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PRIMARY MEASURES FOR LOW-EMISSION RESIDENTIAL WOOD COMBUSTION – COMPARISON OF OLD WITH OPTIMISED MODERN SYSTEMS

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ABSTRACT: Measures for CO_2-emission mitigation as well as dramatically increasing costs for fossil fuels have led to an enforced trend towards residential wood combustion. This changeover to a more renewable sources based energy production however should in future be achieved without increasing harmful emissions such as CO, OGC and PM emissions. Especially during the last two decades, due to intensive R&D work, a rapid technological improvement of biomass boiler and stove technologies towards lower emissions and higher efficiencies took place. In this paper the most relevant primary measures, which form the basis for low-emission residential biomass combustion concepts are summarised. Moreover, the advantages of the application of CFD (computational fluid dynamics) simulations as a design tool to implement these primary measures for emission reduction in modern biomass combustion systems are highlighted. The technological measures presented as well as their effect on the emissions of residential wood combustion systems are mainly based on R&D work, performed during recent years at the BIOS BIOENERGIESYSTEME GmbH in cooperation with the Institute for Process and Particle Engineering, Graz University of Technology, and the BIOENERGY 2020+ GmbH.
Keywords: biomass, combustion, emissions, small scale application

1 INTRODUCTION

Wood combustion for residential heating and hot water supply is traditionally applied in many European regions. As a recent survey concerning the utilisation of biomass for residential heating in Austria, Germany, Finland and Sweden has revealed, in these countries between 10 and 30% of the total energy demand for residential heating and hot water supply are presently covered by small-scale biomass combustion systems [1]. The economic advantages of utilising regionally available biomass fuels, the well secured fuel availability as well as the dramatically increasing costs for fossil fuels have led to an enforced trend towards the installation of residential wood combustion systems. Moreover, in its 2020 targets the European Commission as well as its member states clearly define the goal to further significantly increase energetic biomass utilisation as a measure for CO_2-emission mitigation. Residential biomass combustion systems play a prominent role for reaching this aim. Therefore, it is expected that until 2020 the European market for residential biomass combustion systems, which is a presently strongly growing market, will be approximately tripled (compared to 2008).

However, this does not necessarily mean, that only new applications are taken into operation, it also implies, that old stoves and boilers, as they can be found in many households, are reactivated or used more intensively. As national statistics from e.g. Austria and Germany clearly show, the present stock of residential biomass combustion appliances consists of more than 80% of these old applications (older than 10 years) [1]. It is well known, that these old systems show significantly higher emissions than new combustion devices, especially concerning carbon monoxide (CO), organic gaseous compounds (OGC), particulate matter (PM) and polycyclic aromatic hydrocarbons (PAH), which consequently leads to the fact that they significantly contribute to harmful emissions of the residential heating sector. In Austria for instance in 2004 wood combustion has been the source of more than 85% of the PM_{10} (particulate matter with a diameter <10 µm) emissions from residential heating [2]. For the increased utilisation of biomass in the residential heating sector it is therefore of relevance, that in future old biomass heating systems are replaced by modern ones and that fossil fuel fired residential heating systems are substituted by biomass heating systems. By these measures a changeover from fossil fuel based to renewable heat production will be possible without increasing but even with decreasing the burden of harmful emissions.

It is well known, that modern biomass combustion systems have already achieved a technological level which allows for an operation at comparably low emissions. This is especially true for automated systems (pellet, wood chips and logwood boilers), but also concerning batch combustion devices (stoves) significant emission reductions could be achieved. Permanently reduced limiting values for CO, OGC and PM emissions in some European countries have been and are still a driving force for the further improvement of combustion technologies. However, it has also to be mentioned, that regulations concerning emission limits for residential biomass combustion systems significantly differ between European countries, and therefore the technological standard of the products also significantly differs from country to country.

In this paper primary measures for emission reduction in residential biomass combustion systems are firstly discussed in general. Improvements achieved by applying these measures are then presented by means of selected examples and by comparing emissions from state-of-the-art combustion systems with those of older systems. Moreover, potentials for further improvements are highlighted. Batch combustion devices as well as automatically controlled boilers are considered separately due to the generally different constraints for these technologies. The technological measures presented as well as their effect on the emissions of residential wood combustion systems are mainly based on results of R&D work, performed during recent years at the Institute for Process and Particle Engineering, Graz University of

Technology, at the BIOS BIOENERGIESYSTEME GmbH, Graz, Austria, as well as at the BIOENERGY 2020+ Centre of Competence, Graz, Austria.

2 HARMFUL EMISSIONS FROM RESIDENTIAL BIOMASS COMBUSION

The most relevant parameters regarding harmful emissions from residential biomass combustion are CO, OGC, PAH and PM. Increased emissions of CO, OGC and PAH are a result of an incomplete gas phase burnout. Since, as shown later, there is a considerable number of measures that can be applied to improve the gas phase burnout, also a huge potential for emission reduction exists.

