Guidelines for Low Emission Chimney Stove Design

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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 memberStates 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 wood stoves by the application of air staging concepts as a primary measure for OGC, PM_1 and CO emission reduction. It should support stove 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.

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FutureBioTec project partners

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	Institute of Power Engineering (IEn) Thermal Division Department Warsaw, Poland
	Teagasc, Crops Research Centre Carlow, Ireland

Industrial partners

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

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1 Introduction and objectives

Chimney stoves are one of the most common appliances used for residential heating around Europe. Apart from their use for heating purposes, stoves have recently become decorative accessories, and therefore a broad range of different designs are available nowadays. The combustion of biomass produces air pollutant emissions such as carbon monoxide (CO), organic gaseous carbon compounds (OGC), oxides of nitrogen (NO_X) and particles. The emission levels of these pollutants are closely related to the technology of the appliance and thus, there is potential for the optimization of these appliances.

Within the scope of the ERA-NET BIOENERGY project "FutureBioTec" primary measures for lowering emissions in wood stoves were evaluated on the basis of previous measurements and literature. In addition, test runs investigating the effect of different air staging concepts on the emissions have been performed on a chimney stove. Moreover, the influences of the fuel moisture content, the fuel type (wood logs or briquettes), the fuel mass per batch as well as of early and late recharging on the stove performance have been investigated. The stoves investigated were also operated using temperature and air flow based methods for automatic combustion control as a method for decreasing emissions.

The results from the test runs and the literature are used as the basis for the primary measures for design based reduction of emissions in wood stoves that are suggested in these guidelines.

1.1 Target group

This guideline provides information primarily for stove developers and manufacturers to use the presented design concepts for development of low-emission appliances. Furthermore, the report should also be of interest to researchers, stove users and policy makers.

1.2 Limitations

These design concepts for low-emission wood stoves are applicable to:

- Appliances that have a closed fire box
- Typical stove models
- Stoves using the updraft combustion principle

These guidelines are not applicable to heat storing appliances. Similarly, these design guidelines are not applicable to the following devices:

- Sauna stoves
- Pellet stoves
- Cooking stoves
- Stoves with water jackets
- Stoves which apply the downdraft principle

The stove designs presented here should only be considered as general recommendations. They may have to be adapted to the specific properties of the technology and fuel used.

2 Basic definitions

A schematic picture of a chimney stove is presented in Figure 1.

- *Main combustion chamber* – Space where the fuel gasifies and the majority of the combustion reactions take place. The main combustion chamber can be divided into different sections: *fuel zone* and *secondary combustion zone*
- *Post combustion chamber* – Space provided for combustion gases and particles to sufficiently burn out
- *Secondary combustion* – Combustion of the gasification products and intermediate products
- *PM1 – Particulate matter below 1 µm (aerodynamic diameter)*
- *TSP* – Total suspended particulates
- *OGC* – Organic gaseous carbon compounds

