Final project report

Project acronym	Wood Stoves 2020
Full project Name	Development of Next Generation and Clean Wood Stoves
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1. Status quo of the project *(achievement of milestones and objectives with regard to the work plan; Estimate the current degree of completion of the planned objectives; auto-evaluation of the internal cooperation and added value of internat. cooperation to the project)*

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1 WP 1: Automated process control for stoves

The biggest challenges in stove operation are the unknown user behaviour and the constantly changing boundary conditions due to the rather short batch combustion. The solution is to adjust the air flow with regard to the current combustion condition in order to minimize emissions of unburnt components as well as to reduce unnecessary excess air which prevents standing losses and increases efficiency.

Advanced automated control systems provide the basis for a low emission stove operation at increased efficiency since they also contribute to a minimisation of user induced operation errors. Therefore, the optimisation and introduction of such systems, which are presently not widely-used, can have a huge impact on emission reduction from stoves. Moreover, retrofit control units for existing stoves open a wide field of application with an even larger potential for emission reduction.

Common logwood stove concepts are usually manually controlled (by a control switch). Therefore, process control efforts are usually limited to a change of combustion air distribution at the end of the ignition phase. Recent technical solutions towards stove automation can be differentiated into automatically controlled stoves and stove add-ons, e.g. which apply automatic air control:

Automatically controlled stoves
- Thermo-mechanically operated air flaps (e.g. HWAM automaticT)
- Electronic sensor driven automatic control concepts (e.g. RIKATRONIC™, HWAM Autopilot IHS™)

Stove add-ons and retrofit systems, apply automatic air control
- Chimney draught stabiliser and flue gas fans (e.g. K+W draught stabilizer, ATEC Florian)
- Air and flue gas flaps (e.g. K+W Compact, Schmid SMR, TATAREK RT8OS-G-TD, Brunner EOS, OCOntrol)
- Electronic air distribution systems (ATEC Airmaster)

For advanced control of stove operation both the choice and implementation of reliable sensors as well as the development of useful algorithms for either integrated or retrofit control units were investigated within the project. In a first step, sensors for relevant flue gas components and possible other parameters available on or close to introduction into the market were evaluated and a preliminary assessment of their applicability for process control in stoves was performed. Furthermore, control algorithms for integrated systems adapted to advanced wood stoves as well as retrofit systems were elaborated, implemented and tested.
The outcomes of the investigations regarding the improvement of wood stoves by the application of automated control concepts are summarized in the “Guidelines for automated control systems for stoves” (see section 5).

1.1 Sensors for automated process controlled stoves (RISE/BIOS)

The automated control system has to be able to rely on the information given by the sensors. Therefore the choice of sensors is crucial. Certain specific criteria should be considered when selecting sensors, which include costs, availability, life span, temperature resistance as well as signal selectivity, stability & processing. Within task 1.1, screening & testing of flue gas sensors was performed with regard to the named criteria. The task started with a literature study & market research for finding feasible and available sensors, followed by an experimental evaluation of selected sensors.

Literature study & market research. The literature study focused on sensors for determination of oxygen and unburnt components and their development during the last decade, with special emphasis on gas sensors that had been tested with stoves or other small scale biomass combustion appliances. In general there were a limited but somewhat growing number of sensors that had been studied in the different reviewed projects, especially regarding sensors for unburned gases. Many projects focused on the development of control concepts, mostly for boiler appliances. But there were also some which involved stoves or covered the sensor evaluation itself. In summary, it takes a long time to finally develop a sensor for use in real life environment. Many of the reviewed projects have used the same sensor models and there a constant improvement over the years can be observed, especially with regard to durability. Oxygen sensors showed in general good accuracy and only little cross sensitivity. That means the determination of the oxygen content has been reported to be reliable, at least in the focused oxygen area. Sensors for carbon monoxide and other unburned gases usually generate a combination signal of all unburned components. That means there is still a rather poor selectivity for single components. Most evaluated sensors showed noticeable cross sensitivities for oxygen, moisture and temperature as well as improvement potential regarding accuracy and long term stability. Nevertheless it has been reported that these sensors provide reliable trends and a proper determination of overall ranges. And according to the reviewed studies the initial utilization of sensors for carbon monoxide and unburned components in control concepts has also been successfully proven.

A market research for feasible and available sensors was performed with the aim to be the basis for the sensor selection for automated control systems. With regard to the specified selection criteria the market research collected information on operational characteristics such as

- measured component and measurement range,
- power consumption,
- expected life span,
- permitted temperature range,
- cross sensitivities, long-term drift,
- known risks for sensor poisoning as well as response to stove-typical dust and tar levels.

In addition, it was asked if there was any practical experience with applications in the stove or other biomass sector, and information was collected on availability and price level for sensor and electronics. In accordance with the literature study, the market research resulted in only few sensors, which met the requirements, especially regarding operation range, availability and development status (beyond prototype). It also turned out that the identified oxygen sensors (from manufacturers as NGK Spark Plug, Bosch, LogiDataTech, Scantronic or Heraeus) were mainly commercially available and had in general a greater utilization experience than the detected sensors for unburned components respectively combination sensors for oxygen and unburned components (from manufacturers as LAMTEC, FIGARO, Scantronic, SenSiC).

Experimental Evaluation. Based on the market research four sensor models were selected for a more extended evaluation. These sensors were the two NGK lambda probes OZA685-WW1 (switching type) and ZFAS-U2 (broadband type), the combination probe KS1D (Lamtec) for oxygen and carbon monoxide and the SenSic CO/O_2 sensor.

Figure 1: Evaluated sensors: NGK lambda probes OZA685-WW1 & ZFAS-U2, SenSic CO/O2 probe, Lamtec KS1D (from left to right)

Evaluation of lambda probes. Three units from each of the lambda probes OZA685-WW1 and ZFAS-U2 (manufacturer NGK Spark Plug) were studied in a ca. 550 hour long-term stove evaluation with recurring comparative measurements using standard flue gas analysers. Additionally, the lambda probes were checked against known gas compositions in a test gas rig prior, in the middle and after the stove evaluation period.