While CO and OGC emissions do not attract much public awareness, PM emissions have become a topic of broad public interest during the last decade. In the EU directive 1999/30/EC, a limit value for the protection of human health of 50 µg/m³ PM_{10} (daily mean value) is defined which shall not be exceeded more than 35 times a calendar year. With the introduction of this directive it had to be recognised that at this time in many European regions the PM_{10} limit value has been exceeded more than 35 times per year. Residential biomass combustion systems have been identified as one relevant source for PM_{10}, and especially in regions, where the limit value has often been exceeded, wood combustion was also sometimes criticised due its PM emissions. Fine particulate emissions (PM_{10}) from biomass combustion can be divided into inorganic and carbonaceous aerosols (organic aerosols and soot particles). Inorganic aerosols result from the release of easily volatile ash forming species such as K, S and Cl from the fuel to the gas phase, which then undergo gas phase reactions (formation of K_2SO_4, KCl, K_2CO_3) and later form submicron particles by nucleation and condensation processes. These aerosol formation processes are driven by the supersaturation of the ash forming vapours due to the excessive formation of a compound or due to the cooling of the flue gas in the boiler. Due to this formation pathway the amount of inorganic aerosols formed mainly depends on the release of K from the fuel to the gas phase and can therefore not be influenced in conventional combustion concepts. The second aerosol fraction (carbonaceous aerosols) on the other side originates from incompletely oxidised soot particles as well as from the condensation of unburned hydrocarbons. The formation of this fraction can therefore be reduced by measures for improved burnout. It has for instance been shown that at CO emission levels of more than 1,000 mg/Nm³ (related to dry flue gas and 13 vol% O_2) the PM emissions also significantly start to increase [1]. Consequently, all measures which are applied in order to reduce CO and OGC emissions also contribute to a reduction of carbonaceous PM emissions.

Moreover, NO_x emissions are of relevance for biomass combustion. In heating oil and natural gas combustion NO_x emissions are mainly due to thermal and prompt NO_x formation while fuel NO_x formation is of minor relevance. On the contrary to heating oil and natural gas, biomass fuels contain considerable amounts of N and therefore, NO_x formation from the N bound in the fuel is the dominating mechanism. For excessive prompt and thermal NO_x formation the temperatures in biomass combustion systems are usually too low. Consequently, NO_x emissions usually increase from the combustion of natural wood (low N-content) to herbaceous fuels (higher N-contents).

Besides CO, OGC, PAH, PM and NO_x emissions, also dioxins and furans (PCDD/F) as well as HCl and SO_x emissions could be an issue in combustion processes. In residential biomass combustion however, most commonly chemically untreated wood fuels such as wood pellets, wood chips and wood logs are utilised. These fuels contain comparably low concentrations of S and Cl, and therefore, since almost the whole amount of S and Cl is embedded into the ashes, only neglectable amounts of gaseous HCl and SO_x emissions are formed. As long as the gas phase burnout is in an acceptable range, also PCDD/F emissions are not a relevant issue due to the low Cl contents of these biomass fuels. This is, however, again connected with the burnout quality, since PCDD/F may be formed also during the combustion of rather Cl-poor fuels, if high amounts of unburned carbon are available, which besides the presence of Cl and metals (acting as catalysts) form a relevant basis for PCDD/F formation. In this respect it is important to mention, that during the utilisation of agricultural fuels the emissions of these pollutants may significantly increase due to their, compared with wood, higher S and Cl contents. Since no further combustion technology related primary measures for HCl and SO_x emission reduction exist, the only primary measure to avoid these emissions is not to utilise S and Cl rich fuels in small-scale biomass combustion systems.

3 PRIMARY MEASURES FOR EMISSION REDUCTION - GENERAL ASPECTS

Permanently ongoing R&D work related to small-scale biomass combustion devices, which has been performed in many European countries during the last years, has led to an advanced understanding of the combustion process as well as of emission formation mechanisms. Based on this knowledge, wood burning appliances and boilers have gradually been improved. Better knowledge about the basic mechanisms governing the process also led to a more focused further development of primary measures for emission reduction. In this respect, close co-operation between research organisations and industry, as they have been established in many European countries, significantly contributes to the acceleration of the development process. The main focus of the measures presented in the following traditionally has been put on the improvement of the burnout and thereby on the reduction of CO, OGC, PAH and PM emissions. In this respect the fuel feeding system, the fuel bed arrangement as well as the grate design, the air supply strategy, the burning chamber geometry as well as the process control concept have to be considered. Moreover, the correct dimensioning of boilers as well as the user behaviour may have an influence on the emissions.

3.1 Fuel feeding concepts

Fuel feeding strategies are of relevance for automatically fed boilers, i.e. pellet and wood chip boilers. Usually feeding screws are applied to introduce the fuel into the burning chamber. In this respect two aspects are of major relevance for the combustion process. The fuel feeding system applied should allow for an optimum adjustment of the fuel flow to the actual load conditions. Therefore, it should be flexible with respect to the fuel mass flow achieved which bears the advantage that the fuel to air ratio in the furnace can easier be kept on a rather constant level. Screws with rotation speed control or improved concepts for pulsing operation of the feeding screw are usually applied.

A second important issue is the air tightness of the fuel feeding system. As it is discussed later, optimised air staging represents the most important basis for an improved burnout as well as for NO_x emission reduction. Leak air introduced via the fuel feeding system, cannot be controlled and consequently disturbs the air distribution and control concept. Therefore, leak air introduction over the fuel feeding system must be avoided as good as possible.

3.2 Fuel bed and grate systems

While for pellet furnaces usually underfed or horizontally fed fuel beds are applied, for pellet furnaces also overfed concepts exist [3, 4]. Moreover, different grate systems are applied.

The grate should guarantee for low disturbances of the fuel bed and an even distribution of the combustion air over the whole fuel bed. Uncontrolled and/or rapid movements within the fuel bed can lead to significant disturbances of the combustion process. Moreover, uneven distributions of the combustion air over the fuel bed lead to bed channelling effects which also significantly disturb the combustion process and usually results in an incomplete burnout of the charcoal.

It has also to be taken care that no significant slag formation and slag agglomeration in the fuel bed occurs, since these effects may result in an uneven distribution of the combustion air over the fuel bed.

