ERA-NET Bioenergy

Future Bio Tec

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

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Preface

ERA-NET Bioenergy is a network of national research and development programmes focusing on bioenergy which includes 14 funding organisations from 10 European countries: Austria, Denmark, Finland, France, Germany, Ireland, The Netherlands, Poland, Sweden and the United Kingdom. Its mission is to enhance the quality and cost-effectiveness of European bioenergy research programmes, through coordination and cooperation between EU Member States. The project *FutureBioTec* (Future Low Emission Biomass Combustion Systems) has been supported in the period between October 2009 and September 2012 by ERA-NET Bioenergy under the joint call on Clean Biomass Combustion from 2009.

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.

Against this background, the 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}). Considering the different states of development of the combustion technologies and capacity ranges addressed, the project focused on the following main objectives.

- 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 (staged combustion, utilisation of additives as well as fuel blending).
- The evaluation, development and optimisation of secondary measures for PM emission reduction in residential biomass combustion systems.

In order to reach these objectives, a consortium of 8 research organisations and 2 industrial partners from 7 European countries collaborated within FutureBioTec (see next page).

This document summarizes the outcomes of the investigations regarding the improvement of automated furnaces/boilers by the application of advanced air staging concepts as a primary measure for NO_x and PM_1 emission reduction. It should support furnace and boiler manufacturers concerning the optimization of their products and the development and design of new products with its recommendations which have been worked out based on scientific investigations as well as comprehensive test runs at small-scale and pilot-scale units. Moreover, it shall provide information for plant operators how to choose their control settings concerning air staging in order to reduce emissions.

Ingwald Obernberger
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FutureBioTec project partners

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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
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SP your Science Partner	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

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1 Introduction and objectives

Biomass offers the greatest potential for the generation of heat and power of all renewable energy sources (except hydro power). However, the combustion of biomass results in the emission of air pollutants such as CO, OGC, NO_x, TSP and PM_1. Modern biomass furnaces show already low CO and OGC emissions (which indicate an almost complete burnout) but NO_x, TSP and PM_1 emissions are still too high. NO_x emissions of biomass combustion are mainly formed from the nitrogen contained in the fuel and depend on the operational conditions during combustion. Thermal and prompt NO_x formation are typically negligible. PM_1 emissions are mainly formed from volatile inorganic compounds in the fuel (assuming an almost complete burnout of flue gas and particles) and typically form the main fraction of TSP emissions. Within the scope of the ERA-NET BIOENERGY project “FutureBioTec” the effects of different air staging strategies on NO_x and PM_1 emissions of biomass grate furnaces have been evaluated. Within the scope of comprehensive test runs the following plants and biomass fuels have been considered:

- 150 kW_{th} pilot-scale grate combustion plant; fuels used: chipboard, wood chips and short rotation coppice (willow)
- 40 kW_{th} grate combustion reactor; fuels used: wood chips
- 35 kW_{th} grate furnace; fuels used: wood chips, pellets and different herbaceous fuels

In addition, a literature study has been compiled, which summarizes and evaluates available data regarding the influence of air staging on NO_x and PM_1 emissions for fixed bed biomass combustion. The experiences gained from the tests performed as well as the results from the literature study form the basis for the development of future low emission biomass combustion systems by efficiently applying primary measures. These primary measures are related to the design of the biomass furnace as well as its operation.

1.1 Target group

This report provides primarily information for manufacturers of fixed-bed biomass combustion systems. Furthermore, the report is also of interest for plant operators and researchers.

2 Definitions and limitations

2.1 Basic definitions

PCC … primary combustion chamber

SCC … secondary combustion chamber

PM_1 … particulate matter below 1 μm (aerodynamic diameter)

TSP … total suspended particulates

λ … air supplied / air needed for a complete oxidation of the fuel at stoichiometric conditions

λ_{tot} … total excess air ratio (calculated from fuel, primary air and secondary air flows)

λ_{grate} … air ratio related to the conditions on the grate; calculated from fuel and oxidising agents supplied below the grate (primary air and flue gas recirculation below the grate)

λ_{PCC} air ratio related to the PCC; calculated from fuel and oxidising agents supplied in the PCC (air, recirculated flue gas below the grate and in the PCC)

If no flue gas recirculation is supplied in the PCC, λ_{grate} and λ_{PCC} are equal.