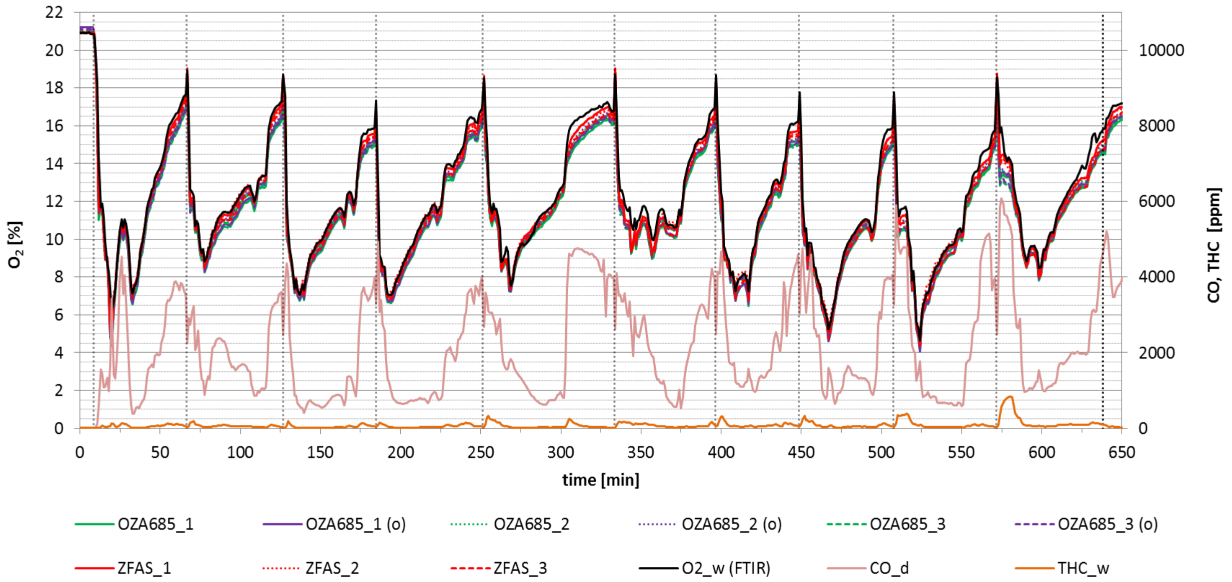


Figure 2: Comparison of lambda probes with standard gas analyser at stove operation

In summary, both lambda probes demonstrated a highly accurate oxygen determination within the whole oxygen range when comparing probe signals with set point values in the test gas rig. Comparing probe signals at stove operation with O_2 values derived from standard analysers only minor deviations could be seen; with broadband type ZFAS-U2 slightly more accurate than switching type OZA685-WW1. This deviation during stove operation is mainly based on cross sensitivities to hydrocarbons & carbon monoxide. Figure 2 shows a comparison of lambda probe signals (3 for ZFAS-U2 probe electronics, 3 for OZA685-WW1 probe, 3 for OZA685-WW1 probe electronics) with values derived from a standard analyser (paramagnetic oxygen analyser corrected to wet conditions by using water concentration measured by FTIR) during a comparative measurement campaign. Regarding durability and long-term stability no aging effect could be observed during the evaluation. The signal characteristics at the end stayed unchanged compared to the ones for the unused probes. Particle deposit on the probe surface, observed both in the middle and at the end of the evaluation, had no noticeable effect on probe functioning. Comparing both probes, the broadband model ZFAS-U2 shows a slightly better accuracy, while the switching type model has advantages in price level and simplicity of implementation.

Evaluation of SenSic CO/O2 probe. In total three units of the SenSic CO/O_2 probe (first one was used in first half of the evaluation, other two in second half) were studied, again in the in total ca. 550 hour long-term stove evaluation.

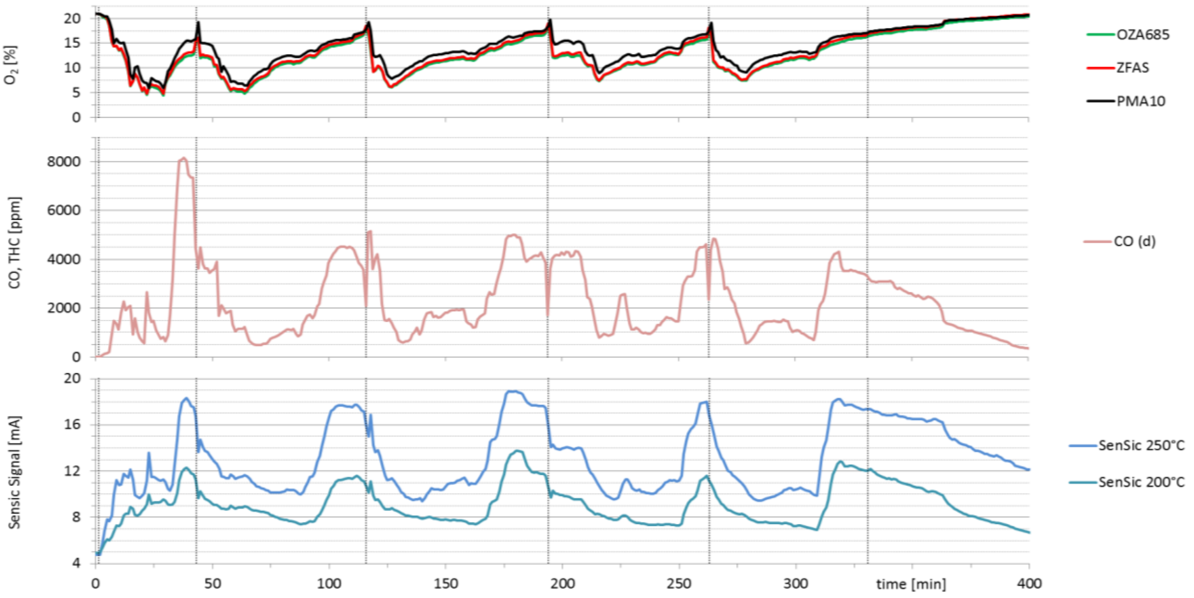


Figure 3: Comparison of SenSic probe signals with standard gas analyser at stove operation

In summary, the SenSic CO/O$_2$ probe enabled for a reliable detection of carbon monoxide gradients & overall ranges, thus allowing for example to identify a successful batch ignition or the start of charcoal burn-out. The oxygen concentration had a noticeable impact on the sensor signal which complicates the determination of precise carbon monoxide concentrations. Oxygen impact can be reduced for example by increasing the temperature on the sensor surface, but this will also affect the CO resolution capacity. On the other hand a combination of sensors operating at different temperatures could be used to improve CO concentration accuracy and also enable for an oxygen determination. Figure 3 shows an example for probe signals during stove operation (with the two probes operating at differing temperatures) in comparison with the dry oxygen and CO concentration derived from standard analysers and the O$_2$ signals from the lambda probes. Regarding long-term durability a noticeable signal drift has been observed during the first hours of sensor operation, which possibly could be managed automatically by the probe electronics. Despite the fact that there was no probe failure during operation, some problems with single sensor channels (two sensors on one probe) still occurred. It can be concluded that the probe electronics were found to be somewhat improvable, mainly regarding robustness, stability as well as miniaturization potential and price level.