Therefore, it is important to design the grate area as well as the openings in the grate for air supply in an optimised way. Presently, a considerable number of different approaches exists (e.g. fixed grates, step grates, hinged grates, moving grates, rotating grates) which all form a good basis to fulfill these demands provided that the air supply and process control system is accordingly adapted to the respective grate.

3.3 Air supply strategies

For burnout optimisation advanced air supply strategies form the most important basis. In order to achieve high thermal efficiencies, the overall excess air ratio should be kept as low as possible and consequently, the aim of advanced air supply concepts must be to achieve low emissions at the lowest possible excess air ratio.

In this respect, air staging has turned out to be the most efficient measure. Air staging means, that one share of the combustion air is supplied directly to the fuel bed (so called primary combustion air), and the remaining share of the combustion air (so called secondary combustion air) is injected into the burnout zone. Several issues have to be considered when optimising air staging.

The primary combustion air flow which is also used to control the fuel burning rate (load control) should be kept as low as possible. In any case an understoichiometric air ratio should be maintained for the primary combustion air supply. The secondary air is then used to almost completely oxidise the gaseous compounds released from the fuel bed (CO, hydrocarbons). This burnout can be improved by an appropriate mixing of the gases released from the fuel bed with the combustion air as well as by the provision of enough residence time at high temperatures (>800°C) after injection of the secondary combustion air. In this respect the burning chamber design as well as the arrangement of the secondary air injection nozzles is of great relevance (see also section 3.4).

As already mentioned, the primary air ratio should be kept as low as possible, which is mainly due to the following advantages of this strategy.

Firstly, by keeping the primary air ratio in the understoichiometric range, the temperatures in the fuel bed can be kept on a moderate level. By that measure, ash melting and slag formation can be reduced to a minimum and therefore, do no disturb the combustion process.

Secondly, reduced amounts of primary combustion air also mean, that at the same overall combustion air ratio, higher amounts of secondary combustion air are applied. Therefore, a higher momentum of the secondary combustion air at its inlet and consequently higher turbulence and an improved mixing with the burnable gases released from the fuel bed with the secondary combustion air can be achieved.

Moreover, low primary air ratios lead to reduced velocities of the combustion air in the fuel bed. Therefore, the entrainment of small fuel, charcoal and ash particles from the fuel bed can be reduced. Small fuel and charcoal particles entrained with the flue gas are subsequently burned in flight with the secondary combustion air. Since this process is significantly slower than the gas phase burnout, complete combustion cannot be achieved within the residence time of these particles within the hot zones of the furnace.

With decreasing fuel bed temperatures also the release of inorganic aerosol forming species (mainly of K) from the fuel to the gas phase is reduced [5]. During the cooling of the flue gas K compounds (sulphates, chlorides and carbonates) form fine particles which represent the inorganic part of the fine particulate emissions. Consequently, with decreasing primary air supply also these emissions can be reduced.

Finally, primary air ratios in the understoichiometric range also provide a relevant basis for the application of air staging as a measure for NO_x emission reduction. The efficiency of this measure however, is strongly influenced by the furnace geometry (enough residence time of the gases released from the fuel bed in hot zones with reducing atmosphere should be provided), as discussed in section 3.4 in more detail.

Modern boiler systems are generally based on air staging, however, still a considerable potential for further improvements and optimisations is given. In batch burning devices (stoves), sometimes no air staging is applied, and therefore, the introduction of this measure bears a great potential for emission reduction.

3.4 Combustion chamber and air supply design

As mentioned in section 3.3, efficient air staging forms the basis for low emission biomass combustion systems. However, to fully utilise the emission reduction potential of air staging, the furnace geometries as well as the air injection concepts must be optimised together. The most efficient way to implement air staging in a furnace concept is to geometrically divide the furnace into two zones, a primary combustion zone, where the fuel and the primary combustion air are introduced and a secondary combustion zone, where the flue gases are burned with secondary combustion air.

The primary combustion zone should not be cooled by water jackets but it can be cooled by surrounding secondary combustion air channels. This bears the advantage that the secondary combustion air is preheated and therefore also the velocity at the secondary air nozzle outlet is increased which improves mixing with the flue gases. With increasing residence time of the flue gas in the reducing atmosphere of the primary combustion zone, the NO_x emission reduction efficiency of the air staging concept increases. However, in most designs of state-of-the-art residential biomass combustion systems the residence times in the primary combustion zones are too low for efficient NO_x emission reduction, and therefore, in this respect still a considerable potential for optimisation is given.

The secondary combustion air should be injected at the beginning of the secondary combustion zone in a way that no reverse flows of the air into the primary combustion chamber occur. Therefore, the geometry of the interface between primary and secondary combustion zone must be designed accordingly and the secondary air injection nozzles must be arranged appropriately. Moreover, a good mixing of the secondary combustion air with the gases from the primary combustion chamber is of relevance. In this respect the geometry of the combustion chamber itself as well as the diameter, number, positioning and orientation of the secondary air injection nozzles must be optimised. Especially the diameter and number of the air injection nozzles determine the outlet velocity of the combustion air and therefore also the degree of turbulence, which is a measure for the quality of the mixing with flue gases, that can be achieved. With higher air outlet velocities higher turbulence can be achieved, however, limitations with respect to the also increasing pressure losses have to be considered, since with increasing pressure loss also the electricity demand for the flue gas fan increases. Consequently an intelligent compromise between auxiliary energy consumption costs and optimisation of turbulence has to be found.

Although the mixing of the combustion air with the flue gases is the most important factor for achieving improved burnout, also the furnace temperatures play an important role. The flue gas should have enough residence time at temperatures >800°C in order to complete the oxidation reactions which means, that it is of advantage not or only moderately to cool the part of the secondary combustion chamber where the main burnout reactions take place.

