Sweden

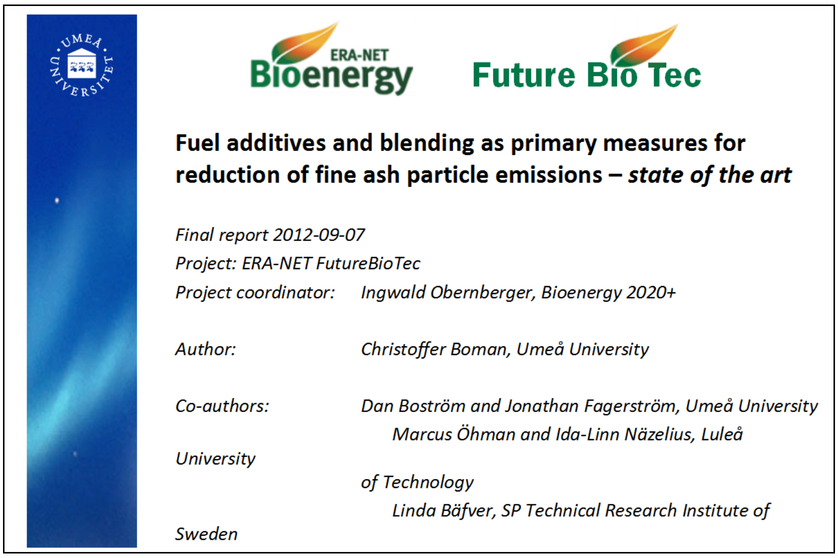
Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec"
October 2012

Figure 19: Design and operation concepts for low-emission biomass grate furnaces based on advanced air staging

3.2.3 Additives and fuel blending as measures for an improved operation and emission reduction

As a basis of the subsequent experimental work planned regarding additives and fuel blending a state-of-the-art report on "fuel additives and blending as primary measures for reduction of fine ash particle emissions" has been compiled (see Figure 20). The report summarizes present knowledge and information related to general ash transformation in biomass combustion, previous work on fuel additives, previous work on fuel blending, regulatory and economic aspects of fuel additives and research needs/critical issues. The report is available for download at futurebiotec.bioenergy2020.eu.

Fuel additives of main interest are calcium based and aluminium-silicate based (e.g. clay minerals). In addition, the use of phosphorus based/containing additives is discussed. There is only a rather limited number of studies performed with focus on the use of fuel additives as a measure for fine PM reduction so far. Ca-additives (mainly $CaCO_3$) have mainly been used with good results to prevent slagging in grate fired systems using woody fuels, but have shown no direct reduction of the K-release (i.e. fine particle formation). Kaolin clay (mainly composed of kaolinite, $Al_2Si_2O_5(OH)_4$) is well known by its ability to capture gaseous alkali compounds, forming e.g. K-Al-silicates which have higher melting temperatures than the pure K-silicates. Both slagging prevention and fine PM reduction have been shown possible. Aspects of limiting additive levels (standards) and ash disposal handling/costs must be considered when applying fuel additives and blending.


ERA-NET Bioenergy

Future Bio Tec

Fuel additives and blending as primary measures for reduction of fine ash particle emissions – *state of the art*

Final report 2012-09-07

Project: ERA-NET FutureBioTec

Project coordinator: Ingwald Obernberger, Bioenergy 2020+

Author: Christoffer Boman, Umeå University

Co-authors: Dan Boström and Jonathan Fagerström, Umeå University
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Linda Bäfver, SP Technical Research Institute of Sweden

Figure 20: Fuel additives and blending as primary measures for reduction of fine ash particle emissions – state-of-the-art report

Regarding the experimental work on fuel additives and blending, dedicated lab-scale reactor test runs have been performed at BE2020 with mixtures of softwood and straw with Kaolin. The main goal was to estimate an optimum Kaolin addition ratio. The tests were accompanied by thermodynamic high-temperature equilibrium calculations (TEC) and fuel index calculations to investigate the behaviour of ash forming elements.

The addition of Kaolin to straw resulted in a decrease of the K-release and an increase of the ash melting temperature (see Figure 21). Furthermore, the results of the thermodynamic high-temperature equilibrium calculations are in good agreement with the results of the experimental lab-scale reactor tests and are able to reproduce the trends correctly. Concluding, TEC and fuel indexes proofed to be suitable tools to evaluate optimal additivation ratios.

At Teagasc tests with the 35 kW tilting grate furnace have been performed. The temperature in the PCC was set to 900 °C, primary lambda to approx. 0.8 and the total lambda to 1.6. Tall Fescue and Miscanthus with different levels of Kaolin additivation have been examined. Both fuels show a large degree of ash melting above 900°C.

The results show that PM_1 emissions decrease with increasing amounts of Kaolin additivation (see Figure 22). However there seems to be an optimum regarding PM_1 emission reduction at Kaolin additivation levels around 4 wt%. Besides PM_1 emission reduction also a positive influence on ash melting problems was confirmed based on the experiences gained from test runs performed by Teagasc.

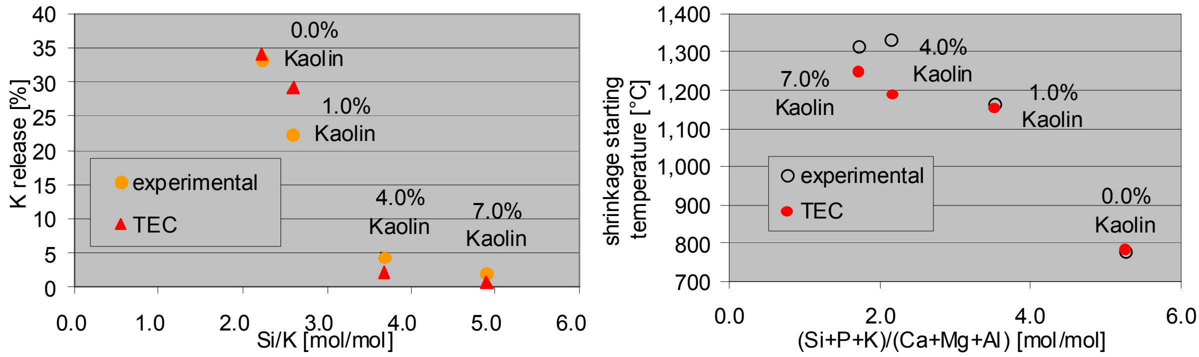

Figure 21: Results from lab-scale reactor and ash melting tests performed by BE2020 with straw pellets under consideration of different kaolin additivation levels

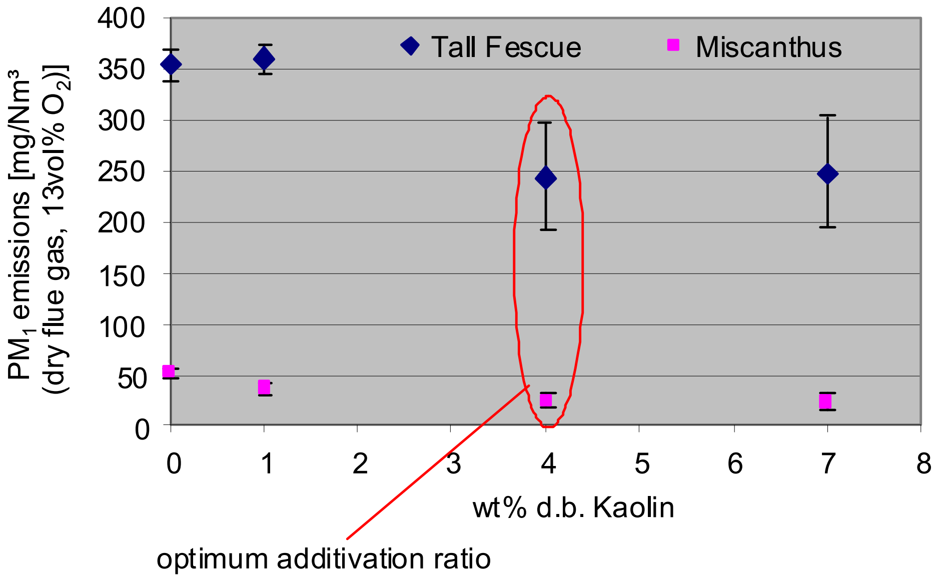

Figure 22: Results from small-scale combustion tests regarding additive application performed by Teagasc

Moreover, tests with fuel blends (peat from Ireland) have been performed. At BE2020 tests with different mixtures of miscanthus and peat in the lab-scale reactor and at Teagasc different mixtures of miscanthus as well as tall fescue and peat from Ireland in the 35 kW tilting grate furnace have been conducted. The tests at BE2020 were accompanied by thermodynamic high-temperature equilibrium calculations.

The results show that peat addition reduces slagging tendencies as well as PM_1 emissions (see Figure 23 and Figure 24). In addition, there is a rather good agreement of the ash softening temperature determined by lab-scale reactor experiments in comparison with TEC analysis (see Figure 23). According to the results, a peat ratio of 25% - 50% is recommended. However, it has to be taken into consideration that these results are related to the fuels investigated and may vary due to changes on fuel composition. Since also the compositions of different peat qualities vary considerably a general recommendation regarding an optimum blending ratio is not possible.

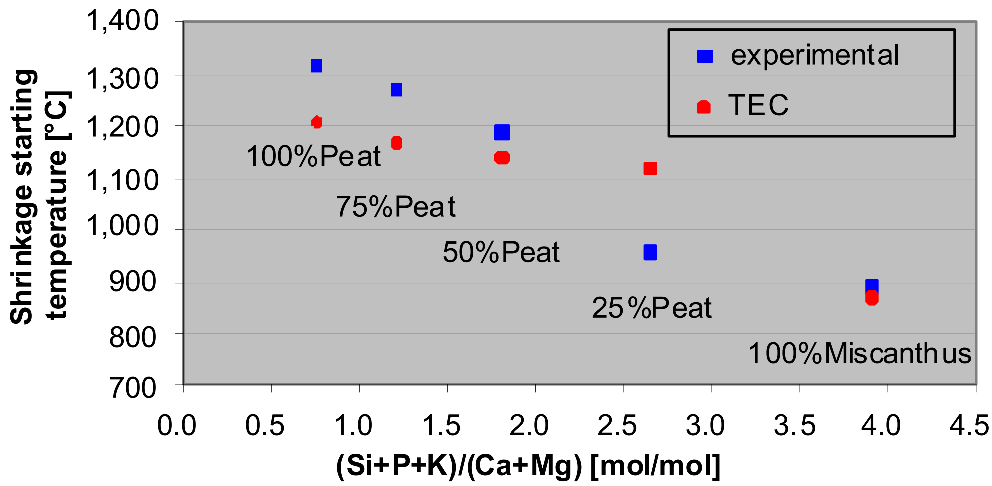

Figure 23: Results from lab-scale combustion tests with fuel blends (miscanthus/peat) performed at BE2020

Explanations: shrinkage starting temperature of the ash determined according to CEN/TS 15370-1

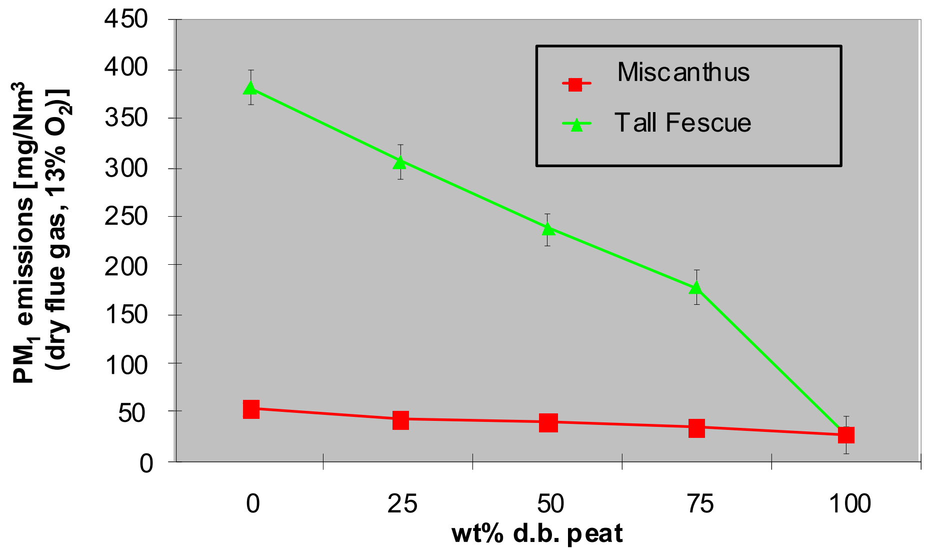

Figure 24: Results from small-scale combustion tests with fuel blends (miscanthus/peat and tall fescue/peat) at Teagasc

Concluding additives and intelligent fuel blending may considerably reduce ash related problems of biomass fuels but a detailed evaluation on a case by case basis is necessary.