Experimental Evaluation of Lamtec KS1D probe at BIOS

The combination probe KS1D (2 identical sensors) has been tested at an adapted 8 kW logwood chimney stove. In total 47 test runs with 273 batches have been performed. The overall operation time of the logwood chimney stove can be amounted to approx. 255 hours. One sensor has been tested for approx. 150 hours. Figure 4 shows the results of a test run with the combination probe at the logwood stove.

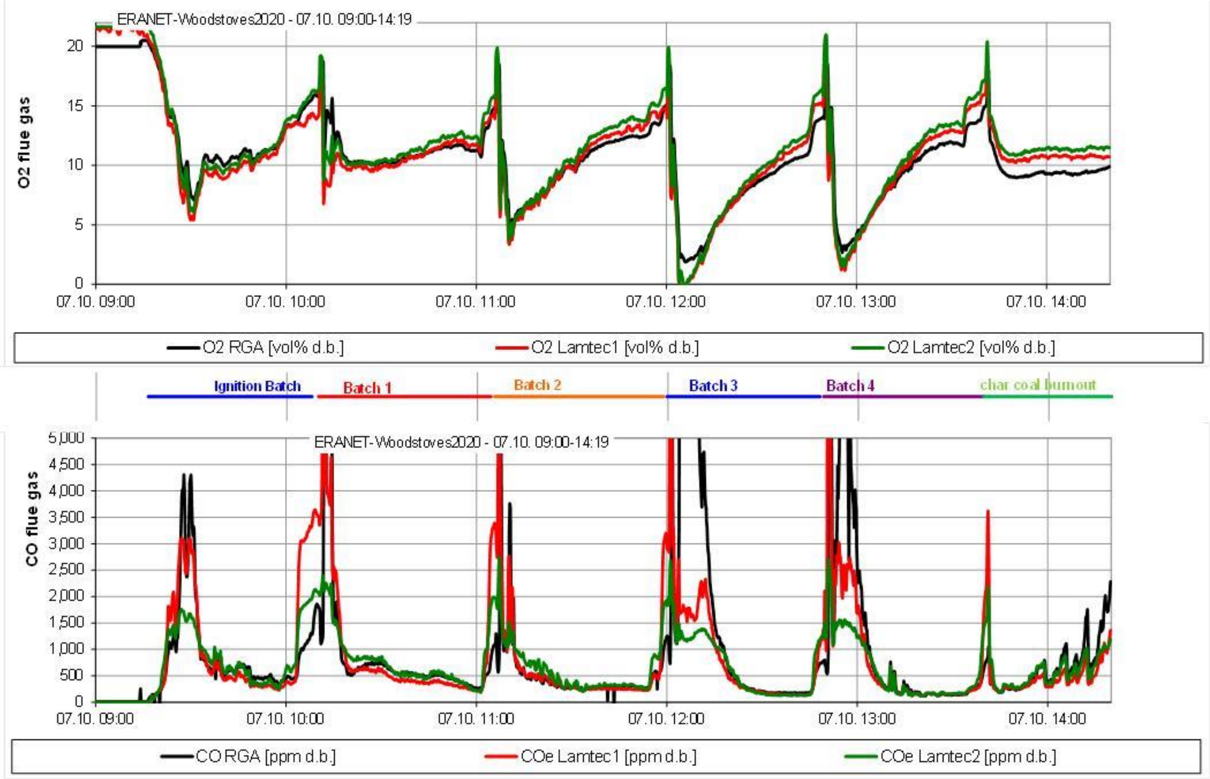


Figure 4: Results of a test run with Lamtec KS1D probe
Explanations: O_2 and CO related to dry flue gas; test run with low-emission logwood stove

The stove was operated at typical air supply conditions leading to average O_2 contents in the flue gas between 8 and 13 vol% (dry flue gas, mean values of batches). The flue gas temperature at the sensors was in the range of 150 to 170 °C (excluding the ignition batches). After an operation time of approx. 255 hours (150 hours for Sensor 1) no deposits have been observed on the sensors during inspection. The particulate emissions (TSP) in the flue gas downstream the stove can be amounted to 20 – 35 mg/MJ (35 – 100 mg/MJ for the ignition batches) according to measurements performed during selected test runs. Generally, the combination probe KS1D seems to be suitable for the implementation into an automated stove control concept based on the results achieved so far. The sensor can well reproduce the O_2 trend over the entire range of operation of a log wood stove. Regarding CO some deviations, especially at higher CO levels (> 1,000 ppmv), occurred. However, the CO trend is sufficiently well predicted. By now the costs of purchase (single unit: 600 – 1,000 € including converter) are too high. In future the converter may be integrated in the controlling plate of the automated control system of the stove and thereby the costs can be significantly reduced. Due to the currently high costs the combination probe KS1D is not recommended for the integration in the automatic control system of stoves.

Conclusions. A fast and reproducible response to gas concentrations changes was observed for all evaluated sensors. The reliable determination of the current combustion condition only on the basis of the sensor signals was possible at all times during the complete evaluation period, and it was shown that the probes withstand the exposure to high temperature, dust load and variable gas concentrations. Based on the evaluation, it can therefore be stated that an automated control system can rely on the signals provided by these sensors. Regarding economic considerations, both lambda probes should be an affordable choice for utilization in an automated control system, while the KS1D combination probe and the SenSic CO/O_2 probe including their electronics are seen as currently still too expensive for a broader use in the stove sector. More information on sensor screening & evaluation can be found in a separate report (see section 5).