Concerning the correct implementation of the measures proposed two additional aspects have to be considered. During partial load operation lower amounts of combustion air are needed and consequently turbulence at the secondary air nozzle outlet also decreases. Moreover, the furnace temperatures decrease. These effects have to be considered in order to optimise the nozzle design as well as the combustion chamber cooling in a way, that also at partial load acceptable burnout conditions prevail.

It has to be mentioned, that the whole concept of air staging only is successful if the combustion air flows are well defined. In this respect leak air is extremely disadvantageous since it is added to the combustion process at undefined points and cannot be controlled. Therefore, leak air should be avoided by an air tight design of the combustion chamber as well as especially of the fuel supply and the de-ashing system.

3.5 Process control concepts

Modern automated wood chip, pellet and logwood boilers are equipped with advanced (micro-processor based) control systems. They provide an important basis to implement the measures discussed above in an appropriate way. In this respect it has to be taken care, that the optimum conditions for staged combustion are not only maintained during continuous full load operation but also during partial load operation and transient operation phases. Therefore, not only an intelligent control concept, but also appropriate hardware such as valves for adjusting the primary and secondary air flows as well as lambda-probes to control the overall excess air ratio are recommended.

Typical batch burning devices (stoves) are usually not equipped with appropriate automated process control devices. The air supply is manually adjusted by the user and due to a lack of measurement equipment the adjustment of the air supply can only be performed based on the visual evaluation of the flame. This leads to the fact, that the user behaviour significantly influences the performance and the emissions of stoves. Consequently, stoves which show comparably low emissions at test stands can be operated at high emissions due to wrong user behaviour under field conditions. The introduction of automated control systems for stoves, which is just at its beginning, would lead to further significant emission reduction since it minimises user induced errors.

3.6 Correct boiler design and user behaviour

Concerning emission formation in automated furnaces it has to be distinguished between stable continuous operation at nominal load, minimum load operation as well as transient operation phases (start-up, shut down, load changes). During type testing only full and partial (30% of full load) operation are considered. Under these conditions modern systems usually operate at very low emissions. In reality of course also transient operation phases play an important role. If the boiler capacity is not appropriately adjusted to the heat demand of the consumer (i.e. the boiler is oversized), transient operation even can become more relevant than stable load conditions (due to stop-and-go operation) which generally leads to higher emissions. Therefore, a correct adjustment of the boiler capacity to the heat demand of the user is also of great relevance.

Regarding stoves it has to be mentioned, that the user might significantly influence the emissions by utilising not appropriate fuel, applying wrong charging and ignition strategies and by bad adjustments of the combustion air supply. Since, as already mentioned, stoves do not have automated control systems, the combustion system cannot react on user induced errors by corrective measures. Therefore, appropriate user training and information for stove users must also be mentioned as an important primary measure for emission reduction.

3.7 CFD simulations as a supporting tool for furnace development

Stove and boiler manufacturers are usually aware of the concepts presented above. However, their correct implementation into real applications represents the major problem and challenge. In order to improve the implementation of primary measures in furnaces, process simulation based on computational fluid dynamics (CFD) has become a design instrument which allows for a quicker and more efficient development process than traditionally applied experimental development work. With CFD it is possible to simulate the combustion process in detail, and thereby to analyse velocity and temperature distributions in the furnace as well as the combustion reactions. CFD can therefore be applied in order to optimise furnace geometries as well as air supply strategies (e.g. secondary air injection nozzle dimensions and arrangements) in a way that the primary measures discussed above can be implemented in an optimised way. Moreover, the results of the calculations are visualised and therefore provide the basis for an improved understanding of the processes going on. CFD simulations cannot substitute classic experimental R&D, but they can significantly increase the probability of the success of the development work and speed up the development process by providing an optimised prototype which then has to be tested. By the simulation of different load cases and fuels, CFD simulations additionally provide relevant basic information for developing an optimised process control concept tailored to the demands of the respective technology.

In the following sections some examples for the application of CFD as supporting tool in stove and boiler development and optimisation are given.

4 EMISSION REDUCTION IN BATCH BURNING DEVICES

Wood stoves are commonly applied all over Europe. They are not only a heating device, in many cases they are also a design element in modern living rooms. Therefore, a high diversity of different designs exists and also the technological performance of the products, especially concerning emissions, strongly deviates.

The combustion process in stoves is characterised by three combustion phases, the ignition phase, the main combustion and the burnout phase (see Fig. 1). At the beginning of a combustion cycle, during the ignition phase, the O_2-content of the flue gas decreases while the furnace temperatures increase. As long as the O_2-concentrations are too high and the furnace temperatures are too low to achieve appropriate burnout conditions, high CO, OGC and PM emissions are detected. As soon as stable combustion conditions have been reached the main combustion phase begins. This phase is characterised by quite stable O_2 concentrations in the flue gas and sufficiently high temperatures in the furnace to provide acceptable burnout conditions. During this phase the CO, OGC and PM emissions are significantly lower than during the ignition phase. At the end of the combustion cycle charcoal burnout takes place, the O_2 concentrations in the flue gas start to increase and the furnace temperatures decrease again. Consequently, the burnout quality decreases and the CO emissions increase. The OGC and the PM emissions however stay on a rather low level which is due to the fact, that the main amount of volatiles has been released from the fuel during the ignition and the main combustion phase.

The major part of the emissions generated during one combustion cycle is related to the ignition phase. Therefore, optimised stove designs should aim at a very short ignition phase which means, that high flue gas temperatures and low O_2-concentrations in the flue gas (around 10 vol% (d.b.)) are reached within short time. During the main combustion phase optimised mixing of the gases released from the wood logs with the combustion air can lead to improved burnout conditions. The implementation of appropriate air staging concepts has shown to be a very efficient measure for emission reduction in stoves. Therefore, the stove should be divided in a main combustion chamber and a subsequent burnout zone. Moreover, a staged combustion air supply should be realised.