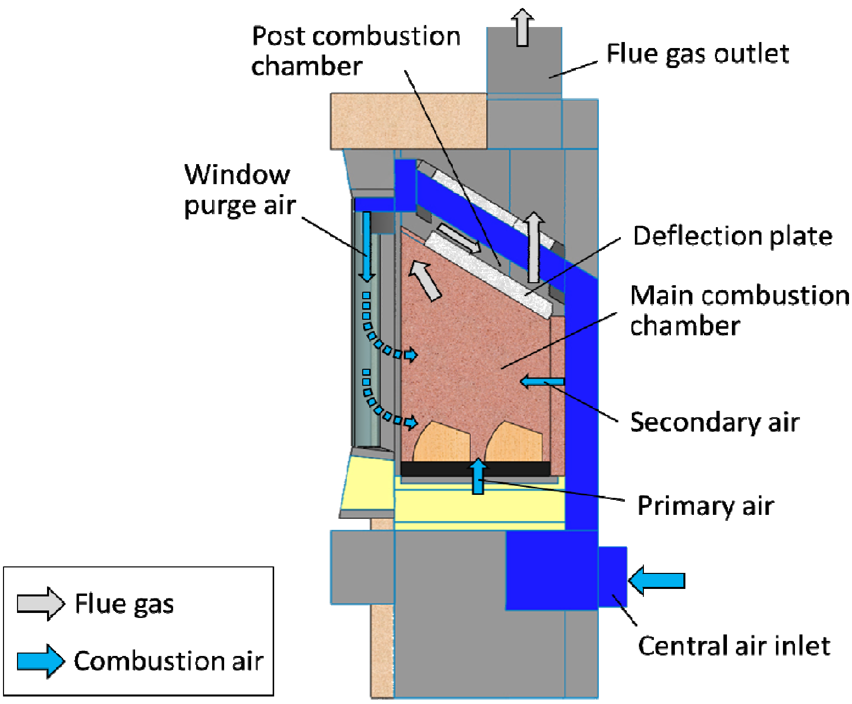

Figure 1: A schematic picture of a typical chimney stove.

3 Parameters affecting emissions of stoves

The particulate emissions can be divided into coarse (particles >1 µm) and fine particles (particles <1 µm). Coarse particulate mass consists of unburned fuel particles and ash particles that the air flow forces to rise from the fuel bed. Coarse particle emissions are affected by the air flow through the grate, and by the shape and length of the ducts after the combustion chamber.

- Long ducts with many bends retain more particles.
- High primary air flow release more coarse particles from the grate.

Fine particulate matter emissions consist of soot, fine fly ash and organic matter. Soot is formed in the flame when the oxidation of the combustion gases is not complete. Fine fly ash is formed by vaporization and nucleation/condensation of inorganic vapors released from the fuel during combustion. Particulate organic matter is a result of incomplete oxidation of combustion gases that condense onto particles. TSP includes both fine and coarse particles.

The relevant gaseous pollutants are organic gaseous compounds (OGC), carbon monoxide (CO) and nitrogen oxides (NO_X). Organic gaseous compounds are released from the fuel during gasification. The amount of OGC in the flue gas is affected by the completeness of the combustion. Carbon monoxide is an intermediate product from the oxidation of carbonaceous material. Generally the efficiency of combustion affects the amount of CO. During the burn out phase (i.e. after flame extinction) the formation of CO is more difficult to control due to low diffusivity of O_2 into the char and because of relatively low firebox temperatures. The NO_X emissions from wood log combustion are fuel derived, and therefore the amount of NO_X is determined by the nitrogen content of the fuel.

4 General requirements for low emission chimney stoves

Adequate quantities of air should be provided for combustion, especially through the secondary air nozzles (if used in the design). It is also important to make sure that the appliance has sufficient draft.

Sufficient temperature in the combustion chamber is needed to oxidize combustion byproducts. The temperature is affected by the refractory lining in the combustion chamber, the shape and size of the combustion chamber, the window material of the door as well as the size of the window and whether single- or double-layer glass is used.

The combustion gases should have sufficient residence time in the combustion chamber. The residence time is affected by the velocity of the air flow versus the size of the firebox, and the location of the air nozzles. The nozzles can be located for example in the back/side walls and at different heights.

Sufficient mixing of air and the combustion gases is crucial in order to achieve complete combustion. Mixing is affected by several factors:

- The direction and geometry of the air nozzles
- The velocities of flue gas and combustion air.
- The distribution of the air to the different air flows such as secondary air and window purge air (air staging)
- The geometry of the fire box
- The use of baffles in the secondary combustion chamber

Avoid leakage air streams by using appropriate material for the door and ensuring that the door seals correctly.

Avoid short-circuiting of flue gas streams within the stove. There should be no gaps between the plate separating the main combustion chamber from the post combustion chamber and the side respectively back walls (see Figure 1), through which unburned gases from the main combustion chamber could flow to the flue gas outlet without passing through the burnout zones in the main and the post combustion chamber.

5 Geometric design concept

This chapter presents points that need to be considered in the geometric and material design of the stove.

The stove should consist at least of a main combustion chamber and a post combustion chamber (or space for post combustion that can also be a duct).

Insulating materials should be used in the main combustion chamber to keep temperatures in the main combustion chamber high.