1.2 Automated process control concepts

Several different systems of automated controls as well as retrofit systems for logwood stoves have been elaborated, implemented and tested. BIOS & RIKA have further developed, implemented and tested an automated control system based on temperature measurements in the combustion chamber and flaps for combustion air supply control. The system has been specially tailored to the stove developed and tested within WP 2 and WP 4. RISE & NIBE have further developed, implemented and tested an automated control system based on a combination of temperature and oxygen measurements and flaps for combustion air supply control. The system has been tested at an advanced wood stove. HWAM A/S and DTU Chemical Engineering have developed and tested a digital control system which is able to control three combustion air inlet valves separately. The control system was implemented on HWAM wood stoves and tested in laboratories and in private homes (field tests). TFZ and K+W have improved a retrofit control unit (with electrically driven combustion air flaps) for continuous adjustment of the air supply of the stove. The work performed is summarised in the following sections (1.3, 1.4, 1.5 and 1.6).

1.3 Testing results and technology-specific reports on temperature based stove control concept (BIOS/RIKA)

BIOS & RIKA have further developed, implemented and tested an automated control system for logwood stoves. The system has been specially tailored to the new stove developed and tested within WP 2 and WP 4.

The automated control system of RIKA is based on a temperature measurement in the combustion chamber and flaps for the combustion air supply control. The different combustion phases can be identified by temperature changes and since temperature sensors are the cheapest sensors available and also rather robust, they offer a suitable opportunity for stove control. The basic control strategy can be described as follows:

Ignition phase

- Mainly primary air and a low amount of window purge air is supplied in order to facilitate a quick ignition and rapid increase of the combustion chamber temperatures

Transition to main combustion phase

- As soon as the temperature in the combustion chamber exceeds a certain level the primary air damper is closed to avoid excessive burning rates.
- At the same time secondary air and window purge air flows are increased to maintain adequate combustion air supply.
- During the main combustion phase the secondary and window purge air flow should be kept rather constant. The distribution between these two flows depends on the furnace design (combustion chamber and air injection nozzle geometries) and should be experimentally optimised for a specific stove type.

Transition to charcoal burnout and charcoal burnout phase

- When the furnace temperature starts to drop below a certain value, the amount of secondary and window purge air should be reduced to keep the temperature at a reasonably high and nearly constant value until the end of the batch.
- Thereby, excess oxygen is kept low and too much cooling of the combustion chamber is prevented.
- As soon as the flames extinguish the CO and OGC emissions strongly increase. Thus, re-charging of fuel should be performed as soon as the flames extinguish.

The automated control has been integrated into the new Low-emission wood stove with integrated PCM heat exchanger of RIKA (see also WP2 and WP4). Then, test runs have been performed with the new stove in order to evaluate the performance of the automated control system. The test stand setup of BIOS is shown in Figure 5.

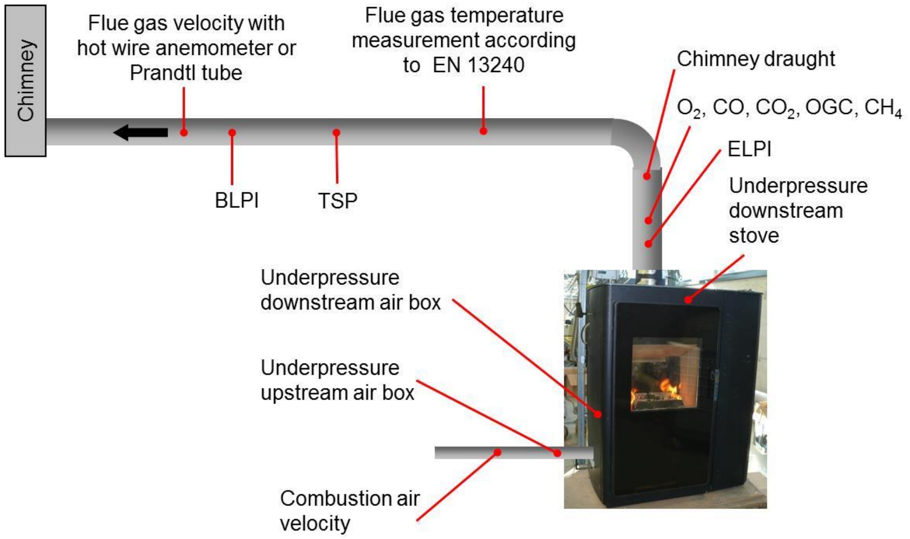


Figure 5: Test stand setup with flue gas measurements
Explanations: TSP ... Total suspended particulate matter; BLPI ... Berner-type low pressure impactor; ELPI ... Electrical low-pressure impactor

Test runs with and without automated control system were carried out in order to compare the results and to evaluate the influence of the automated control system on the combustion behaviour. Figure 6 shows the comparison of stove operation with manual and automated control. The controlled air supply shall reduce the emission peak at the beginning of the batch and shall keep the emissions during the main combustion and the charcoal burnout phase lower due to higher combustion chamber temperatures.