3.2.4 Improved characterisation of the combustion behaviour by single pellets reactor tests

Studies with small lab-reactors burning single-pellet samples were performed by UmU and SP. The experimental set-ups and methodological approaches were to a large extent developed within the project and this task had the aims to *i)* support the information gained from combustion tests regarding both air-staging (see chapter 3.2.1) and fuel additive (see chapter 3.2.3), and *ii)* evaluate the potential/applicability of these novel laboratory methods to assess ash formation with focus on the alkali release behaviour. The more specific aim within the project was to study the release of alkali (focus on K), both qualitatively and quantitatively, during combustion of single pellets in two different "macro-TGA" set-ups using softwood and wheat straw. The influence of the process parameters oxygen content and temperature as well as kaolin addition was studied.

These kind of small laboratory methods using single-pellets have a number of specific features that make them an excellent complement to research and tests in larger combustion systems. Such features are: *i)* the use of real pelletized fuels and "real" combustion atmospheres, *ii)* possibilities for flexible studies of the influence of different fuel and combustion parameters, *iii)* possibilities to test a large number of samples in a short time period, *iv)* combines both quantitative and qualitative information from the different fuel conversion phases, *v)* relatively fast heat-up rate, *vi)* small amounts of fuel needed (1-5 g), and *vii)* possibilities for subsequent chemical and morphological analysis of residues.

At UmU controlled fuel conversion experiments have been performed in a specially designed reactor using one pellet at a time under specific atmospheres and furnace temperatures. The "release" of alkali and other ash forming elements has been determined by wet chemical analysis (ICP-methods) of the residual ash at BE2020. In total 24 different cases have been studied (variations in fuel, furnace temperature and kaolin addition) and a total number of 72 experiments (3 replicates/case) have been performed. At SP, small samples of pellets (normally 3 pellets each time) have been combusted in a laboratory reactor where the release of ash forming elements (e.g. K, Na and Zn) has been determined by using an on-line ICP-MS connected to the exhaust gas outlet. Within the scope of the experiments fuel, furnace temperature, oxygen partial pressure and kaolin addition has been varied. The experiments at UmU and SP have been coordinated and the information gained is complementary, mainly due to the fact that the SP method is more qualitative and the UmU method is more quantitative.

As a complement to the experimental work, thermodynamic high-temperature equilibrium calculations have also been performed at UmU. In this project, the modelling work had the objectives to support the definition of test matrices for the single-pellets studies and to compare modelled and experimental results.

The single-pellet studies supported the project with new and valuable information related to the alkali transformation behaviour during the combustion process in general and the interactions between potassium and kaolin additive specifically.

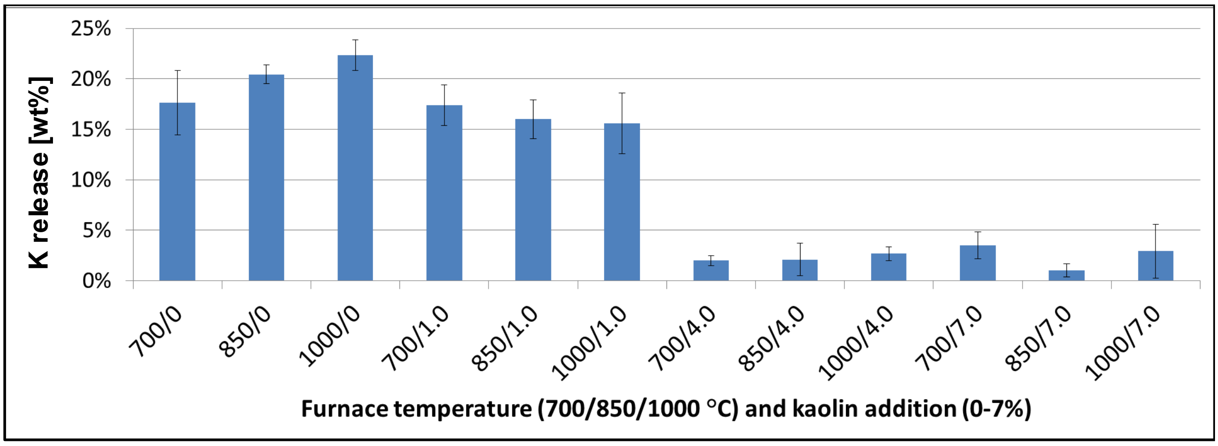

Figure 25: Release of potassium in single-pellet studies using wheat straw (at Umeå University) at different furnace temperatures and kaolin addition levels (O_2 fixed at 10%)

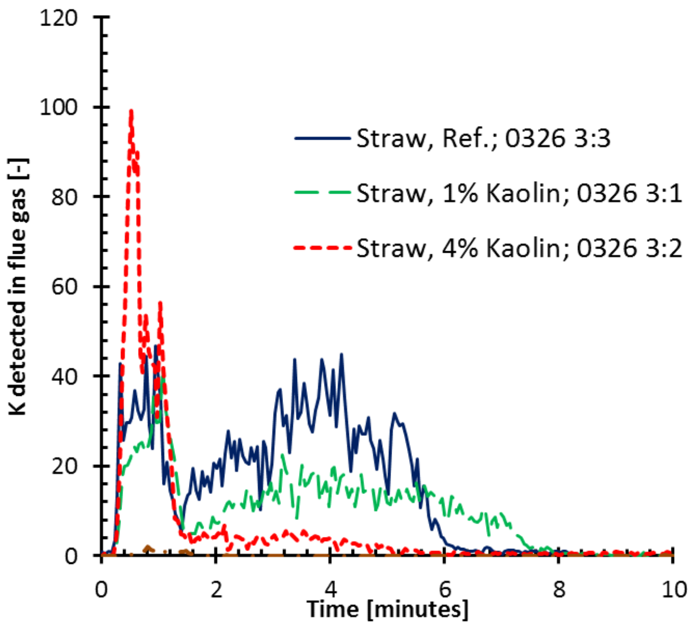

Figure 26: Results of on-line K release measurements performed at SP (Sweden)

In general, a somewhat higher release of K was seen in the single pellets tests compared to the K found in fine PM from the pellet burners. This is rather expected and presumably explained by "secondary" capture mechanisms in the fuel bed of the burners and also by losses on surfaces in the boiler/flue gas systems. Furthermore, the measurements showed a difference between the wood and straw pellet fuels regarding the release behaviour of potassium when kaolin was added. For wood, no effect of kaolin was seen while a considerable reduction of K release was achieved by kaolin addition to the straw fuel. The reduction effect was only minor at 1% but significant at 4% addition of kaolin. The difference in K release and interactions with kaolin between the two fuels may possibly be explained by the presence of different forms of potassium present in wood and straw. In Figure 25, the results of K release from the straw experiments at UmU.

Exemplary results from the tests performed at SP (see Figure 26) show that for pure straw K is partly released during the devolatilization but a considerable amount of K is also released in the charcoal combustion phase. If Kaolin is added the amount of K released in the charcoal combustion phase is considerably reduced.

Overall, the single-pellet combustion approaches developed and applied within the project FutureBioTec have, from different perspectives, proven to be useful tools for research and testing, but further evaluations and development is needed both related to the design of the set-ups and methodologies as well as to a deeper understanding of the underlying phenomena of ash transformation.

3.2.5 New combustion technology for pulverized biomass fuels

Within the scope of the project the following tasks regarding the development of a combustion technology for pulverized biomass fuels have been performed at IEn:

- Investigations of the fuel ignition phenomena
- Investigations of the fuel combustion kinetics
- Development of a numerical CFD model for pulverized biomass combustion
- Development of a 5-15 kW and a 0.5 MW burner for pulverized biomass fuels
- Burner up-scaling to 20 MW

Investigations of the fuel ignition phenomenon were carried out using 1.5 m long drop tube furnace. The tests were performed for different temperatures of the reactor as well as for different fuel fractions and velocities of the fuel injection into the furnace. As an important result of these investigations the flame stand-off distance from the burner outlet in dependence of the parameters (temperature, velocity and fineness of the fuel particles) has been obtained. Exemplary results for 800°C and 1,000°C are shown in Figure 27.

a) b)

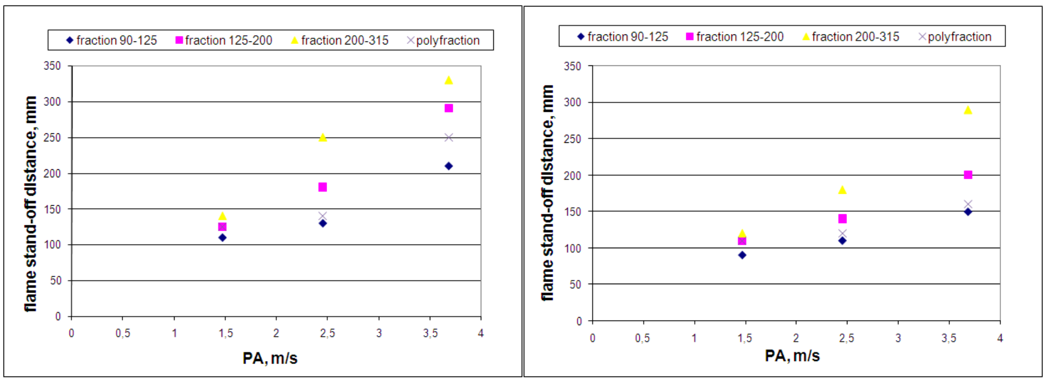

Figure 27: Comparison of the flame stand-off distance for different PA velocities, particle sizes and temperatures of the furnace

Explanations: temperatures of the furnace a) 800 °C, b) 1,000 °C; PA – primary air, polyfraction … mixture of all 3 sieve fractions examined

Investigations of the fuel combustion kinetics has been performed using two drop tubes: 1.5 m long one for investigations of devolatilisation kinetics and another 4 m long one for determination of kinetics of char oxidation. The results have been used for development and validation of a numerical CFD model for pulverized biomass combustion.

Regarding CFD modelling, initially a 2D model and finally a 3D model was investigated. The Discrete Ordinates model describing the process of radiation and the semi-empirical standard k-ε model for calculating the phenomenon of turbulence were taken into consideration. A single-rate model for modelling the devolatilisation process and a new charcoal combustion model was utilized. In contradiction to the standard Fluent code, the new model assumes that the type of combustion can change from homogeneous to heterogeneous and the char combustion does not have to occur after the full devolatilisation process. The model determines rates of devolatilisation, homogeneous oxidation of volatiles and the heterogeneous oxidation of char. The results achieved show quite good agreement between numerical and experimental values (flame stand-off distance, concentrations of O_2 and CO). Figure 28 shows a comparison of the calculated and measured flame stand-off distance.