- Use appropriate isolation strategies for the side and back walls of the main combustion chamber, e. g. refractory bricks in combination with a layer of heat resistant mineral wool and a small air volume between isolation and the outer (steel) stove casing.
- Keep the window to a moderate size and use glass qualities for the window with low radiation coefficients. Also, the application of coated glasses and of double glazed windows (with an air gap) is an option.

The temperature in the main combustion chamber should be distributed so that the chamber is hot enough, whereas the fuel bed should be kept at moderate temperatures to prevent excessively high burning rates.

The flue gas should have enough time to efficiently cool down downstream of the combustion chambers. Sufficient heat exchanging surfaces are needed to maximize the efficiency of the appliance. Heat exchanging surfaces should be mainly associated with the post combustion chamber. The heat exchange to the room air can be improved by introducing forced ventilation via a fan, if the stove is equipped with adequate air ducts or exchange surfaces.

In general, it is recommended that a grate should be used in the stove. This is to simplify deashing before the next use. However, it must be guaranteed, that the air flow through the grate can be shut down completely. Grate air flow is only suitable during the first ignition phase and during the last batch after flame extinction (last burnout phase in a stove operation). A grate is essential if the stove shall also be declared suitable for combustion of coal briquettes.

Firebox geometry: High and slim combustion chamber geometry is usually preferable compared to a wide and low shape of the firebox (although the smaller base area may then require shorter wood logs). A high and slim shape improves flame dispersion and leads to a more homogeneous residence pattern for the produced pyrolysis gases in the hot zones (i.e. less danger of short circuit flows to the exhaust pipe).

6 Air supply and air staging

Air staging is an efficient way of reducing the emissions in a chimney stove. Air staging means that different air flows are introduced to facilitate optimized fuel decomposition and char burnout as well as an almost complete gas phase burnout. Chimney stoves without air staging are usually operated with only primary air. Combustion air can be supplied as primary, secondary and window purge air.

- *Primary air* is usually supplied directly to the fuel bed either from below the grate or at the bottom of the combustion chamber if there is no grate.

- *Secondary air* is supplied to the secondary combustion zone, i. e. where the burn out of the combustion gases happens (e.g. via dedicated air nozzles through the refractory lining)
- *Window purge air* is mainly used to create a flush air for the window, and is generally necessary to keep the window clean. Window purge air can also take part in secondary combustion. It can also add to the primary combustion air since a part of the air flow may also hit the logs. In order to facilitate and optimize this contribution of the window purge air to primary and secondary combustion, it is recommended to introduce the window purge air only at the top of the door so that it flows downwards along the window.

A minimum requirement for air staging is to add primary air and window purge air. The air streams should be separately controllable. To avoid false operation the manual air control should be achieved by a single handle only.

In addition to the minimum requirement, it is strongly proposed that an injection of secondary air (e.g. through the back wall and/or side walls etc.) is added. This enhances the mixing of the flue gases with the combustion air. However, the secondary air should not directly hit the logs. As before, all air streams should be separately controllable.

Other points that should be taken into account when designing air staging:

- The air streams that take part in secondary combustion should be preheated. This can be arranged without an external heating system by the design of air ducts. In contrast, the primary air should not be preheated (but preferably delivered at room temperature) in order to avoid too fast burning rates.
- An even distribution of the window purge air over the window is important.
- Due to limited chimney draught the pressure drops of the combustion air supply and flue gas canals have to be considered and to be kept low.
- Special care has to be taken regarding the position of secondary air nozzles. If they are mounted too low, the air stream can hit the wood logs and act as primary air. If they are mounted too high (at the upper end of the backwall of the main combustion chamber), no optimized mixing of air and flue gases is achieved.

7 Automatic combustion control

Automatic combustion control reduces user influence on the combustion process, and therefore, it is an efficient measure for low emission combustion and improved combustion efficiency.