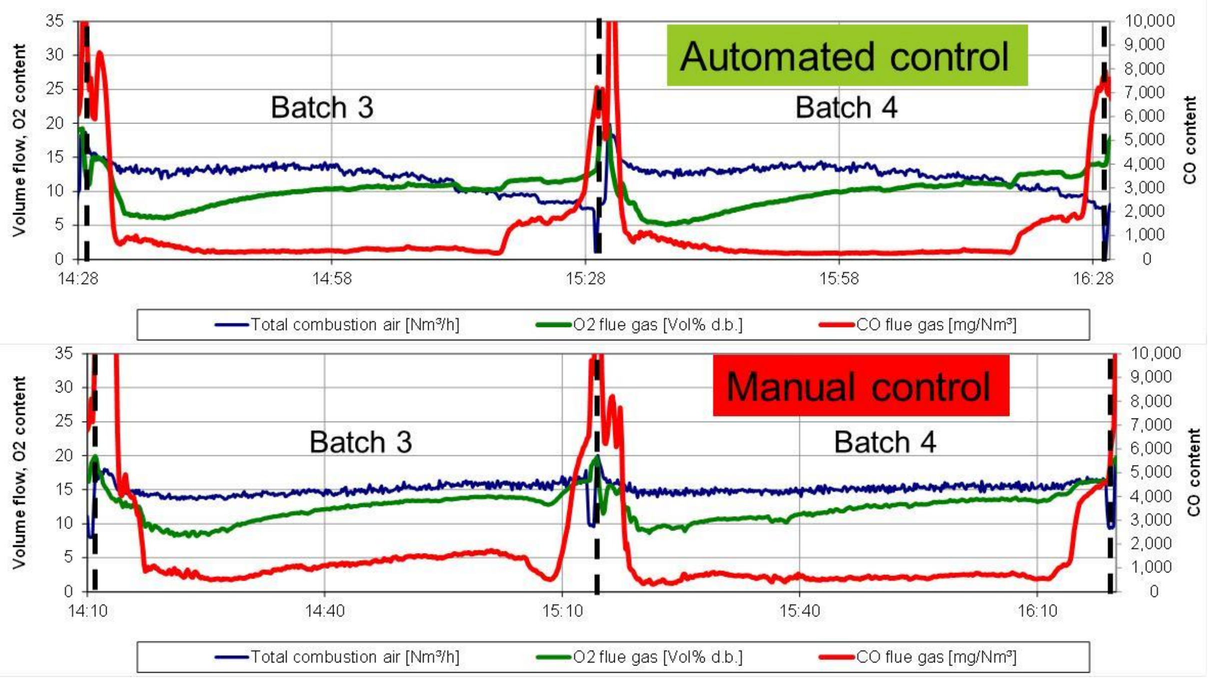


Figure 6: Results from test runs with the new stove applying automated and manual control systems
Explanations: O_2 related to dry flue gas; emissions related to dry flue gas and 13 vol.-% O_2

High furnace temperatures and consequently lower emissions could be reached within a shorter time during the ignition phase by a proper balancing of primary and window purge air. More stable O_2 concentrations in the flue gas, generally lower O_2-levels (relevant for a high thermal efficiency of the stove) as well as sufficiently high temperatures for improved burnout could be achieved during the main combustion phase as well as during the burnout phase by controlling the combustion air flow in dependence of the furnace temperature as well as temperature gradients; this resulted in lower gaseous as well as particulate emissions compared to manual control as shown in Figure 7.

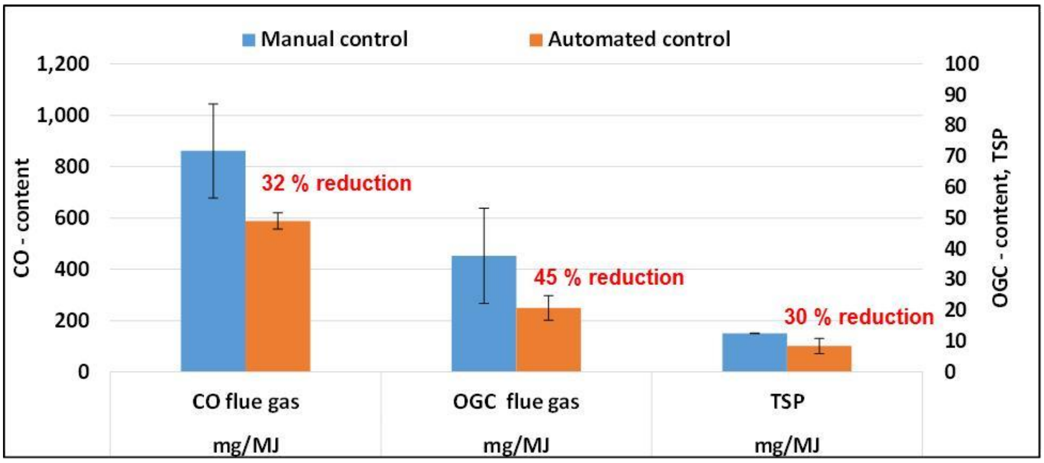


Figure 7: Emission reduction achieved by implementing an automated control system
Explanations: Mean values and standard deviations of averaged emissions over entire batches 3 to 5 (from closing the door until opening the door again for recharging) according to prEN 16510 / DIN EN 13240

By the implementation of the automated control the thermal efficiency could be increased (up to 2 % points) mainly due to lower O_2-levels in the flue gas as shown in Figure 8.

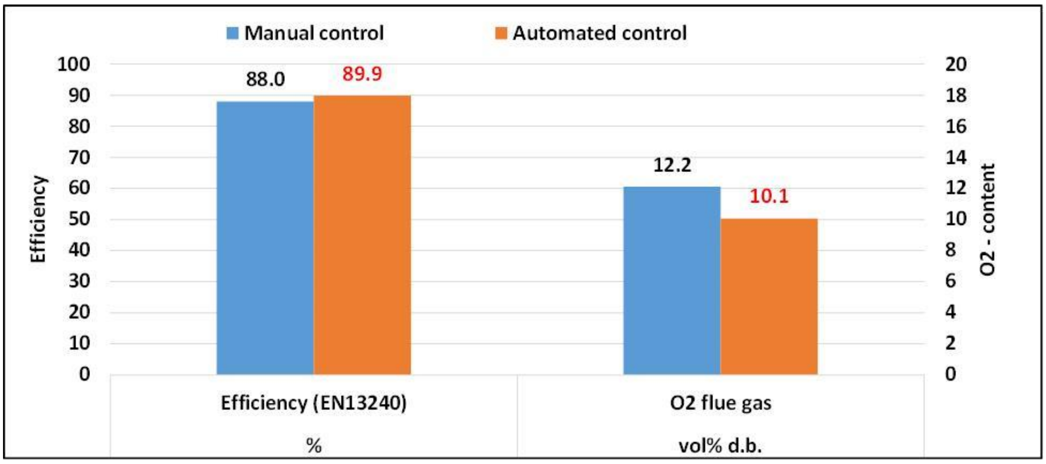


Figure 8: Efficiency increase achieved by implementing an automated control system
Explanations: Mean values of O_2 over entire batches 3 to 5 (from closing the door until opening the door again for re-charging); calculation of efficiency according to prEN 16510 / DIN EN 13240)

Conclusions. An integrated automated stove control system based on combustion air control in dependence of the combustion chamber temperature has been developed and proven as suitable concept for stoves to reduce emissions and to increase efficiency. Test run results show that a considerable reduction of the gaseous as well as the PM emissions and an increase of the thermal efficiency is possible by an appropriate automated control of the air supply of the stove.
It is of importance that the automatic control system is specifically adapted to the stove on which it is implemented. Therefore, an integrated solution is definitely preferable compared to an add-on solution, particularly if this add-on solution can only adjust the total combustion air without allowing any differentiated adjustment of primary, secondary and window purge air flow.