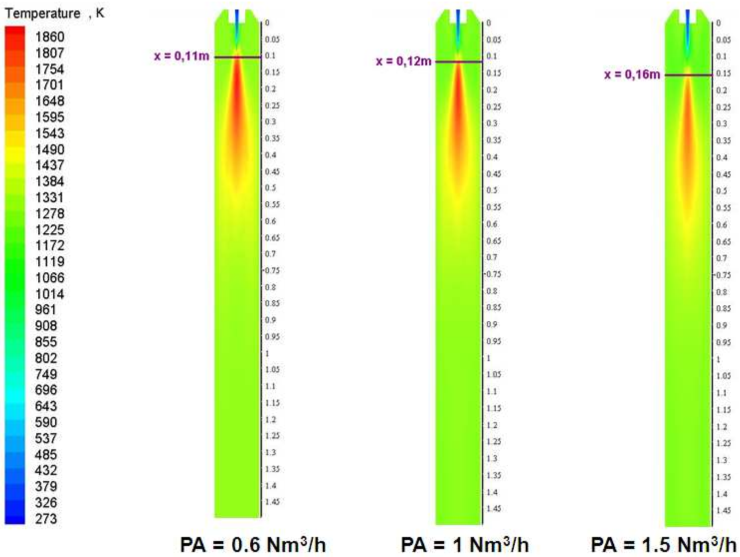

Figure 28: Comparison of the calculated and measured flame stand-off distance
Explanations: experimental results are shown as violet lines

Using the new CFD model a 5-15 kW pulverised fuel burner was developed in 3 steps. Figure 29 shows the final model of the 5-15 kW burner. The results of tests with the new burner with pulverized straw are shown in Figure 30. The results indicate that air staging has a strong influence on NO_x emissions.

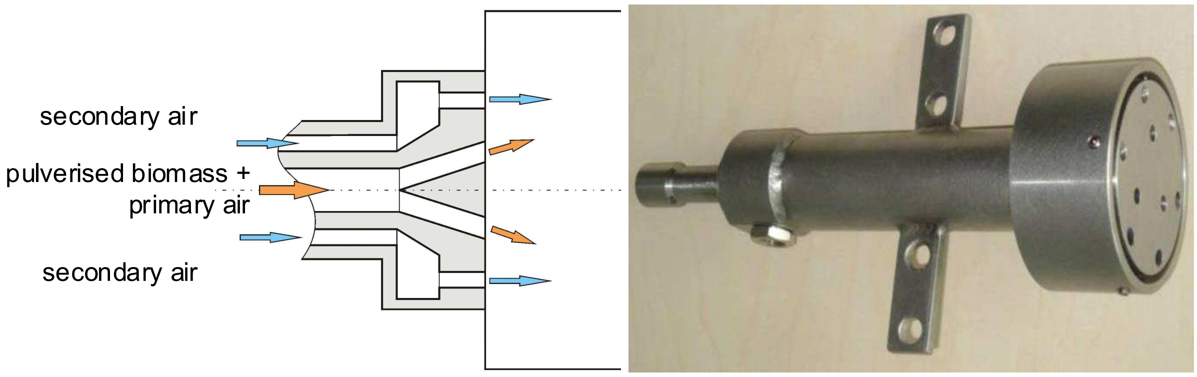

Figure 29: Final model of the 5-15 kW burner for pulverized biomass fuels

Subsequently, a 0.5 MW burner has been developed (see Figure 31). It is a swirl-type burner with swirled primary and secondary air induction. The burner was fed with three different types of pulverized biomass fuels: straw, tobacco waste and conventionally milled willow. The flexible properties of the burner enabled stable operating conditions for all fuel types. Exemplary results for fuels with different nitrogen contents are presented in Figure 32 (straw 0.4 wt% N, tobacco waste dust 1.55 wt% N). Air staging again proofed the potential to significantly decrease NO emissions (by a factor up to 2).

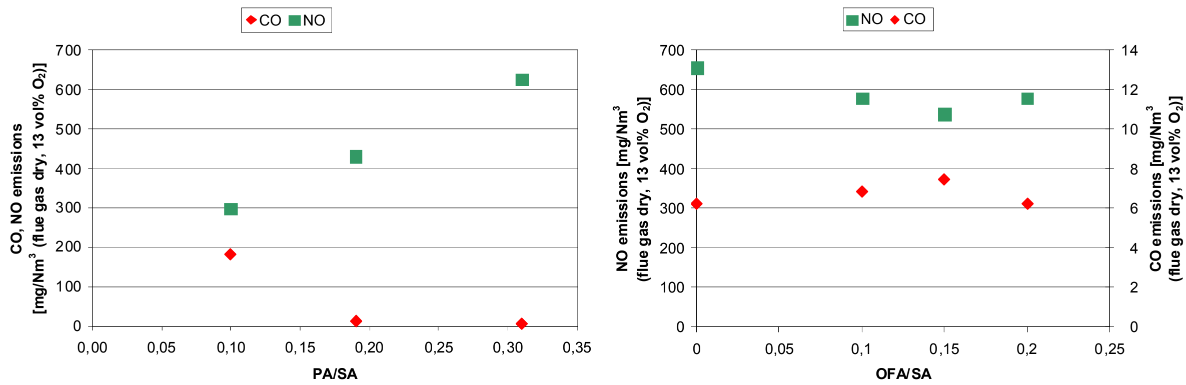

Figure 30: Influence of air staging on emissions of the 5 - 15 kW burner
Explanations: PA – primary air, SA – secondary air, OFA – over fire air, OFA is induced in the combustion chamber, load during test runs: 10 kW, NO in mg/Nm^3 calculated as NO_2

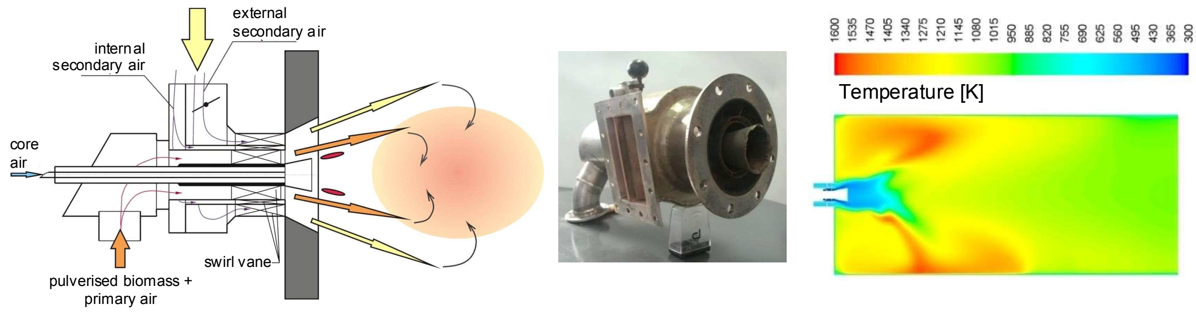

Figure 31: 0.5 MW burner model and temperature profiles calculated for pulverized straw

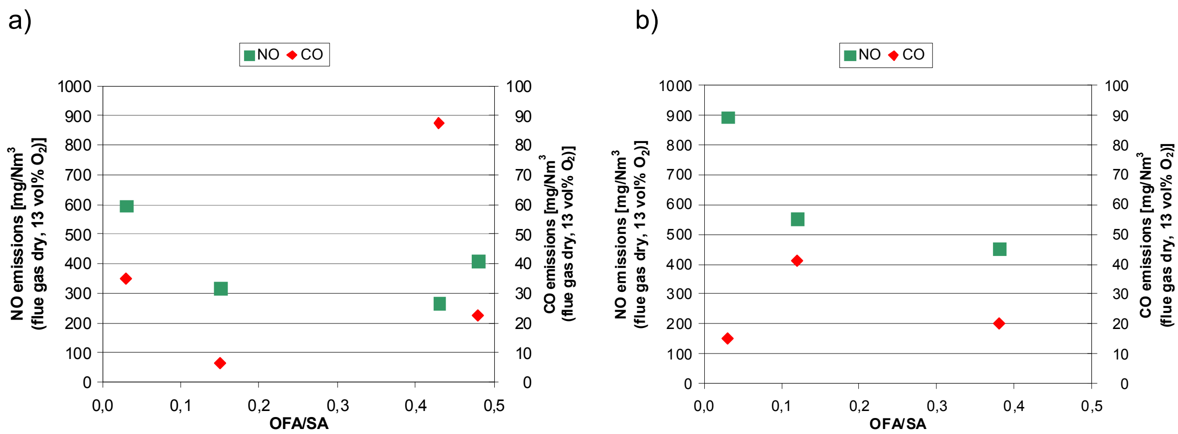

Figure 32: Comparison of the air staging on emissions of the 0.5 MW burner for pulverized straw (a) and tobacco waste (b)

Explanations: PA – primary air, SA – secondary air, OFA – over fire air, NO in mg/Nm^3 calculated as NO_2

Finally the 0.5 MW burner has been scaled up to 20 MW. The 20 MW scale-up is also a swirl burner with a partial regulation of the secondary air swirling ratio.

3.2.6 Relevant literature

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3.3 Work package 3: PM emission reduction by secondary measures - evaluation of existing particle precipitation technologies for residential biomass combustion systems

Solid biomass combustion is increasingly criticised as a major source of PM emissions. With the introduction of the EU directive 1999/30/EC, which limits PM_{10} concentrations in the ambient air, it had to be recognised that these limiting values are frequently exceeded in many European regions. The main sources for PM emissions have been identified to be traffic, industry and domestic heating. It is already known that residential biomass combustion contributes with more than 80% to the total PM emissions of the residential heating sector in some European countries. However, the main contributors of residential biomass combustion regarding PM emissions are old stoves and boilers due to incomplete combustion and the resulting tar and soot formation. Modern state-of-the-art systems show considerably lower PM emissions (by a factor of up to ten compared to old systems). Some emission limits for residential wood combustion are listed in Table 1.

Table 1: Emission limits for TSP and national quality labels in countries involved in the project.
Explanations: (*) Limit depends on type of combustion device, valid from1/1/2015

Country	Emission limit (residential)	National quality label
Austria	60 mg/MJ (NCV)	Umweltzeichen 37
Finland	No limit	Nordic Swan
Germany	20-40 mg/Nm3 @ 13% O2 (*)	Blue Angel
Ireland	150 mg/Nm3 @ 13% O2	N/A
Sweden	No limit	Nordic Swan, Swedish P-mark

Consequently, filters for residential biomass combustion systems may especially help to reduce particle emissions of existing old installations considerably, but until now only a small number of such particle precipitation devices (e.g. ESP – Electrostatic Precipitator) have been introduced on the market. However, a considerable number of devices is presently under development and are expected to be demonstrated soon. Subsidies or incentives as well as testing certificates for small-scale particle precipitation devices are only available in Germany at presence. In Germany also accreditation tests are defined for small-scale filters.

Common disadvantages of these residential flue gas cleaning devices are relatively high investment costs and that the operation behaviour under poor combustion conditions is not sufficiently tested. Moreover, almost no long-term experiences are yet available (e.g. whole year operation). Detailed studies concerning applications of different particle precipitation devices in small-scale combustion systems are scarce.

3.3.1 State-of-the-art of particle precipitation devices for residential biomass combustion

Within the scope of the project a report on “Particle precipitation devices for residential biomass combustion – survey on the present state in Europe” (nominal boiler capacity <50 kW_{th}) was compiled in cooperation with IEA Bioenergy Task 32 “Biomass Combustion and Cofiring”. The work focused mainly on technologies which are already available on the market or which are close to market introduction with a special emphasis on ESP systems. The survey involves the evaluation of more than ten electrostatic precipitators, two catalytic converters, one ceramic filter and one condensing heat exchanger.