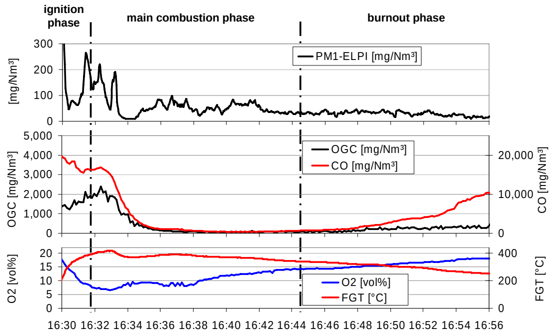


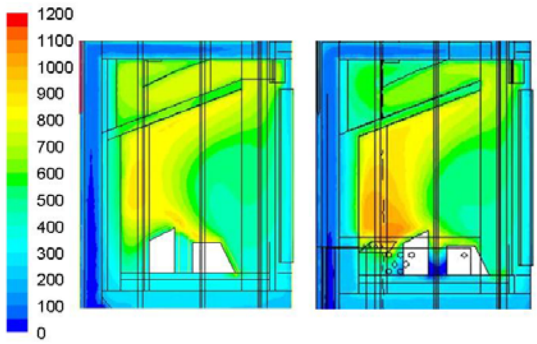
Figure 1: Combustion phases during logwood combustion in a stove
Explanations: fuel: 1.5 kg beech logs; FGT … flue gas temperature at stove outlet; ELPI … electric low pressure impactor; O_2 related to dry flue gas; PM_1, CO and OGC related to dry flue gas and 13 vol% O_2

In Fig. 2 results from a CFD-based design study for such a stove are presented. In the basic design the combustion air is injected as flush-air along the front window of the stove (right side of the left hand pictures in Fig. 2) while in the optimised design, besides the flush-air also secondary combustion air is supplied from the backside of the combustion chamber. As it can be seen, the temperature distribution in the optimised version shows zones with high temperatures in the region above the wood logs, where the gases mix with the secondary combustion air. Moreover, the O_2 profile is much more evenly distributed over the combustion chamber. Especially the CO strain which flows along the backside wall of the furnace (left side of the pictures) can be avoided. Due to the higher temperatures and the more even O_2-profile, which is also a good indicator for an improved mixing of the flue gas with the combustion air, significantly better burnout conditions are provided. The results of the CFD simulations indicate a substantial decrease of the CO-emissions (see Fig. 2).

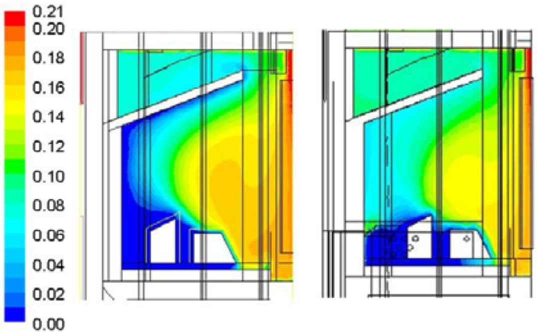
During test runs with a non-optimised 8 kW stove and a stove equipped with air staging according to Fig. 2, the emission reduction potential predicted could be proven. While for the non optimised stove average emissions of about 1,900 mg/MJ CO, 220 mg/MJ OGC and 35 mg/MJ PM_1 have been determined (average emissions during one complete combustion cycle including ignition, main combustion and burnout phase), the optimised stove showed average emissions for CO in the range below 670 mg/MJ, for OGC <30 mg/MJ and for PM_1 <20 mg/MJ. This example also underlines how measures for improved gas phase burnout reduce PM emissions.

Moreover, when analysing the diagrams in Fig. 1, another significant potential for optimisation becomes obvious. During the ignition phase the O_2 concentrations in the flue gas quickly decrease and can reach values which are too low for a complete burnout. During the burnout phase on the other side, the O_2 concentrations start to increase again. As a consequence the furnace temperatures decrease and therefore also the burnout quality decreases. The introduction of an automated air supply control system, which helps to avoid too low excess air ratios during the ignition phase and too high excess air ratios during burnout may help to further decrease the average emissions of a complete burning cycle. In an appropriately adapted optimised stove prototype (as presented in Fig. 2) such a combustion air supply control system has been implemented and tested. A further decrease of the average emissions over the whole combustion cycle to 300 to 400 mg/MJ CO could be achieved. These results clearly underline the advantages of the implementation of automated process control systems in stoves.

Flue gas temperatures in [°C] in the vertical symmetry plane of the stove



O_2 concentrations in [vol% (d.b.)] in the vertical symmetry plane of the stove



CO concentrations in [ppm] in the vertical symmetry plane of the stove

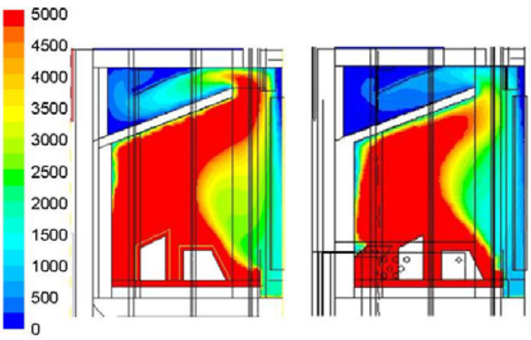


Figure 2: Results of CFD-simulations for a stove without (left) and with (right) air-staging
Explanations: 8 kW stove; fuel: beech logs; simulation based on the combustion conditions at the beginning of the main combustion phase

5 EMISSION REDUCTION IN AUTMATICALLY CONTROLLED BOILERS

Concerning residential biomass boiler technologies it has generally to be distinguished between automatically fed systems (pellet boilers as well as wood chip boilers) and manually fed systems (logwood boilers).