1.4 Testing results and technology-specific reports on flue gas sensor based stove control concept (Nibe/RISE)

The automated stove control concept is mainly based on flue gas sensors for temperature and oxygen (thermocouple & lambda probe). It uses the information from these sensors and an additional door switch to identify the current combustion phase by detecting operational events, as for example door opening, successful batch ignition or the start of the charcoal burn-out. With regard to the identified phase it adjusts settings for three combustion air dampers as a function of the measured oxygen & temperature in order to achieve optimal conditions for highly efficient combustion at low emissions. The three dampers regulate the combustion air through the grate (primary dampers), the window purge air (secondary dampers) and the air flow from rear wall nozzles (tertiary dampers). The basic control strategy for the main operational states can be described as follows:

Check ignition (Ignition phase). The aim is to ignite the wood and increase the temperature in the combustion chamber as quickly as possible to avoid unnecessary release of unburnt components. In order to achieve a high air flow the air dampers are opened when the check ignition signal is triggered. During ignition the oxygen content in the flue gas is reduced while temperature increases. When both signals reach a certain lower respectively upper value the primary damper is closed. This marks the transition to the next operation state.

Burning (main combustion phase). With primary damper closed the wood gasification rate is slowed down in order to avoid insufficient oxygen supply in the gas combustion zone. In the following the control adjusts secondary and tertiary dampers to keep temperature and oxygen in the flue gas within defined ranges. The secondary damper setting is thereby based on temperature and tertiary damper on oxygen content. In order to achieve a smooth combustion, rapid and too large changes in damper settings should be avoided. In the end of this phase, when less volatile matter will be released from the fuel and mainly charcoal remains, the oxygen signal will increase above the desired range despite having the corresponded dampers adjusted to its defined minimum position. This marks the end of this state and the transition to the next operation state.

Burnout (charcoal combustion). During this phase the control is based on oxygen signal and adjusts primary and secondary dampers accordingly in order to keep the oxygen level within a defined range. Enabling primary air accelerates charcoal burnout in the fire bed, thus generating heat to avoid a rapid drop in combustion chamber temperature. When the oxygen content rises above the desired range, despite that the dampers are at their final positions, the stove will trigger the signal for the next batch.

If the user follows this recharging signal the stove will switch back to check ignition, starting a new cycle. If the user refuses to recharge, the stove switches to shutdown operation state. At its end (when reaching the final levels for oxygen & temperature) the dampers are closed to minimize standing losses.

The control system is a further development of a previous concept that was using only oxygen signals to adjust two dampers, with the aim to obtain a more improved control system which has a wider tolerance to user interaction and can be more easily adapted to other stove models. For situations where a flue gas fan is necessary (e.g. insufficient draft due to installation limitations, weather conditions or secondary measures such as filters or catalysts) the integration of such a fan into the stove control concept is possible, either for intermittent operation for certain phases (as for example cold ignition or recharging) or for continuous draft dependant operation (using for example the existing additional pressure transmitter).

Laboratory tests and conclusions: Automated control concepts have been implemented and tested with different stove models. Several test runs have been carried out with these stoves to evaluate the performance under recommended conditions (mainly concerning wood mass, wood properties, log orientation, etc.) as well as deviations from these recommendations to simulate user interaction. Compared to manual operation at fixed dampers the stove performances consistently improved when using the automated control. Carbon monoxide and hydrocarbon emissions were significantly reduced, while the efficiency increases. The control system itself is also self-sustaining in terms of reacting on unforeseen combustion conditions. This means that real life stove operation will result in similar performance characteristics as achieved when testing at optimized laboratory conditions.
Regarding particles, a further decrease in PME could unfortunately not be obtained when comparing to the already quite low values from manual operation under recommended conditions. Any additional particle reduction would therefore require further design optimization or the integration of effective secondary measures.
A preferable control of the heat output is another challenge that has been identified. The heat output is largely based on the amount, size and moisture content of the wood and can only marginally be controlled by damper settings that will be adjusted for achieving optimal combustion conditions. And finally, since the integration of an automated control system will increase the end consumer price of the stove, the market potential remains limited if such appliances continually have to compete with simple and cheap stoves (which however still comply with current regulations).

1.5 Testing results and technology-specific reports on stove control based on combination of

temperature measurement and flue gas sensors (HWAM/ DTU)

The control system consists of an advanced software program based on the definition of different combustion phases, and it uses three process parameters: measured flue gas temperature, O_2-concentration in the flue gas, and room temperature. The basic control strategy for the main combustion phases can be described as follows:

Ignition phase:

- The secondary and primary air inlets are fully opened to achieve a fast ignition of the wood and thereby a fast increase of the temperature in the combustion chamber.

Combustion (flame) phase

- The primary air inlet is closed to stabilize the temperature and the secondary and – if available – the "tertiary air" (air flow from rear side air nozzles) are open to keep the temperature and the oxygen in the flue gas within defined ranges.

Charcoal burnout

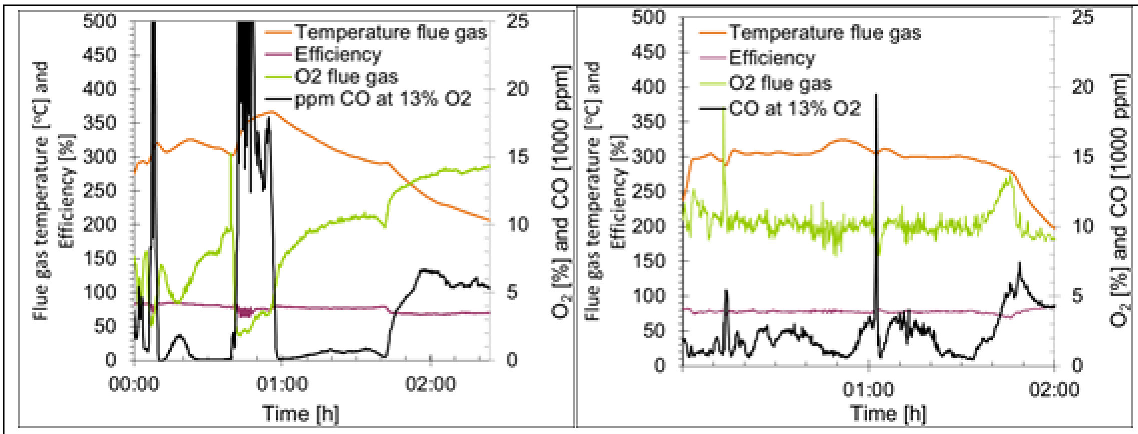
- The tertiary air is closed and the primary and secondary air inlets are opened to a level keeping the oxygen and the temperature level within defined ranges. When the temperature falls below a certain level, the stove signalizes the recharging for the next batch.