The ESP technology seems to be the most promising technological approach. Up to now at least four ESPs for residential biomass combustion systems have been introduced on the market, but a considerable number of devices are under development and can be expected to be demonstrated within the next years.

Most ESPs have been developed under rather favourable combustion conditions at test stands. Consequently, in general, the questions of long time availability and applicability for old combustion systems are insufficiently investigated. Particle precipitation devices have the potential to substantially reduce emissions from old combustion systems which show the highest PM emissions. Therefore, it seems unfortunate that most devices under development focus on modern combustion systems. To design an ESP applicable for old combustion systems is quite demanding. Among other things, the filter has to be of a robust design and be equipped with an automatic cleaning system for the electrodes.

Common problems of the ESPs evaluated are long-term operation stability and limited applicability for old combustion systems. Automatic (vibration, brush or water spray) and manual cleaning are applied for some ESPs. The frequency of cleaning and maintenance procedures depends on operating time, on the fuel and on the type of combustion system connected. The power consumptions of tested ESPs were in the range of 10 to 100 W (mostly 10-30 W). The investment cost of an ESP is found to be between 800 and 1,700 €, excl. VAT (mostly 1,000-1,250 €).

The conclusions regarding the catalytic converters investigated are that the results for wood boilers/stoves are, so far, not very promising. Conventional condensing heat exchangers are focusing on heat recovery. Their particle precipitation potential is typically low (10 – 20%).

3.3.2 Dedicated results of different filters evaluated

ESP tests performed with the Ruff Tech ESP at TFZ

Lab tests have been performed with a chimney-mounted ESP developed and manufactured by Ruff Tech (see Figure 33, left picture). One main goal of these tests has been the evaluation of different electrode types and high voltage power on precipitation efficiency (see Figure 33, right picture). In addition, field tests have been performed with old and modern logwood stoves and boilers.

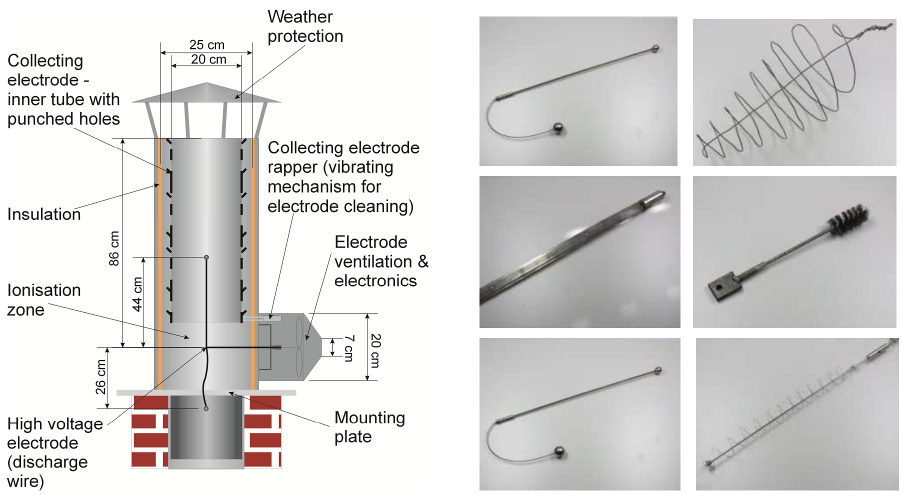


Figure 33: Scheme of the chimney-mounted Ruff Tech ESP (left) and pictures of different electrodes tested

<u>Explanations:</u> source: RUFTEC AG, http://www.ruff-kat.de, 2012

Figure 34 shows results of the lab test series performed with different electrode geometries. The results show that long electrodes (the 2 steel helix rod electrode) achieve best precipitation efficiencies at a voltage of approx. 22 kV (approx. 75 %). However, the high precipitation efficiencies determined within the scope of the lab test measurements could not be approved in the field tests. The respective average precipitation efficiencies have been approx. 45 to 50 %. In this respect, further optimization of the ESP is required.

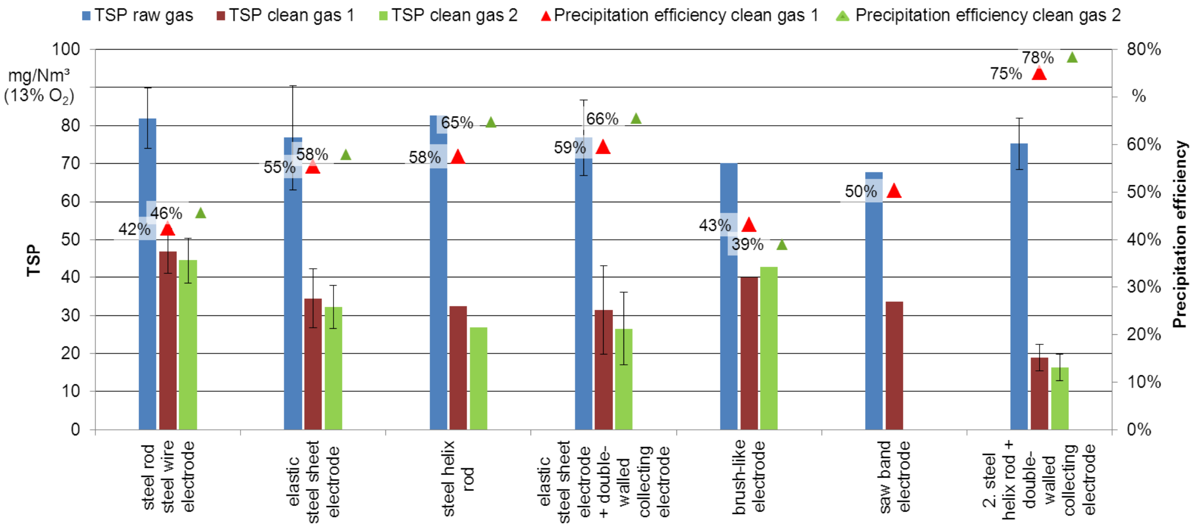


Figure 34: Results from tests with the Ruff Tech ESP performed at TFZ – TSP emissions and precipitation efficiency

Tests performed with the Oekotube ESP at BE2020

At BE2020 tests with the Oekotube ESP with different old and modern logwood stoves and boilers have been conducted. The Oekotube ESP is a chimney mounted system with a long elastic steel sheet electrode (see Figure 35).

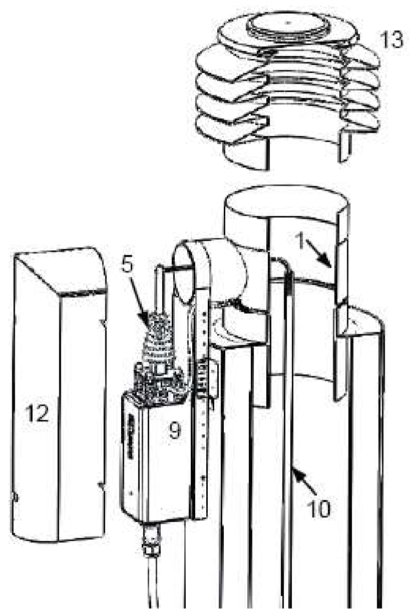


Figure 35: Scheme of the chimney-mounted Ökotube ESP
Explanations: 1 ... metal tube, 5 ... insulator, 9 ... electronic circuit, 10 ... electrode, 12 ... ESP cover, 13 ... chimney hood, source: http://www.oekotube.ch/, 2010

The Ökotube ESP shows a very good precipitation efficiency for modern boilers and stoves (for PM_1 75 – 92% and for TSP 71 – 83%, see Figure 36). Also for old stoves and boilers (even at very poor combustion conditions) the precipitation efficiency is relatively good (for PM_1 66 – 85% and for TSP 54 – 57%). No sparkovers occurred and the ESP worked well during all test runs performed. The voltage of the high-voltage power supply varied between 20 kV and 31 kV.

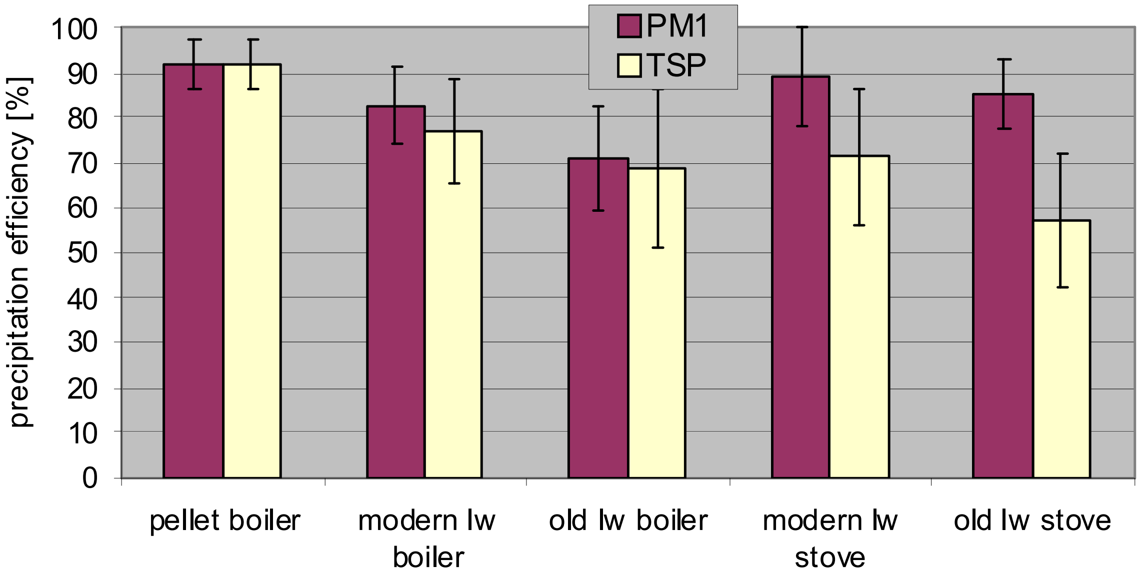


Figure 36: Results from tests with the Ökotube ESP performed at BE2020 – TSP and PM_1 precipitation efficiency

Explanations: lw … logwood

Tests performed with the Al-top and Oekotube ESP at Teagasc

At Teagasc 2 different ESP systems have been evaluated, the Oekotube ESP (see Figure 35) and the Al-top ESP (see Figure 37). The Al-top ESP is directly placed downstream the boiler and consists of a charger electrode and a bed with metal filing downstream the electrode, where the charged particles are precipitated. The bed with metal filing is cleaned with a water spray at regular intervals.

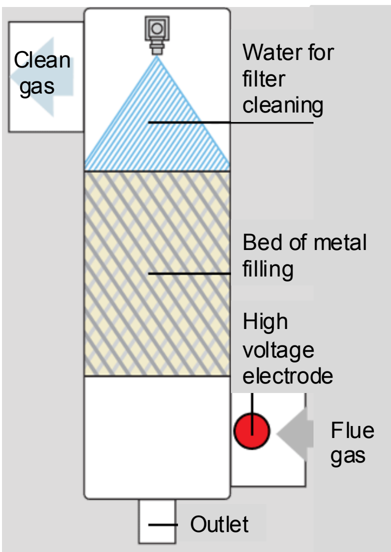


Figure 37: Scheme of the Al-top ESP

Explanations: source: Schräder Abgastechnologie, http://schraeder.com, 2012

Test runs performed show that the average TSP emissions at boiler outlet (without ESP operation) were approx. 8 mg/Nm^3 (dry flue gas, 13 vol% O_2) for wood, approx. 110 mg/Nm^3 for willow and approx. 315 mg/Nm^3 for tall fescue.