2.2 Definition of air staging concepts

Figure 1 shows the basic principle of an efficient air staging concept (staged combustion). Primary combustion air (1) is supplied directly to the fuel bed (2) and secondary combustion air (3) is injected into the burnout zone. The furnace must be clearly separated in a primary (4) and a secondary (5) combustion zone with independently controllable combustion air supply. Flue gas recirculation can be applied to control furnace and fuel bed temperatures. For an efficient air staging concept (simultaneous NO_x and PM_1 reduction) is should be possible to supply recirculated flue gas above the fuel bed (6) and/or below the grate (7).

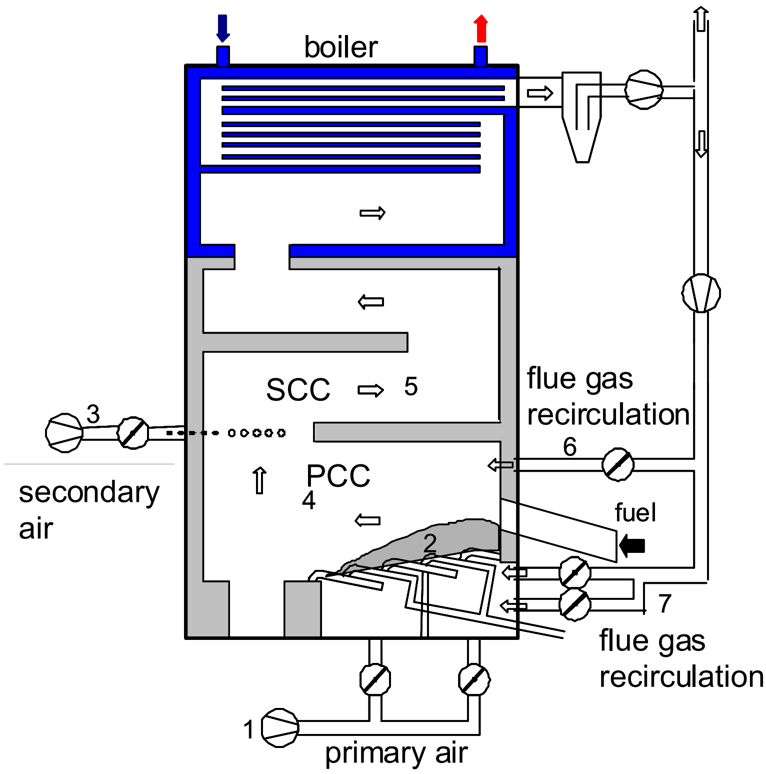

Figure 1: Scheme of a plant equipped with air staging technology

2.3 Limitations

The present design concepts for low-emission biomass furnaces based on advanced air staging are limited to fixed bed combustion systems with λ_{grate} down to approx. 0.5. For gasification systems (with considerably lower λ_{grate}) with coupled burners the design concepts presented in this report may not be valid. Moreover, the design concepts are valid for moving grate furnaces and may not be valid for fixed grate systems typically applied for residential pellet boilers where no horizontal fuel transport over the grate takes place.

Furthermore, a clear separation of PCC and SCC is essential for an efficient air staging. If secondary air is supplied in the PCC or if there is a reverse flow of secondary air into the PCC the design concepts defined are not applicable.

The design and operation concepts presented should only be considered as general recommendations. They may have to be adapted to the specific side constraints of the technology and the fuel used.

3 Basic remarks regarding the influence of air staging on NO_x and PM_1 emissions

Air staging forms the basis for an efficient combustion at low emissions. This accounts not only for NO_x and PM_1 emissions but also for e.g. CO and OGC emissions. The test runs performed within the project have shown that there are several parameters influencing PM_1 and NO_x emission formation in biomass furnaces.

Regarding NO_x emissions these parameters are

- The air ratio in the PCC (very relevant)
- The residence time in the PCC (very relevant)
- The temperature in the PCC
- The application of flue gas recirculation in the PCC (regarding temperature control and mixing)

Regarding PM_1 emissions (fine particle emissions) these parameters are

- Volume flow of the gas (air and recirculated flue gas) through the fuel bed (cooling effect of the fuel bed with increasing flow decreases PM_1 emissions)
- Temperature in the PCC (increasing flue gas temperatures also increase the bed temperatures and thus the PM_1 emissions)

Regarding TSP emissions no relevant influence of the parameters mentioned above was detected during the test runs performed. However, from former studies it is known that emissions of coarse fly ashes usually increase with increasing volume flow through the fuel bed (higher entrainment of ash and fuel particles from the fuel bed). Moreover, the grate technology itself has an influence on coarse fly ash emissions (disturbance of the fuel bed).