The measurement and optimization of the oxygen concentration avoid both, too high excess air ratios and under-stoichiometric combustion which may result in low thermal efficiency and in high pollutant emissions, respectively.

Field tests. The control system was tested on a number of wood stoves operated by ordinary wood stove owners to see the influence of private stove user practices on emissions and efficiency.
At each test site continuous measurements of O_2, CO_2, CO and flue gas temperatures were conducted with both, the existing stove and the new HWAM IHS stove (Intelligent Heat Systems) (Figure 9). For the same wood stove users the measuring period for each stove was one week. All the tested IHS wood stove models were equipped with a prototype of the automatic control system. The person handling the firing on the test site was instructed to use the stoves as usual, that means using the same kind of wood and firing in the same way; so no instructions were given to the private wood stove users on how to operate the IHS stoves with respect to firing etc.

Figure 9: Illustration of a test set-up in a private household.

An example of a typical situation is shown below (Figure 10) where the user for the manually controlled wood stove applies too little air during the flame phase and too much air during the char combustion.



a) b)

Figure 10: Field test measurements conducted with privately operated wood stoves with the user applying a manually controlled stove a) and an automatic HWAM IHS stove b) (two combustion cycles).

As seen from Figure 10 very constant flue gas temperatures, O_2 and CO concentrations were obtained when the user applied the HWAM IHS wood stove. Especially in the flame combustion phase, a significant reduction of the CO concentration was seen. For almost all the measurements at the six test sites significant improvement of the combustion process was observed resulting in higher thermal efficiency and lower CO emissions.

Laboratory tests. The research wood stove experimental set-up at DTU Chemical Engineering included a digitally controlled wood stove on a scale, a stack, a dilution tunnel for collecting particles on filters (Norwegian Standard), a counting device the particle numbers (SMPS), sampling sites for measurement of gaseous emissions (CO, VOC, O_2, CO_2, NO_x), as well as thermocouples to measure the temperatures in the combustion chamber and in the chimney.
Figure 11 shows typical examples of emission levels for CO, VOC, particles and temperatures in the combustion chamber.

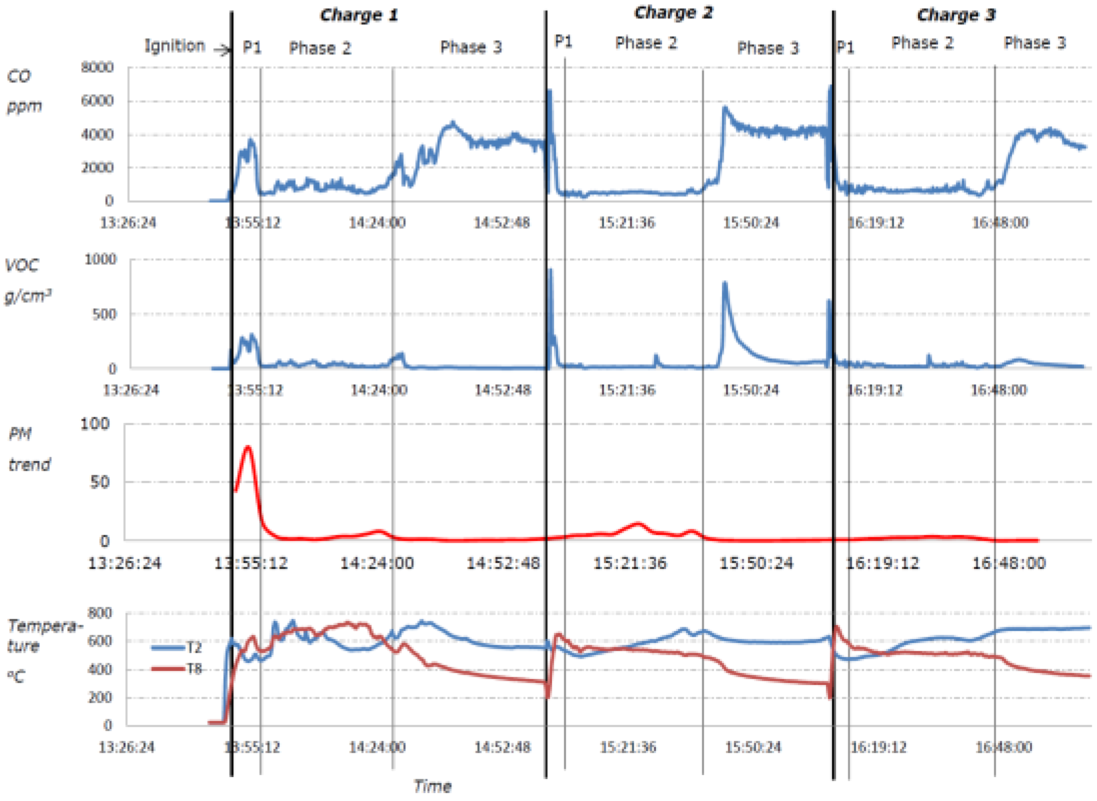


Figure 11: Emission and temperature trends for three batches illustrating the levels in the different combustion phases (Phase 1: ignition phase, Phase 2: flame phase, Phase 3 char phase). T2: Temperature in the fire just above the grate, T8: Temperature in upper part of the free board.

The highest particle emission was seen for the first batch when starting-up the cold stove. For the subsequent batches only relatively small increases of the emissions were observed in the ignition phase. Furthermore, the ignition phases are relatively short, especially for the second and third batches. During the flame combustion phases low and constant emissions of CO, VOC and particles are observed. In the char combustion phase an increase of CO emission was observed but the particle emission level was low in this phase.