Figure 38 shows results of the tests performed with the Oekotube and the Al-top ESP. With the Oekotube ESP precipitation efficiencies up to 70% are possible over an operation period of more than 50 hours with wood. For willow the excellent precipitation efficiency (up to 85%)

decreases quickly over time due to dust build-up on the electrode. Manual cleaning was required after every 5 hours of operation. For tall fescue the precipitation efficiency was below 40% even after cleaning which is probably due to the high particle emissions with tall fescue. However, the manufacturer of the Oekotube system stated that it is designed for wood and not suitable for high dust loads (since no automatic cleaning system is installed).

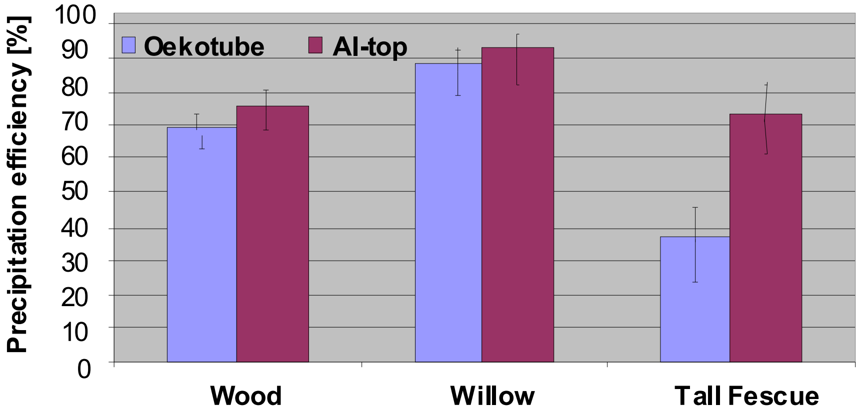


Figure 38: Results from ESP tests performed at Teagasc – TSP precipitation efficiency

The Al-top ESP shows excellent precipitation efficiencies for wood and willow. Even for tall fescue the precipitation efficiencies are above 70%. In this respect the automatic cleaning system of the Al-top ESP maintains high precipitation efficiencies even at long term operation. However an open question is the handling of the waste water from the Al-Top ESP.

Tests performed with the R_ESP at SP

The R_ESP is a tubular ESP designed to be mounted on top of a chimney (see Figure 39). It requires manual cleaning by a chimney sweep at regular visits. According to the manufacturer, the R_ESP is applicable for old wood stoves, coal stoves and automated boilers (<20 kW) firing fuels of high ash content, such as bark and reed canary grass pellets.

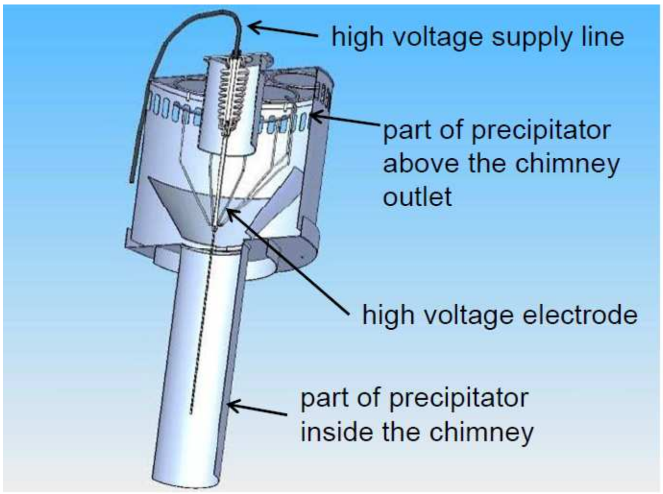


Figure 39: R_ESP, cross-section (left) and a picture of an installation (right)
Explanations: source: Applied Plasma Physics ASA, http://www.app.no, 2010

The R_ESP has been tested for modern stoves as well as for automated boilers at SP Technical Research Institute of Sweden and within the scope of other projects at TFZ Straubing. The two research laboratories used different combustion devices and had different set-ups, providing somewhat different results.

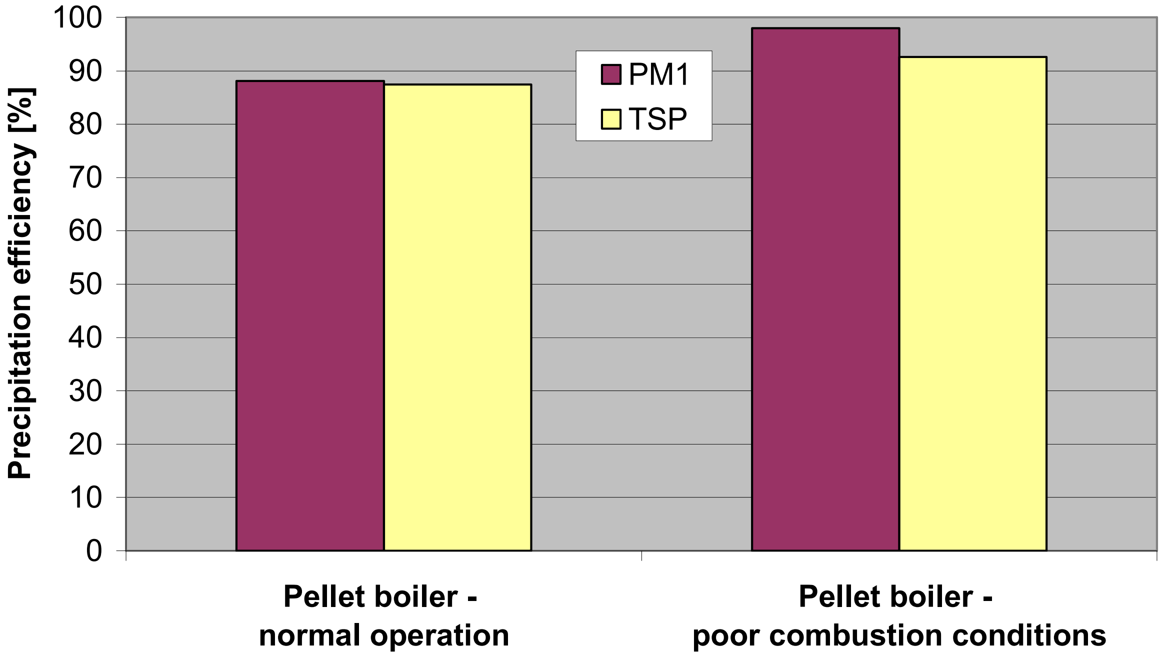


Figure 40: Results from tests with the R_ESP performed at SP – TSP and PM_1 precipitation efficiency

Experiments at SP within the scope of the project with a pellets boiler under normal and poor combustion conditions showed that the precipitation efficiency regarding PM_1 emissions is approx. 88% for normal and 98% for poor combustion conditions (see Figure 40). Regarding TSP emissions, the precipitation efficiency amounts to approx. 87% for normal and 92% for poor combustion conditions. However, the respective tests were only performed over a few hours of operation (no evaluation of the long term behaviour of the ESP).

The R_ESP has also been extensively tested at TFZ within the scope of other projects, with an estimated operation time of 4,300 h, for both old and modern wood log stoves. The tests with the modern stove showed collecting efficiencies between 22 and 95 %, with a mean of 69 %. For the old wood stove, the mean collecting efficiency was found to be 55 %.

The tests performed have shown a collecting efficiency of the R_ESP in the range of 50-99 %, depending on the fuels, loads and temperatures etc. The R_ESP is basically suitable for old firing systems, but further long-time tests are needed to prove its long time availability. The field tests performed showed that the filter is easy to install and operate. Improvements of the control system are recommended to handle spark-over issues that occurred repeatedly during the tests at TFZ. Such sparkovers are noisy and may disturb neighbours.

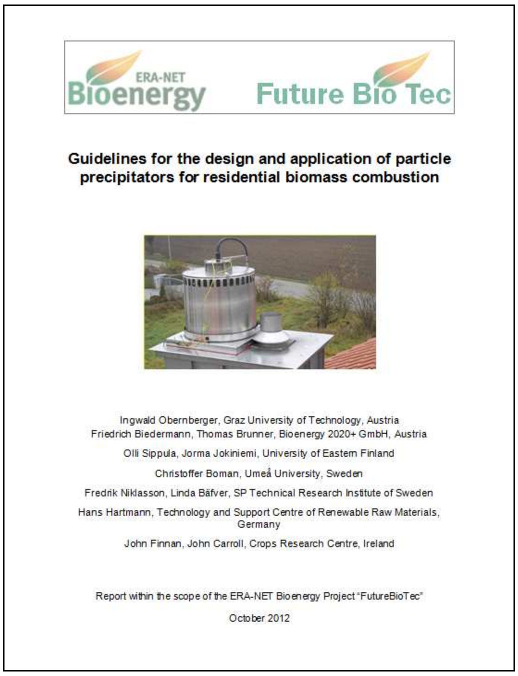
3.3.3 Guidelines for design and application of electrostatic precipitators for residential biomass combustion

Experiences and results from the project work as well as information available have been summarized in the document "*Guidelines for design and application of electrostatic precipitators for residential biomass combustion*" (see Figure 41). The target groups for this guideline are manufacturers of residential combustion devices, retailers, and central authorities. Furthermore, the report may also be of interest to consumers and researchers.

The guidelines provide information regarding:

- Design criteria regarding pressure drop, high voltage supply and electrode
- Control system
- Maintenance, availability and applicability

- Cleaning issues (solid waste: ash, coke and soot, waste water)
- Safety and noise related issues
- Costs


ERA-NET Bioenergy Future Bio Tec

Guidelines for the design and application of particle precipitators for residential biomass combustion

Ingwald Obernberger, Graz University of Technology, Austria
Friedrich Biedermann, Thomas Brunner, Bioenergy 2020+ GmbH, Austria
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Fredrik Niklasson, Linda Bäfver, SP Technical Research Institute of Sweden
Hans Hartmann, Technology and Support Centre of Renewable Raw Materials, Germany
John Finnan, John Carroll, Crops Research Centre, Ireland

Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec"
October 2012

Figure 41: Guidelines for the design and application of particle precipitators for residential biomass combustion

3.3.4 Relevant literature

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3.4 Work package 4: Development of a specially designed condensing heat exchanger for simultaneous heat recovery and efficient particle precipitation

3.4.1 Technological principle of the condensing heat exchanger

UEF has developed a condensing heat exchanger (CHX) for efficient heat recovery and reasonable fine particle reduction. The CHX is applicable for continuously fired small-scale biomass combustion systems. The principle of operation is based on high temperature gradients between the flue gas and the heat exchanger walls, which drives aerosol particles to the walls by thermophoretic forces and enhances water condensation on heat exchanger surfaces. The water condensation forms an additional diffusiophoretic force which further enhances particle deposition on the heat exchanger walls. Furthermore, the water condensation decreases fouling of the heat exchanger by forming a flowing water film on the heat exchanger surface and it naturally increases the efficiency of the heat exchanger due to the recovery of energy from water condensation.

A scrubber unit was developed to assist in keeping the heat exchanger inlet as well as the walls clean. The scrubber unit generates small water droplets in the flue gas flow upstream of the heat exchanger during specific cleaning periods. The CHX is operated in downdraft flow at flue gas inlet temperatures up to 700 °C. Also higher inlet temperatures may be used, as it increases the particle precipitation efficiency, but care must be taken to avoid problems with high temperature corrosion and regarding material properties. The cooling works in counterflow. The condensate flow is collected downstream of the CHX.