5.1 Wood chip and pellet boilers

During the last two decades a rapid improvement of the boiler technologies towards lower emissions took place. In Fig. 3 the development of emission factors for carbon monoxide and TSP (total suspended particulate matter = total dust) from old (1996) to new (2008) pellet furnaces based on test stand measurements is presented [6, 7]. The data clearly show a decreasing tendency, which is mainly due to a steady improvement of the burner technologies, furnace geometries and combustion control systems applied. The same tendencies have also been observed for wood chip boilers.

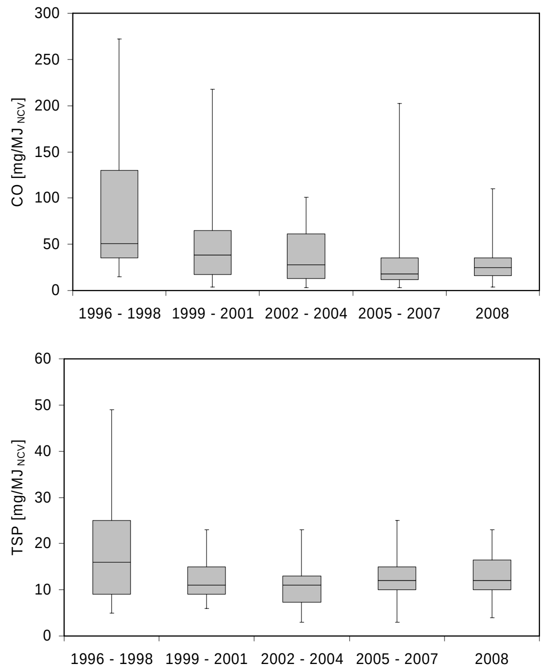


Figure 3: Development of CO and TSP emissions of Austrian pellet boilers between 1996 and 2008
Explanations: results from test stand measurements; source [6, 7]; TSP … total suspended particulate matter

While for wood chip boilers mainly underfed systems are presently applied, for pellet boilers a considerable number of fuel supply and grate concepts exists [4]. They all have their advantages and disadvantages but generally they provide a good basis for the implementation of air staging concepts. However, there is still a potential for further technological improvement. In the following some examples how air staging could be implemented even more efficient than today into wood chip and pellet boiler concepts are presented.

Important issues for an efficient implementation of air staging concepts are the correct arrangement of the secondary air injection nozzles as well as the geometry of the combustion chamber. In Fig. 4 an example for the optimisation of the secondary combustion air injection by CFD-simulations is presented. In the figure the vectors of the flue gas velocity in the horizontal cross-section right over the secondary air nozzles are shown. The basic nozzle design (upper image) leads to an uneven distribution of the flue gas velocity with a peak in the middle and very low velocities especially in the regions close to the furnace walls. This indicates insufficient mixing conditions over the cross section of the furnace which leads to increased CO and OGC emissions. Moreover, the uneven velocity distribution causes local temperature peaks. The improved nozzle design (lower image) leads to a homogenisation of the flow across the furnace cross-section due to the induction of a swirling flow. As a consequence, lower CO, OGC and PM emissions at reduced excess air ratios (leading to an increased plant efficiency) can be achieved. Such optimisations can only be achieved efficiently with the support of CFD simulations because they provide the basis to evaluate flow, temperature as well as O_2 and CO distributions in the furnace and thus make it possible to optimise the furnace and nozzle design stepwise without the need for additional time consuming test runs. Thus, only the optimised boiler will then undergo a final test to check and verify the simulation results.

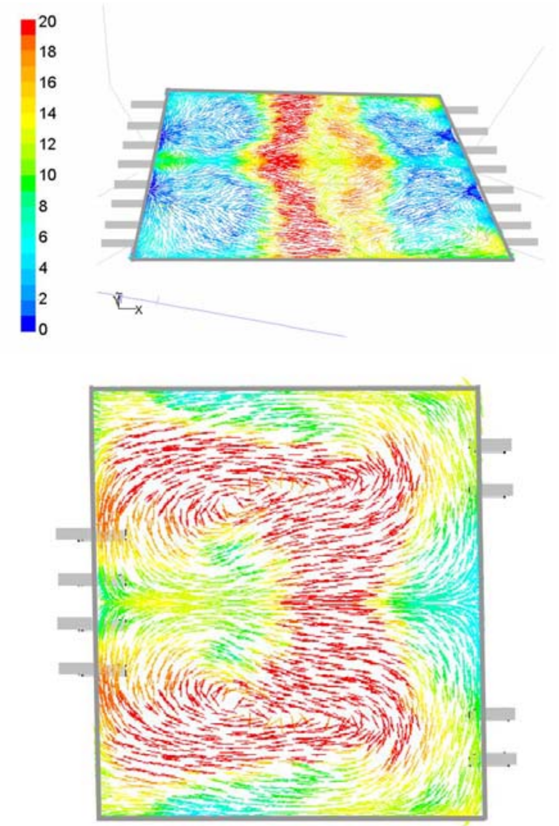


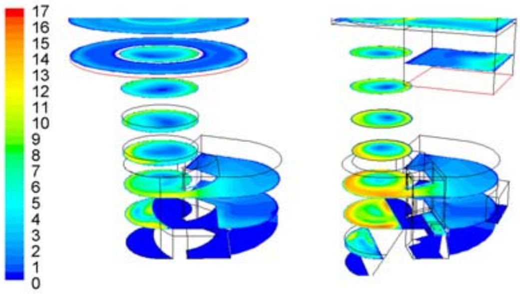
Figure 4: Design and optimisation of the nozzles for the injection of secondary air by CFD