The simplest way of combustion control is to employ a thermo-mechanical operated primary air flap (e.g. below the grate). Electronic sensor driven automatic control can be done by monitoring temperature, oxygen or incompletely burned compounds. At the moment low-priced sensors such as temperature and lambda sensors are available for this purpose. The sensors must be placed in representative locations, e.g. the positioning of a temperature sensor in the flue gas socket provides a less sensitive and less dynamic control signal compared to a sensor located in the secondary combustion zone.

Automatic combustion control must be adapted and optimized separately for each appliance.

Here are examples of automatic control concepts:

- The different combustion phases can be identified by temperature changes and since temperature sensors are the cheapest sensors available they offer a suitable means of stove control → furnace temperature based control
- The combustion air supply can easily be controlled by appropriate dampers → temperature controlled combustion air supply

With primary air injection at the beginning of the first batch a shorter ignition phase can be achieved. This means that high furnace temperatures and consequently lower gaseous and particulate emissions can be achieved within a shorter time.

- Control strategy: as soon as the furnace temperature exceeds a certain level, the primary air damper should reduce the air supply in order to avoid excessive burning rates; at the same time secondary air is increased so that adequate combustion air can be maintained.

With combustion air flow control during the main combustion and burnout phase a more stable O_2 concentrations in the flue gas can be achieved. In addition, generally lower O_2 levels as well as sufficiently high temperatures can be achieved.

- Control strategy: as soon as the furnace temperature drops below a certain value, the amount of window purge air should be reduced stepwise in order to keep the temperature at a reasonably high and nearly constant value over the batch.
- In the burnout phase the air supply should be adjusted so that excess oxygen is kept low and too much cooling of the combustion chamber is prevented.

Control of secondary air injection (if available):

- As soon as high combustion temperatures are reached at the end of the ignition phase, secondary air should be supplied to improve mixing of the combustion air and flue gases released from the logs to improve burnout.
- Control strategy: the ratio of window purge air and secondary air is recommended to be fixed.
- During charcoal burnout the secondary air should be closed again and only primary air should be injected in order to expedite char burnout.

A flue gas temperature sensor could be applied. It allows to identify proper charging times that indicates to the user that the stove is too hot and that no more wood should be added. It indicates overloading or the use of too reactive fuel (too dry or too small logs).

8 CFD-aided design of wood stoves

BIOS BIOENERGIESYSTEME GmbH together with researchers of Graz University of Technology and BIOENERGY 2020+ has developed a CFD model for the development and optimisation of biomass grate furnaces. The model consists of an in-house developed empirical fixed bed combustion model, which can also be applied for wood log combustion, as well as CFD models implemented in ANSYS / Fluent, which were especially adapted and validated for turbulent reactive flows in biomass combustion plants.

For wood-log fired stoves, a time-dependent profile of wood log combustion is derived by the transformation of release profile along the grate calculated by the basic packed bed combustion model. Since an unsteady CFD simulation of the whole batch process is impossible so far, virtual steady-state operating conditions have to be defined. In order to reduce a possible falsification of the CFD simulations of the stove by the heat storage of the stove, an energy balance around the stove as a function of time has to be performed based on test run data. By this energy balance, two virtual steady-state operating cases with a heat storage of the stove, which is approximately zero, can be estimated.

For the simulation of the gas phase usually the Realizable k-ε Model for turbulence, the Discrete Ordinates Model for radiation, as well as the Eddy Dissipation Model (EDM) in combination with a global Methane 3-step mechanism (CH_4, CO, H_2, CO_2, H_2O, O_2) are applied.

By the in-house developed CFD model for stoves a number of relevant processes can be analysed: the flow of the combustion air and the flue gas in the stove, the flow of the convective air in the double air jacket of the stove, gas phase combustion in the stove as well as heat transfer between gas phase and stove material (insulation, sheets and glass windows). By these simulations, velocities and temperatures of combustion air, convective air and flue gas, path lines of air and flue gas, O_2 and CO concentrations in the flue gas, material and surface temperatures of the stove materials, as well as heat transfer, efficiency and pressure losses can be analysed.

Numerous applications showed, that the CFD-aided development and optimisation of wood-log fired stoves leads to reduced emissions (CO and fine particulates), a better utilisation of the stove volume as well as an enhanced plant efficiency. Furthermore, the CFD simulations result in reduced development times, test efforts and an increased security during plant development.