3.4.2 Design of the condensing heat exchanger

The condensing heat exchanger is a complete stainless steel welded construction and it consists of 120 tubes with 8 mm tube diameter (see Figure 42). The tubes inside the heat exchanger have a fixed length of 745 cm and a baffle spacing of 150 cm.

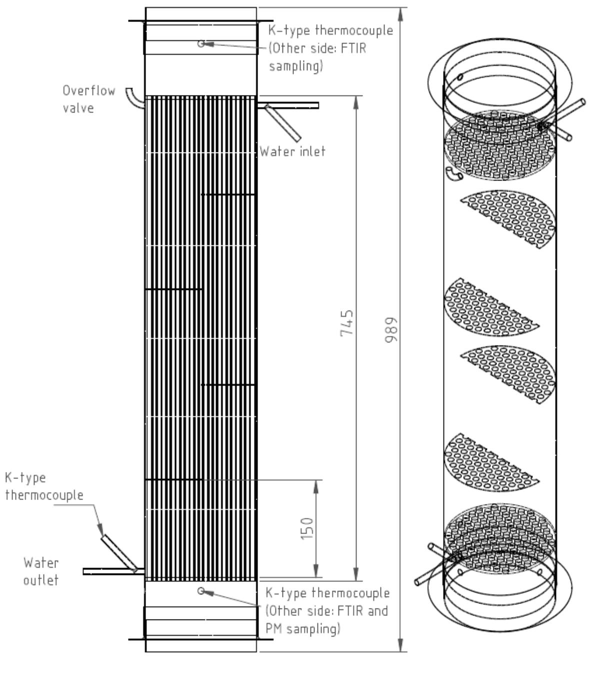

Figure 42: Scheme of the condensing heat exchanger

The CHX was designed for flue gas inlet temperatures up to 700°C. It was operated during the experiments in two different modes: low-temperature and high-temperature water return mode. The target values for return and feed water temperatures for the low-temperature mode were 25 ˚C and 30 ˚C and for the high-temperature mode 50˚C and 55˚C, respectively.

3.4.3 Modelling

The aerosol behaviour was simulated with a computational model. The goal of this simulation was to calculate the dynamics and behaviour of fine particles in the heat exchanger. When the behaviour of suspended particles is known, it is possible to evaluate the deposition of fine particles. The core of the model consists of a thermodynamic section where conditions in the exchanger are computed and the particle calculation section, where the forces affecting the particles, are calculated.

The conditions in the heat exchanger were modelled using heat transfer and condensation equations. Forces affecting the particles were computed from equations involving thermophoresis, diffusiophoresis and the Brown diffusion process. The core model used the Eulerian method where the computation domain was divided into finite elements of equal length. All the equations and flow parameters were calculated sequentially in each section and the complete system was assumed to be in a steady state thus the solutions exist in space-domain only. Flow properties such as densities, heat capacities, viscosities and thermal conductivities of water and steam were collected from engineering tables.

The flue gas flow in the tubes was assumed to be laminar except for the inlet region where Nusselt numbers were computed as function of temperature, otherwise Nu=3.66. The model did not take into account the effect of condensed water on tubes or fouling effects. As this model simulated a counterflow type heat exchanger, the outlet temperature of the cooling water has been set as initial condition. This is necessary since cooling water exits the system at X=0 in which flue gases enter the system and some iteration was needed when operational parameters were tuned for experimental purposes. Cooling tube wall temperatures were calculated from the temperature difference between cooling water and flue gas. The initial value of the wall temperature was the same as the one of the cooling water temperature. This was necessary since it ensures a consistent temperature profile at the beginning and errors due to this in final results could be assumed negligible since temperature gradients there are high in any case and temperatures usually converge at the exit side.

3.4.4 Results of test runs and simulations performed

The condensing heat exchanger was mounted to a 40 kW combustion system which is equipped with a burner working with step grate principle (see Figure 43). The combustion chamber is designed for research purposes and enables the use of CHX after the combustion chamber. Water spraying by a scrubber unit was done above the CHX. The flue gas and water temperatures upstream and downstream of the CHX as well as pressure drop over the heat exchanger were monitored continuously. Gaseous species were measured with FTIR before and after the CHX. After the CHX, condensing water was collected and it was later quantified by weighing and analysed for its contents of inorganic species. Particle measurements were done from the stack downstream of the CHX. Porous tube diluter and ejector diluter were used for dilution of the sample gas (dilution ratio: 23–32). Pre cut-off impactors were used before filter collection to collect only fine particle (PM_1) size fraction. The filters were weighed to determined particle mass and analyzed for OC, EC and inorganic species (ash). Particle number-size distribution and mass-size distributions were also determined.

During the experiments, the air to fuel ratio ranged from 1.9 to 2.3 for the low-temperature mode and from 1.7 to 2.0 for the high-temperature mode. The emissions of CO, particulate organic carbon (OC) and elemental carbon (EC) were in all of the measured cases very low, showing that the combustion conditions agreed well between the measured cases and ensured a good burnout. The fine particles were mainly composed of potassium, sodium, sulphate, chloride and zinc (see Figure 44) which is a typical result for pellet combustion in modern small-scale appliances.

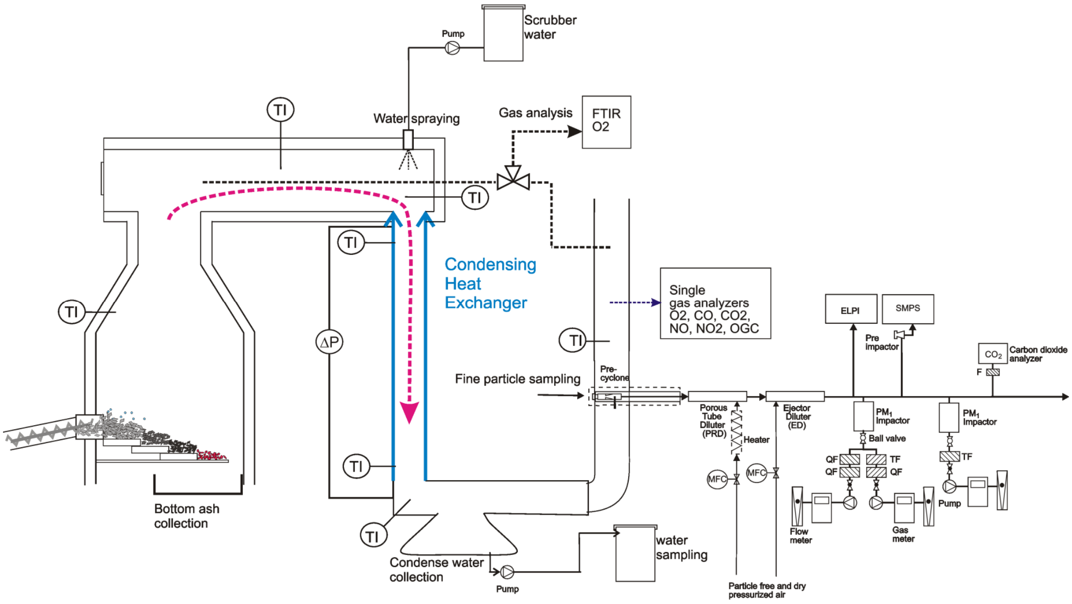

Figure 43: The experimental setup with the condensing heat exchanger coupled with a biomass grate furnace

Explanations: FTIR, gas analyzer; single gas analyzers; TI temperature measurement; ELPI, Electrical Low Pressure Impactor; DLPI, Dekati Low Pressure Impactor; TF, Teflon filter; QF, Quartz filter

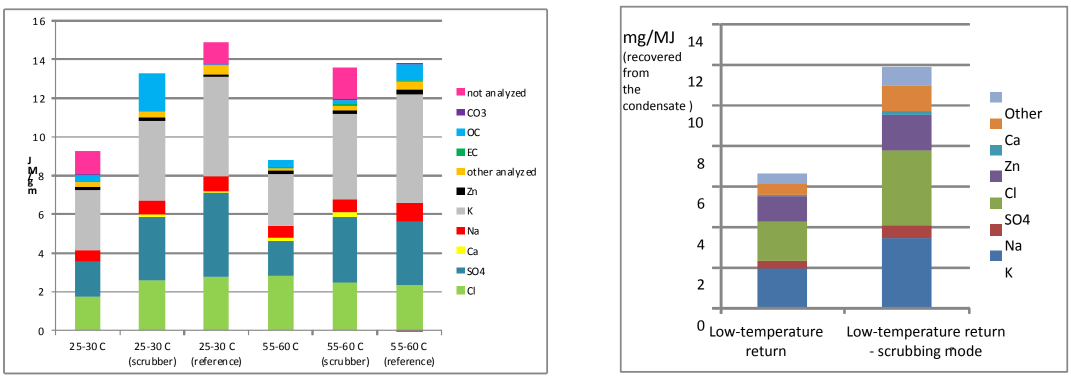

Figure 44: PM_1 emissions downstream the condensing heat exchanger respectively conventional boiler - chemical compositions of the particles (left) and of the condensed water (right)

Explanations: mg/MJ related to NCV; OC … organic carbon; EC … elemental carbon; other analysed … total of other inorganic species analysed; not analysed … emissions in mg/MJ minus compounds detected in mg/MJ; reference case … test run with conventional boiler; scrubber … test run with scrubber operation

For the low-temperature mode the flue gas outlet temperatures were on average 55 ˚C and about half of the flue gas moisture condensed, yielding condense water flows of 1.3-1.5 liters per hour. The condense water was analysed for inorganic species and it showed a similar chemical composition as shown for the particle emissions (see Figure 44). For the high-temperature mode no condensation occurred and the flue gas outlet temperature was on average 76 ˚C. The average pressure drops over the CHX were on average between 27 and 47 Pa.

The average PM_1 emissions with CHX were 10.1 mg/MJ (average of 6 measurements) for the low-temperature mode and 7.7 mg/MJ (average of 3 measurements) for the high-temperature mode, while with conventional tube exchanger it was 14.9 mg/MJ for the low-temperature mode (2 measurements) and 12.0 mg/MJ for the high-temperature mode (3 measurements). Overall, the operation with a condensing heat exchanger generated 32 %

respectively 36 % lower fine particle emissions when compared to the reference boiler cases. For the low-temperature mode, due to the heat released by water condensation and very efficient heat recovery, thermal efficiencies above 100 % were achieved.

The use of the scrubber for flushing of the heat exchanger was found to increase the PM_1 emissions in comparison to the CHX operation without scrubbing by 20 % and 80 % for the low-temperature and the high-temperature mode, respectively. The effect is partially due to the decrease in the flue gas inlet temperature by the scrubbing which drastically decreases thermophoretic deposition of particles on the heat exchanger surfaces (due to the lower temperature gradient between the flue gas and the tube). Secondly, the formation of particles in the size range of about 5 µm was observed during the scrubbing mode which did not occur without scrubbing. As the scrubber is needed only time to time to keep the heat exchanger clean, its effect on emissions should remain relatively small.

The model calculations on the experimental cases regarding the PM concentrations at CHX inlet and outlet indicated 56 % PM_1 reduction for the low-temperature mode and 50 % reduction for the high-temperature mode. In both cases the main deposition mechanism is thermophoresis while the Brownian diffusion is negligible. The diffusiophoretic deposition caused by water condensation increases the deposition for the low-temperature mode by 3.4 %, according to the simulations, while it had no effect for the high-temperature mode due to the lack of condensation. For the reference boiler the simulations predict 19 % PM_1 deposition. This value was used to calculate the particle concentrations at heat exchanger inlet from the results of the emission measurements downstream the reference boiler. By using this inlet concentration, the absolute deposition in the CHX can be estimated, showing 45 % PM_1 reduction for the low-temperature mode and 48 % reduction for the high-temperature mode (see Table 2).