Explanations: top: basic nozzle design; down: improved nozzle design; vectors of the flue gas velocity in [m/s] in the horizontal cross-section right over the secondary air nozzles; source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

In Fig. 5 CFD-analyses which have been performed in order to optimise the design of the secondary combustion zone of a wood chip furnace are presented. For optimisation the diameter of the secondary combustion chamber as well as the design of the secondary air injection system have been adapted. As the schematic drawing of the furnace shows, it consists of a primary and a secondary combustion chamber. In the latter a vortex flow is introduced in order to improve mixing and burnout conditions. Results of the CFD simulations regarding the temperature and velocity distributions in the secondary combustion zone are presented, whereas the left hand images represent the basic design case and the right hand images the optimised case. From the flue gas velocity development it can be derived, that the optimisation measures resulted in a more pronounced swirling flow. This bears the advantage of a better mixing of the flue gases with the secondary combustion air due to higher turbulence which leads to a significant improvement of the flue gas burnout and consequently to decreased CO and OGC emissions. The drawings concerning the temperature distributions in the different horizontal cross sections show that also a more even temperature distribution could be achieved by the measures taken. Especially the hot spots at the furnace walls could be significantly reduced which is of advantage concerning material wear and the reduction of ash deposit formation.

KWB TDS Powerfire 150

Iso-surfaces of the flue gas velocities in [m/s] in horizontal cross sections of the furnace



Iso-surfaces of the flue gas temperatures in [°C] in horizontal cross sections of the furnace

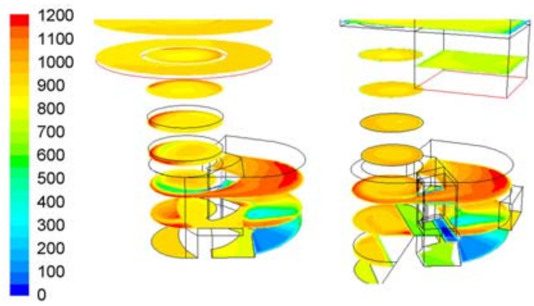


Figure 5: Optimisation of the burnout conditions of a wood chip furnace by CFD

Explanations: top: schematic drawing of the furnace (source: KBW – Kraft und Wärme aus Biomasse GmbH, Austria); mid and lower row: left hand pictures: basic design; right hand pictures: optimised design; source [8]

5.2 Logwood boilers

One milestone in the development of low emission logwood boiler technologies has been reached with the introduction of the downdraft combustion concept as well as the implementation of automated combustion control systems. In Fig. 6 schematic drawings of an old fashioned updraft combustion concept and of a modern downdraft concept are presented.

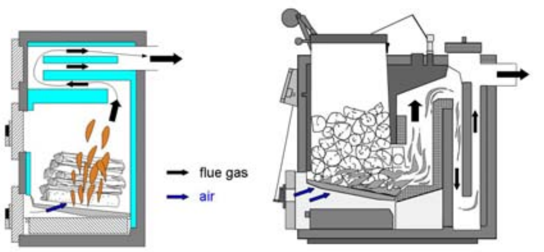


Figure 6: Updraft (left) and downdraft (right) combustion concept for logwood boilers

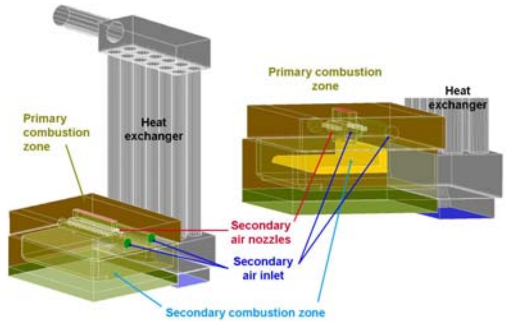
In Fig. 7 a typical example for a modern downdraft boiler is shown. It represents an optimised application of the air staging concept. The wood logs are gasified with primary combustion air at comparably low temperatures. The flue gases released during the gasification step are then lead into a secondary combustion chamber and oxidised with secondary air. In this special case the secondary combustion chamber is designed as a vortex chamber, where a swirling flow, which provides an extremely good mixing of the combustible gases with the combustion air, is introduced.

Figure 7: Modern downdraft boiler
Explanations: source: Fröling GmbH (A)

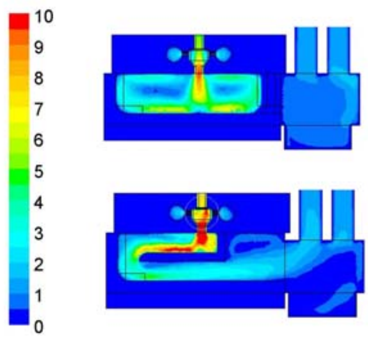
For such types of logwood furnaces especially the optimisation of the burnout zone and the secondary air injection are of great relevance. In Fig. 8 results of a CFD-based design study are presented, which clearly underline the advantages of an optimised secondary combustion chamber concept.

In the first line of Fig. 8 the basic concept of the logwood furnace is presented. The log storage with the gasification zone is located above a small grate, through which the flue gases enter the secondary combustion chamber. There, a swirling flow is introduced due to the positioning and arrangement of the secondary air nozzles. The flue gas leaves the secondary combustion chamber on the right side and enters the boiler. In the optimised concept the nozzle size and position has been re-arranged and a deflector plate is installed, which forces the flue gas to change the flow direction two times before entering the boiler.