4 Design and operation concepts of staged combustion systems

4.1 Furnace geometry

The furnace must have two geometrically well defined combustion zones, namely

- a primary combustion chamber (PCC, which includes the fuel bed)
- and a secondary combustion chamber (SCC).

The PCC and SCC have to be geometrically separated in order to make a dedicated reduction zone in the PCC possible.

The secondary air injection should be designed in a way that no reverse flows of secondary air into the PCC occur.

The volume of the PCC should be reasonably large since with increasing residence time NO_x emission reduction efficiency increases

- Target value for the mean residence time (at flue gas temperatures above 800 to 900°C): ideal ~1.0 s; minimum: ~0.5 s

The volume of the SCC should be large enough to achieve a complete gas phase burnout.

In order to optimise furnace and nozzle geometries a CFD-based furnace design is recommended.

4.2 Air supply strategies and flue gas recirculation

The PCC and the SCC must have separate air supplies which can also be separately and independently controlled and adjusted.

It is of great relevance to avoid leakage air since it acts as combustion air but cannot be controlled. Most relevant leakage air flows occur

- through the fuel supply system (stoker or screw)
- through the de-ashing system

Leakage air should be normally below 20% of the total combustion air input (ideally below 10% of the total air).

Ideally, flue gas recirculation below the grate and into the PCC (above the grate) should be foreseen. In this respect, the following design criteria exist:

- Flue gas recirculation below the grate provides flexibility regarding fuel bed temperature control which is a measure for PM_1 emission reduction and additionally controls the temperature in the PCC.
- Flue gas recirculation into the PCC should be designed in a way that it supports the mixing of the flue gases (avoid streak formation) and controls the temperatures in the PCC.
- Temperature peaks in the PCC and SCC should not exceed 1,400°C in order to avoid thermal NO_x formation.
- The design of the flue gas recirculation above the grate should consider that the flue gas recirculated does not hit the fuel bed (to avoid excessive particle entrainment).

4.3 Process control strategies and optimisation of process control settings

The process control should have the possibility to control

- air settings and air ratios (in the PCC as well as in the SCC)
- temperatures in the PCC and in the SCC

Therefore, the following measurements are strongly recommended

- Combustion air and flue gas recirculation flow should be continuously measured.

- Correctly calibrated temperature measurements in the PCC and the SCC are important. During the initial operation phase of a plant the signals of the temperature measurements should be checked with suction pyrometers. Deviations detected should be corrected in the process control systems.
- During the initial operation phase of a plant the amount of leakage air should be determined and relevant leakage air flows should be identified. If possible they should be eliminated or minimised. If elimination is not possible, the magnitude has to be considered for the definition of the settings of the air flow control.
- During the initial plant operation phase the lowest possible total air ratio (λ_{tot}) to achieve an efficient burnout should be identified in order to maximize efficiency (definition of the CO-λ-characteristics of the furnace in dependence of load and fuel moisture content).

5 Recommended settings for an efficient air staging

The following air staging and flue gas recirculation settings are proposed for moving grate combustion plants:

- The air ratio in the PCC (λ_{PCC}) should be below 1
  - The exact value of the air ratio in the PCC depends on the mixing of the flue gases in the PCC and on the specific side constraints of the combustion technology used. It must be determined by accompanying measurements. The goal of these measurements is to determine the optimised air ratio in the PCC where minimum NO_x emissions can be achieved.
  - According to the measurements performed so far the optimised air ratio in the PCC does not depend on the fuel used for a specific plant.
- The temperature in the PCC should be in a range between 900°C and 1,100°C depending on the fuel used.
  - For fuels with low ash melting temperatures slagging risks have to be considered.
  - Temperatures below 900°C are not recommended since NO_x reduction reactions need high temperatures.
- Flue gas recirculation below the grate should be applied 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 be applied to improve the mixing of the flue gases (reduce streak formation) and to control the temperature in the PCC.

Concluding, in order to reduce both, NO_x and PM_1 emissions

- **the air ratio in the PCC (λ_{PCC}) should be kept 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 applied mainly below the grate and**
- **the flue gas temperature in the PCC should be kept moderate (900 – 1,000°C).**

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