Table 2: Precipitation efficiencies of PM_1 mass

Test case	**Particle precipitation in heat exchanger (%)**		**Flue gas outlet T (°C)**
	Measured*	Simulated	
Low-temperature return (25-30 °C)	45	56	55
High-temperature return (55-60 °C)	48	50	76
Reference heat exchanger (low-temp.)		19	140
Reference heat exchanger (high temp.)		19	122

*based on precipitation estimation in the reference heat exchanger

3.4.5 Concluding remarks

The results showed that heat exchangers in small-scale biomass-fired boilers can be designed to decrease fine particle emissions while simultaneously operating with high thermal efficiency. Especially an operation as a condensing heat exchanger is advantageous as it gives a possibility to recover latent heat of water vapour from the flue gas and helps to keep the heat exchanger clean. The flue gas inlet temperature was noticed to be a critical parameter affecting the precipitation efficiency. The particle reduction was found to be mainly based on thermophoresis of fine particles on heat exchanger walls.

The prototype which was tested, is compact in size, has a high heat transfer efficiency combined with a moderate particle reduction. During the experiments, no problems with heat exchanger plugging have been observed, however the long term tests are yet to come. The thermal efficiency of the heat exchanger was high due to efficient flue gas cooling. The system is especially suitable for floor heating cases and for use with moist fuels, for example wood chips.

3.4.6 Relevant literature

GRÖHN, A., SUONMAA, V., AUVINEN, A., LEHTINEN, K., E.,J., JOKINIEMI, J. Reduction of Fine Particle Emissions from Wood Combustion with Optimized Condensing Heat Exchangers. Environmental Science and Technology, 2009, 43, 6269 – 6274.

NISHIO, G., KITANI, S., TAKAHASHI, K. Thermophoretic deposition of aerosol particles in heat – exchanger pipe. Ind. Eng. Chem. Process Des. Dev., 1974, 13 (4), 408 – 415.

LAMBERG, H., SIPPULA, O., TISSARI, J., JOKINIEMI, J. Effect of air staging and load on fine-particle and gaseous emissions from a small-scale pellet boiler. Energy & Fuels, 2011, 25, 4952–4960.

4 Executive summary

Introduction and objectives

The ERA-NET Bioenergy project "FutureBioTec" aimed to provide a substantial contribution concerning the development of future low emission stoves and automated small- and medium-scale biomass combustion systems (<20 MW_{th}) and therefore had the following overall objectives, which have been defined under consideration of the different states of development of the different combustion technologies and capacity ranges addressed. The project focused on the further development of wood stoves towards significantly decreased CO, OGC, PM and NO_x emissions by primary measures (air staging and air distribution, grate design and implementation of automated process control systems), the improvement of automated furnaces in the residential and the small to medium-scale (<20 MW_{th}) capacity range towards lower PM and NO_x emissions by primary measures (extremely staged combustion, utilisation of additives and fuel blending concerning new biomass fuels, development of a new combustion system for pulverized fuels), as well as the evaluation, development and optimisation of secondary measures for PM emission reduction in residential biomass combustion systems. This technology development was accompanied by techno-economic evaluations in order to proof that the new technologies are also economically competitive. According to the different working fields addressed, the project is structured in 4 work packages (WP):

WP1: Reduction of PM, CO, OGC and NO_x emissions from wood stoves by primary measures

WP2: Reduction of PM and NO_x emissions from automated boilers by primary measures

WP3: PM emission reduction by secondary measures - evaluation of existing particle precipitation technologies for residential biomass combustion systems

WP4: Development of a specially designed condensing heat exchanger for simultaneous heat recovery and efficient particle precipitation

In order to reach the aims of the project defined, a consortium of 9 internationally recognised R&D partners as well as 2 industrial partners from 7 European countries has been formed. The project which has been coordinated by the Austrian Competence Centre Bioenergy 2020+ GmbH has been started in October 2009 and completed in September 2012. In September 2012 the results of the project have been presented at an international workshop in Graz (in total 67 participants from 7 countries attended).

Summary regarding the work performed within work package 1

Stoves are one of the most common technologies for residential heating all over Europe. However, the technical standard of different stove technologies varies significantly and thus there is a remarkable potential for the optimisation of these appliances. Within the scope of work package 1 it was the aim to provide knowledge and guidance for the reduction of PM, CO, OGC and NO_x emissions from wood stoves by primary measures. As an initial step and support for the subsequent experimental work planned, country reports regarding

“Operational influences of hand-charged wood stoves” have been compiled by the partners involved. These country reports have subsequently been summarized in an overview report prepared by TFZ.

Based on this overview report the present state-of-the-art was defined and a test run program was designed in order to answer open questions, to identify potentials for improvements and to verify the effects of specific optimisation measures during dedicated test run series. In the following experimental work has been performed at TFZ, BE2020 and UEF. The results of these test runs together with the overview report, formed the basis for the compilation of the two guidelines *Operational influences of hand-charged wood stoves* as well as *Guidelines for low emission stove design*.

Test runs at TFZ mainly focused on the investigation of operational influences on emissions from stoves. The effects of the fuel moisture content, the low wood dimensions, the ignition strategy, the mass of the logwood charged for one batch as well as the time of recharging were systematically investigated. Moreover, TFZ tested the influence of the presence of a grate on the emissions as well as the applicability of a retrofit combustion control unit which varies the air supply based on flue gas temperature measurements via a flap.

BE2020 focused on the implementation and test of specific measures for emission reduction in stoves. Therefore, a state-of-the-art stove was further optimised by means of CFD simulations of the combustion process. Geometric optimisations of the post combustion chamber, different options regarding the air staging (introduction of secondary air injected from the back wall of the main combustion chamber) as well as furnace insulation were thereby investigated. Moreover, an automated control system was developed. The measures proposed were implemented in a stove and verified during test runs. It could be shown that with the optimisations performed a considerable reduction of the emissions (60% for CO, 86% for OGC and 55% for PM) could be achieved.

Partner UEF, in cooperation with Warma-Uunit Ltd., performed combustion experiments using a hybrid masonry heater for both logwood and wood pellets. This new design offers higher fuel flexibility for stoves by only applying a different grate system for the operation with pellets. Air-staging, grate design, operational practises and combustion chamber materials were improved during the project and their effect on emission reduction was verified by test runs.

The major outcomes of work package 1 are the two guidelines mentioned above. The Guideline on *Operational influences of hand-charged wood stoves* was compiled for stove users. It contains al relevant findings of the project regarding a low emission stove operation such as information about the fuel that should be applied (log wood dimensions, moisture content, permissible and non permissible fuels), stove technologies (design and function of stoves, information to distinguish between high and low quality products, etc.), stove operation (ignition strategy, correct re-charging) as well as information regarding maintenance and troubleshooting.

The *Guidelines for low emission stove design* were prepared to support stove manufacturers in optimising their concepts. It contains information on parameters affecting emissions of stoves, general requirements for low emission chimney stoves (materials to be applied, reduction of false air intake, implementation of air staging strategies in general), recommendations regarding geometric design concepts and air supply strategies (air staging) as well as information concerning the design and implementation of automatic combustion control systems.

Summary regarding the work performed within work package 2

Within the scope of work package 2 comprehensive tests and evaluations regarding the reduction of PM and NO_x emissions from automated boilers by primary measures have been performed. In a first step a summary report regarding the evaluation of existing data on air staging strategies has been compiled by BE2020, UEF and UmU. The report summarizes and evaluates available data regarding the influence of air staging on NO_x and PM emissions for fixed bed biomass combustion.

Air staging as a primary measure

At BE2020 test runs with chipboard, wood chips and willow (short rotation coppice) have been performed at a pilot-scale moving grate combustion plant with a nominal boiler capacity of 180 kW. The following influencing parameters on NO_x and PM_1 emissions have been investigated for all fuels: the air ratio in the primary combustion chamber (PCC) (0.4 – 1.4), the residence time in the PCC (large or small PCC), the temperature in the PCC (900°C, 1,000°C, 1,100°C) and the type of flue gas recirculation (above or below the grate). The total excess air ratio (λ_{tot}) was set to approx. 1.4 for all test runs performed. At UEF a novel grate combustion reactor with a nominal boiler capacity of 40 kW has been used for tests. Wood chips, wood pellets and a mixture of wood chip and reed canary grass have been used as fuel. Test runs have been performed at full load with flue gas temperatures at the end of the PCC between 800 to 1,000°C and a total excess air ratio (λ_{tot}) between 1.8 to 2.0. At Teagasc test runs with wood, miscanthus, cocksfoot and tall fescue have been performed with a tilting grate boiler (nominal boiler capacity: 35 kW). All test runs have been performed at full load with a total excess air ratio (λ_{tot}) set to approx. 1.6. The flue gas temperatures in the PCC were kept constant with flue gas recirculation (between 900 and 1,000 °C).

The results of all test runs performed by the three partners show that the clearest and strongest dependence on NO_x emissions is given by the air ratio in the PCC, with lowest NO_x emissions at an air ratio below 1.0. The optimum regarding NO_x emissions seems not to be fuel dependent (for a given technology). However, the optimum regarding NO_x emissions seems to be technology dependent to a certain extent. Consequently, the optimum has to be determined for a given technology with dedicated test runs and the process control should be adjusted accordingly. NO_x emissions also increase with decreasing residence time in the PCC. This effect seems to have rising importance the smaller the residence time available in the PCC is. Moreover, it seems to be more pronounced at air ratios in the PCC close to the optimum. The temperature in the PCC within the investigated range of 900°C to 1,100°C does not seem to be a relevant influencing parameter on NO_x emissions. Flue gas recirculation above the grate seems to be slightly more efficient regarding NO_x reduction than flue gas recirculation below the grate (at same temperature conditions) most likely due to better mixing. The comparison of the test results shows that the reduction potential regarding NO_x emissions increases considerably with increasing N content in the fuel. In general, the results show that the potential to reduce NO_x emissions by primary measures is considerable.

PM_1 emissions decrease with increasing volume flow through the fuel bed due to most probably lower fuel bed temperatures at higher air flows. The temperature in the PCC is also of relevance for the fuel bed temperature and has an influence on PM_1 emissions. However, this influence decreases with increasing air ratios in the primary combustion chamber. No clear dependency of the volume flow through the fuel bed on the TSP emissions has been found.

In order to reduce both, NO_x and PM_1 emissions, the air ratio in the PCC should be kept slightly below 1.0 (the optimum value of the air ratio in the PCC is technology specific and has to be determined within the scope of measurements). The mean residence time in the PCC should be reasonably high (above ~0.5 s). Flue gas recirculation should be mainly applied below the grate to avoid slagging when fuels with low ash melting temperatures are utilised. Moreover, flue gas recirculation below the grate provides the possibility to cool the fuel bed in order to reduce the release of ash forming vapours and thus to reduce PM_1 emissions. Flue gas recirculation into the PCC should also be applied to improve the mixing of the flue gases (reduce streak formation) and to control the temperature in the PCC. The flue gas temperature in the PCC should be kept moderate (900 – 1,000°C).

Based on the results of the test runs performed as well as on data from literature, design and operation concepts for low-emission biomass grate furnaces based on advanced air staging have been compiled. This guideline includes information and recommendations for furnace and boiler manufacturers.

Additive utilisation and fuel blending as a primary measure

Regarding the work performed on additives and fuel blending a state-of-the-art report on "Fuel additives and blending as primary measures for reduction of fine ash particle emissions" has been compiled as a first step. Regarding the experimental work on fuel additives and blending, dedicated lab-scale reactor test runs were performed at BE2020 with mixtures of softwood and straw with Kaolin. The tests were accompanied by thermodynamic high-temperature equilibrium calculations (TEC) and fuel index calculations to investigate and evaluate the behaviour of ash forming elements. The addition of Kaolin to straw and agricultural fuels resulted in a decrease of the K-release and an increase of the ash melting temperature.