Basic concept Optimised concept



Flue gas velocities in [m/s] in the vertical symmetry plane



CO concentrations in [ppm] in the horizontal and vertical symmetry plane

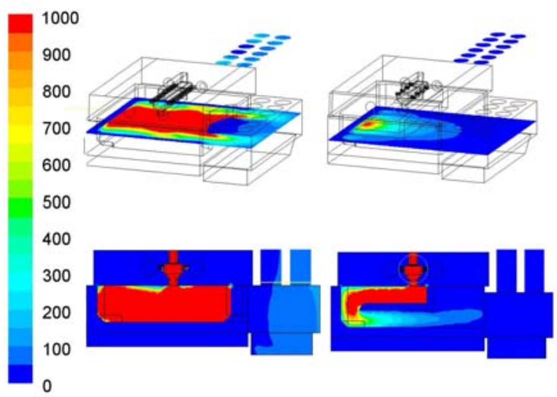


Figure 8: Results of a CFD design study for the optimisation of the secondary combustion chamber of a logwood boiler
Explanations: velocity distribution: upper image: basic concept, lower image: optimised concept; CO emissions: left hand images: basic concept; right hand images: optimised concept; simulations shown for full load operation

From the velocity distributions is can be derived that in the basic concept a part of the flue gas (on the right side of the image) is not integrated into the swirling flow but directly enters the boiler while in the optimised concept the whole flue gas flow has about the same residence time in the secondary combustion zone.

Moreover, the integration of the deflector plate leads to better mixing of the flue gas with the combustion air and to a better utilisation of the volume of the secondary combustion zone. All these effects together provide a better burnout which is documented by the CO-profiles for both design options also presented in Fig. 8. The optimisation approach discussed is only one example for different options that can be applied for burnout optimisation, however, when applying CFD, the effects of different measures can be analysed much quicker and more accurately than with time consuming prototype reconstructions and test runs.

Old logwood boiler technologies show CO emissions in the range of 4,300 mg/MJ, OGC emissions in the range of 450 mg/MJ and particulate emissions in the range of 90 mg/MJ [9]. With modern optimised technologies, as they are presented in Fig. 7 and Fig. 8, significantly lower emissions can be achieved (CO: <70 mg/MJ, OGC: <5 mg/MJ, PM: <13 mg/MJ).

Compared with wood chip and pellet boilers modern logwood boilers usually show the lowest PM emissions [10]. Some products even reach emissions levels of <10 mg/MJ at stable full load operation (see Fig. 9). This is mainly due to the fact, that gasification of the fuel takes place at rather low temperatures. Consequently, the release of K is lowered and thus a lower potential for the formation of inorganic aerosols exists [5, 10]. Organic aerosol emissions and soot are almost avoided due to the improved burnout conditions. However, it has also to be mentioned, that logwood boilers still have problems with changing load conditions. Especially in case of steep load reductions significant CO, OGC and PM emission peaks occur. This drawback is system inherent, since the fuel supply cannot be adjusted in a way as it is done in automatically fed systems and therefore, logwood boilers should only be applied in connection with heat storage tanks.

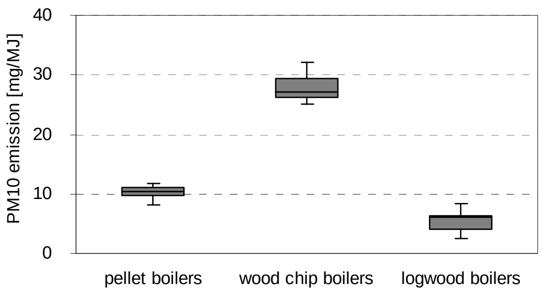


Figure 9: PM_{10} emissions of modern pellet, wood chips and logwood boilers
Explanations: measurement results from test runs at stable full load operation with 6 pellet boilers, 4 wood chip boilers and 2 logwood boilers; source [10]

6 CONCLUSIONS AND OUTLOOK

As presented in this paper, a considerable number of primary measures for the reduction of CO, OGC and PM emissions from residential biomass combustion systems exist. The most important ones are the implementation of appropriate air staging, the provision of an intensive mixing of the combustion air and the flue gases in the secondary combustion zone, enough residence time in the secondary combustion zone at temperature >800°C as well as furnace geometries and air injection concepts which allow for an optimised realisation of these measures in real applications. These measures can be implemented in all types of common residential biomass combustion systems (stoves, automated boiler systems) however, due to the different constraints provided by different combustion technologies, the final solutions of course differ.

The primary measures for emissions reduction discussed are to a certain extent already implemented into state-of-the-art furnace and stove concepts. However, a considerable optimisation potential still remains. It has been shown, that CFD simulations can be used as an efficient tool to analyse different options and approaches in order to optimally implement primary measures into combustion concepts and thereby also provide the possibility to analyse the effects of different design options without time consuming reconstructions of testing units. CFD simulations will never fully substitute experimental research but they can contribute to a significantly faster, more problem oriented and more successful problem solution process and will thus play a relevant role in the future development of small-scale biomass combustion systems.

Comparisons of emission data from old and state-of-the-art systems clearly demonstrate the significant advancements within stove and boiler technology development that have been achieved within the last 2 decades. However, permanently decreasing emission limits, especially for PM, demand for a further improvement of residential biomass combustion systems. The major aim for future developments will therefore be to develop new combustion systems which come close to almost zero emission systems with regard to CO, OGC and PM emissions. Another future challenge will be to further downscale the applications to capacities in the range below 5 kW, since an increasing demand for micro-systems is given due to a clear trend towards low-energy houses.

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9 LOGO SPACE