In Figure 2 the CO concentrations of a wood log fired stove before and after optimisation are depicted as an example (see also [6]). In the basic variant the emissions are rather high due to a bypass flow in the redirection baffle of the post combustion chamber. Furthermore, the post-combustion chamber was not insulated. In the pre-optimised variant (before the realisation as testing plant) first improvements could be achieved by a closure of the bypass flow and an insulation of the post combustion chamber. By these measures, the temperature in the post-combustion chamber was elevated and the CO burnout considerably improved. Moreover, the efficiency was improved by a considerably larger heating surface of the transition between the post-combustion chamber and the chimney.

A further improvement could be achieved by the optimised variant which was realised as testing plant. Here, additional tertiary air nozzles have been installed in the rear part of the combustion chamber, which lead to an improved flue gas burnout already in the combustion chamber. Moreover, the CO emissions are a leading parameter for the burnout quality of the flue gas and can be used as an important indicator concerning organic fine particle emissions from incomplete combustion. Besides the considerably reduced CO emissions also the organic fine particle emissions could be reduced. Finally, the excess air could be reduced, leading to higher plant efficiency.

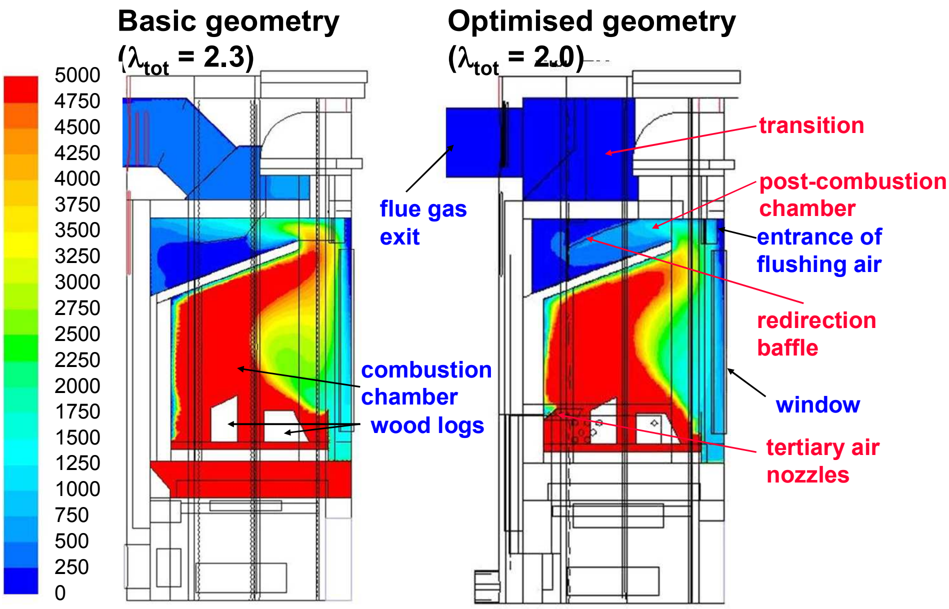

Figure 2: Iso-surfaces of CO concentrations [ppmv w.b.] in the flue gas in the vertical symmetry plane of a stove

Modifications: closure of opening in the redirection baffle; additional tertiary air nozzles; larger transition to the chimney and insulation of the post-combustion chamber

In Table I results from comprehensive test runs with the optimised stove in comparison with benchmark values (values according to relevant emission limits) are shown. The measurements confirmed the predicted trends and showed that the emissions from incomplete combustion (CO, OGC) are considerably lower than the benchmark values defined. This shows that by means of the in-house developed wood log model CFD simulations can also be applied to efficiently support the optimisation of modern wood log stoves with increased efficiency and low CO and fine particle emissions.

Table I: Test run results in comparison with benchmark values

Parameter	Unit	Test run	Benchmark value
CO emissions	[mg/MJ]	429	750
OGC emissions	[mg/MJ]	15	50
Fine particle emissions	[mg/MJ]	16	-
Total dust emissions	[mg/MJ]	18	20

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