At Teagasc tests with the 35 kW tilting grate furnace have been performed: Tall Fescue and Miscanthus with different levels of Kaolin additivation have been examined. The results show that PM_1 emissions decrease with increasing amounts of Kaolin additivation. However there seems to be an optimum regarding PM_1 emission reduction at Kaolin additivation levels around 4 wt%. Besides PM_1 emission reduction also a positive influence on ash melting problems was confirmed based on the experiences gained from the test runs performed by Teagasc.

In addition, tests with fuel blends (peat from Ireland) have been performed. At BE2020 tests with different mixtures of miscanthus and peat in the lab-scale reactor and at Teagasc different mixtures of miscanthus and peat as well as tall fescue and peat in the 35 kW tilting grate furnace were conducted. The tests at BE2020 were accompanied by thermodynamic high-temperature equilibrium calculations. The results show that peat addition reduced slagging tendencies as well as PM_1 emissions. According to the results, a peat ratio of 25% to 50% is recommended. However, it has to be taken into consideration that these results are related to the fuels investigated and may vary due to changes of the biomass fuel and peat composition. Concluding additives and intelligent fuel blending may considerably reduce ash related problems of biomass fuels but a detailed evaluation on a case by case basis is necessary.

Improved characterisation of the combustion behaviour by single pellets reactor tests

Studies with small lab-reactors burning single-pellet samples have been performed by UmU and SP. The experimental set-ups and methodological approaches have to a large extent been developed within the project. Accompanying thermodynamic high-temperature equilibrium calculations have also been performed at UmU to support the definition of test matrices for the single-pellets studies and to compare modelled and experimental results. In general, a somewhat higher release of K was seen in the single pellets tests compared to the K found in fine PM from the pellet burners. This is rather expected and presumably explained by "secondary" capture mechanisms in the fuel bed of the burners and also by losses on surfaces in the boiler/flue gas systems. Furthermore, the measurements showed a difference between the wood and straw pellet fuels regarding the release behaviour of potassium when kaolin was added. Summing up, these single-pellet combustion tests provide valuable on fuel decomposition as well as on K release.

Development of a combustion technology for pulverized biomass fuels

At IEn a new combustion technology for pulverized biomass fuels has been developed. Investigations of fuel ignition and fuel combustion kinetics were performed using two drop tube furnaces. Moreover, a CFD model was developed that enables a parallel consideration of homogeneous and heterogeneous combustion reactions. The new model determines rates of devolatilisation, homogeneous oxidation of volatiles and heterogeneous oxidation of char.

The results achieved show a quite good agreement with experimental data (flame stand-off distance, concentrations of O_2 and CO). In a next step a 5-15 kW and a 0.5 MW burner for pulverized biomass have been developed. The 0.5 MW burner was tested with three different types of biomass fuels: pulverized straw and tobacco waste as well as conventionally milled willow. The results of the tests performed show that air staging has a strong influence on NO_x emissions (up to a factor 2). In a final step, the new burner system was scaled-up to 20 MW.

Summary regarding the work performed within work package 3

Within the scope of work package 3 a report on "particle precipitation devices for residential biomass combustion – survey on the present state in Europe" (nominal boiler capacity <50 kW_{th}) was compiled in cooperation with IEA Bioenergy Task 32 "Biomass Combustion and Cofiring". The work focused mainly on technologies which are already available on the market or which are close to market introduction with a special emphasis on ESP systems. The survey involved the evaluation of more than ten electrostatic precipitators, two catalytic converters, one ceramic filter and one condensing heat exchanger.

Furthermore, a number of ESPs has been tested by the project partners within the scope of work package 3. At TFZ lab tests have been performed with a chimney-mounted ESP developed and manufactured by Ruff Tech. In addition, field tests have been performed with old and modern logwood stoves and boilers. The results show that with optimised electrodes at a voltage of approx. 22 kV precipitation efficiencies of approx. 75 % can be achieved. However, the high precipitation efficiencies determined within the scope of the lab measurements could not be approved during field tests performed in another project. The respective average precipitation efficiencies in the field have been approx. 45 to 50 %. In this respect, further optimization of the ESP is required.

At BE2020 tests with the ESP Oekotube with different old and modern logwood stoves and boilers have been conducted. The Oekotube ESP is a chimney mounted system with a long elastic steel sheet electrode. The Ökotube ESP shows a very good precipitation efficiency for modern boilers and stoves (for PM_1 75 – 92% and for TSP 71 – 83%). Also for old stoves and boilers (even at very poor combustion conditions) the precipitation efficiency is relatively good (for PM_1 66 – 85% and for TSP 54 – 57%) and filter operation was stable. The Oekotube ESP seems to be well suitable for old and new wood boilers and stoves.

At Teagasc two different ESP systems have been evaluated with different fuels, the Oekotube ESP and the Al-top ESP. The Al-top ESP is directly placed downstream the boiler and consists of a charger electrode and a bed with metal filing downstream the electrode. The bed with metal filing is cleaned with a water spray at regular intervals. With the Oekotube ESP precipitation efficiencies up to 70% are possible more than 50 hours of operation using wood as fuel. For willow and for tall fescue the precipitation efficiency was considerably lower and manual cleaning was required after a few hours of operation. However, the manufacturer of the Oekotube system stated that it is designed only for wood and not suitable for high dust loads. The Al-top ESP shows excellent precipitation efficiencies for wood and willow (up to 90%). Even for tall fescue the precipitation efficiencies have been above 70%. In this respect the automatic cleaning system of the Al-top ESP maintains high precipitation efficiencies even at long term operation. However an open question is the handling of the waste water from the Al-Top ESP.

At SP the R_ESP was tested which is a tubular ESP designed to be mounted on top of a chimney. Experiments at SP within the scope of the project with a pellets boiler under normal and poor combustion conditions showed that the precipitation efficiency varies between approx. 87% for normal and 98% for poor combustion conditions. However, the respective tests were only performed over a few hours of operation (no evaluation of the long term behaviour of the ESP). The R_ESP has also been extensively tested at TFZ within the scope of other projects for both old and modern wood log stoves. The tests with the modern stove showed collecting efficiencies between 22 and 95 %, with a mean of 69 %. For the old wood stove, the mean collecting efficiency was found to be 55 %.

Experiences gained within the project as well as know-how of the partners have been summarized in the document “Guidelines for design and application of electrostatic precipitators for residential biomass combustion”. The target groups for this guideline are manufacturers of residential combustion devices, retailers, and central authorities. Furthermore, the report may also be of interest to consumers and researchers.

Summary regarding the work performed within work package 4

UEF has developed a condensing heat exchanger (CHX) for efficient heat recovery and particle reduction. Within the scope of the project, a scrubber unit was developed to assist in keeping the heat exchanger inlet as well as the walls clean. The CHX is operated with downdraft flow at flue gas inlet temperatures up to 700 °C. The cooling water passes in counterflow to the flue gas through the CHX. The condensate flow is collected downstream the CHX.

The condensing heat exchanger is a completely stainless steel welded construction. It consists of 120 tubes with 8 mm tube diameter. The tubes inside the heat exchanger have a fixed length of 745 cm and a baffle spacing of 150 cm.

The aerosol behaviour was simulated with a computational model. The goal of these simulations was to calculate the dynamics and behaviour of fine particles in the heat exchanger. The conditions in the heat exchanger were modelled using heat transfer and condensation equations. Forces affecting the particles were computed under consideration of thermophoresis, diffusiophoresis and Brown diffusion. The model calculations on the experimental cases regarding the PM concentrations at CHX inlet and outlet indicated 56 % PM_1 reduction for the low-temperature mode and 50 % reduction for the high-temperature mode. For the reference boiler the simulations predict 19 % PM_1 deposition. This value was used to calculate the particle concentrations at heat exchanger inlet from the results of the emission measurements downstream the reference boiler. By using this inlet concentration, the absolute deposition in the CHX can be estimated, showing 45 % PM_1 reduction for the low-temperature mode and 48 % reduction for the high-temperature mode

In addition, experiments have been performed where the heat exchanger mounted to a 40 kW combustion system was operated in two different modes: low water return temperature and high water return temperature. The target values for return and feed water temperatures for the low-temperature mode were 25 ˚C and 30 ˚C and for the high-temperature mode 50 ˚C and 55 ˚C, respectively. The average PM_1 emissions with CHX were 10.1 mg/MJ for the low-temperature mode and 7.7 mg/MJ for the high-temperature mode. Overall, the operation with a condensing heat exchanger generated 32 % and 36 % lower fine particle emissions when compared to the reference boiler cases. For the low-temperature mode, due to the heat released by water condensation and very efficient heat recovery, thermal efficiencies above 100 % (based on NCV) were reached.

The use of the scrubber for flushing of the heat exchanger was found to increase the PM_1 emissions by 45 % and 80 % (in comparison to the CHX operation without scrubbing) for the low- and high-temperature mode, respectively. The effect is partially due to the decrease in the flue gas inlet temperature which drastically decreases thermophoretic deposition of particles on the heat exchanger surfaces (due to lower temperature gradients between the flue gas and the tube surface). Moreover, formation of particles with a size of around 5 µm was observed during the scrubbing mode which were not found during operation without scrubbing. As the scrubber is needed only time to time to keep the heat exchanger clean, its effect on emissions should remain relatively small.

The prototype which was tested, is compact in size, has a high heat transfer efficiency combined with a moderate particle reduction. During the experiments, no problems with heat exchanger plugging have been observed, however long term tests have not been performed yet. The thermal efficiency of the heat exchanger was high due to efficient flue gas cooling. The system is especially suitable for low-temperature heating systems (floor heating) and for use with moist fuels, for example wood chips.

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	Swedish Energy Agency, Sweden
	NCBiR – National Centre for Research and Development, Poland
	Sustainable Energy Authority of Ireland, Ireland

6 Relevant documents compiled within the scope of the project (available at futurebiotec.bioenergy2020.eu)

State-of-the-art reports

1. **Operational influences of hand-charged wood stoves.**
   HARTMANN Hans, SCHÖN Claudia, TUROWSKI Peter, KELZ Joachim, BRUNNER Thomas, OBERNBERGER Ingwald, BÄFVER Linda S., BOMAN Christoffer, 2010. Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec", http://futurebiotec.bioenergy2020.eu
2. **Summary and Evaluation of Existing Data on Air Staging Strategies.**
   BIEDERMANN Friedrich, BRUNNER Thomas, OBERNBERGER Ingwald, SIPPULA Olli, BOMAN Christoffer, ÖHMAN Marcus, BÄFVER Linda, 2010. Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec", http:// futurebiotec.bioenergy2020.eu
3. **Additives and Blending as Primary Measures for PM Reduction – State-of-the-Art.**
   BOMAN Christoffer, OBERNBERGER Ingwald, BOSTRÖM Dan, FAGERSTRÖM Jonathan, BÄFVER Linda, 2011. Fuel Report within the scope of the ERA-NET Bioenergy Project "FutureBioTec", http:// futurebiotec.bioenergy2020.eu
4. **Survey on the present state of particle precipitation devices for residential biomass combustion with a nominal capacity up to 50 kW in IEA Bioenergy Task32 member countries.**
   I. OBERNBERGER, C. MANDL. final report, 2011, Bios Bioenergiesysteme GmbH (Ed.), work performed in cooperation with IEA Bioenergy Task 32 "Biomass Combustion and Cofiring", http://www.ieabcc.nl/

Guidelines

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