Conclusions: The automatically controlled wood stove, HWAM IHS, was developed and launched on the market. The experimental results showed that the digital control of the combustion process ensures constant and optimal temperatures and overall oxygen concentrations in the combustion chamber, resulting in low PM and CO emissions well below current standards, and high efficiency. From field tests significant reduced emissions and high efficiency were seen for the IHS stoves compared to manually controlled stoves. Emission measurements at the research wood stove set-up at DTU Chemical Engineering showed a short increase in the emissions of CO, VOC and PM in the ignition phase, a small particle peak in in the flame phase, and an increase of CO emission in the char combustion phase due to decreasing temperature in freeboard. Almost no particle emissions were observed in the char combustion phase. The new control system ensures improved stove operation even when used by private wood stove owners - this improved performance has been verified by field tests in private homes.

1.6 Testing of several retrofit controllers and draught stabilizers (TFZ)

Several retrofit control units and one mechanically draught stabilizer were tested in WP4, Table 1 shows an overview. The three control systems which are regulating the combustion air inlet were tested under controlled draught conditions. The ATEC Florian and the draught stabilizer were tested under natural draught conditions, as described in chapter 4.1.

Table 1: Overview of the tested devices

Testing conditions:	Controlled draught			Natural draught	
Type:	TATAREK RT8OS-G-TD	Schmid SMR	K+W Compact	ATEC Florian	K+W draught stabilizer
Functioning principle	Thermocouple + electronical flap	Thermocouple + electronical flap	Thermocouple + electronical flap	Thermocouple + draught and velocity sensor + electronical flap + fan	Mechanical flap
Position of installing	Air supply socked	Air supply socked	Air supply socked	Between chimney wall and flue gas pipe	Between chimney wall and flue gas pipe or at chimney sole
Approx. end costumer price incl. accessories	276 €	1,100 €	1070 € (without Display)	300 €	300 €

In a pre-testing phase, the controller settings were adjusted to the stove during an optimisation routine (where possible); this was to allow the best possible stove performance with each particular controller.

Figure 12 shows the CO and the OGC emissions when using the particular retrofit controllers compared with the manual operation of the stove. The best stove performance regarding the gaseous emissions at controlled draught could be achieved by using the TATAREK controller, which reduces the CO emissions by 56 % and the OGC emissions by 38 %. The Schmid SMR controller causes quite similar CO and OGC reduction. The K+W compact reduced CO emissions by 40 % and OGC emissions by 15 %. For the three combustion air controllers tested when applying controlled draught conditions, the main influencing parameters to the gaseous emissions were the refilling signal given by the controller, and the throttling of oxygen at the end of the batch. The closer the refilling signal is given at flame extinction the lower are the CO and OGC emissions at the end of the batch.

At natural draught the ATEC Florian reduces CO emissions by 37 % and OGC emissions by 27 % while the draught stabilizer yields to higher gaseous emissions. This may be due to the fact that some stoves have lower CO and OGC emissions at higher draughts as shown in WP2.

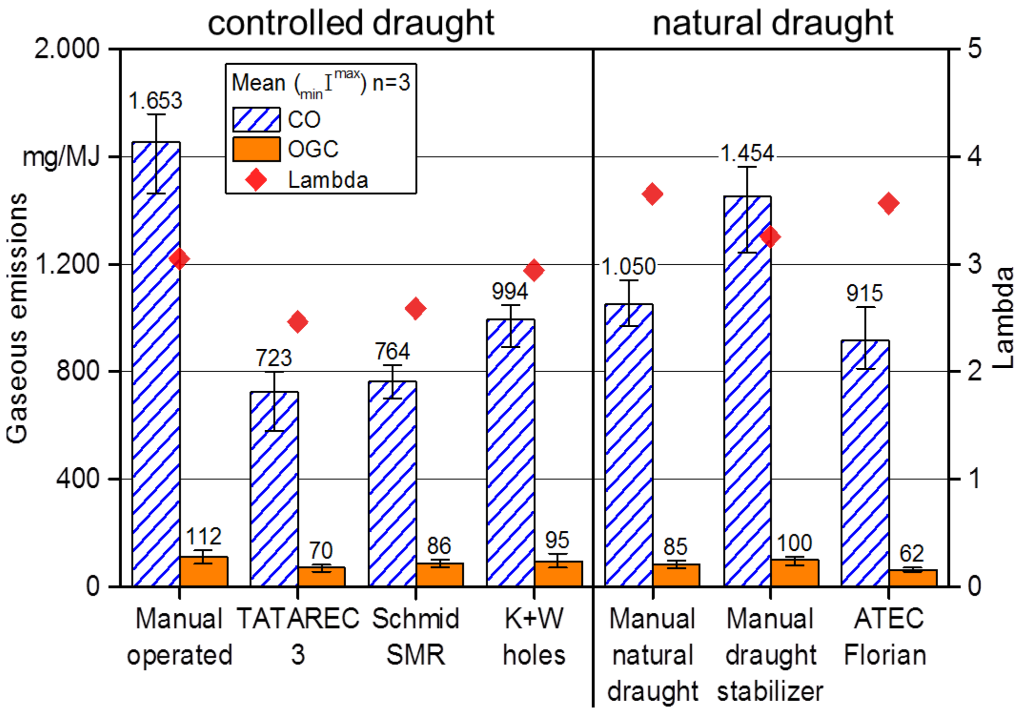


Figure 12: Comparison of the CO and OGC emissions using several retrofit semi-automatic controllers compared to completely manual log wood stove operation

Regarding the particle emissions measured (Figure 13) the manual operation seems to be the best case. But it should be stated, that by using the TATAREK or the K+W controller the particle emissions are in a similar range, considering the uncertainty of the particle measurement. Certainly the particle emissions can be more than twice as high if the controller doesn't allows enough adjustment possibilities for individual adaptation to the particular stove type. One reason for possibly higher particle emissions is a higher air supply during the beginning of each batch (when the automatic flap is fully open); this could result in higher furnace temperatures and thereby higher mass burning rates (especially Schmid SMR). At natural draught operation the ATEC Florian reduces the particle emissions by approx. 31 % while the draught stabilizer leads to 14 % higher particle emissions. In the case of the ATEC controller this may have been caused by the additional baffle in the flue gas duct (ATEC) which has presumably influenced the flow condition in the particular stove positively, leading to lower CO, OGC and PM emissions.

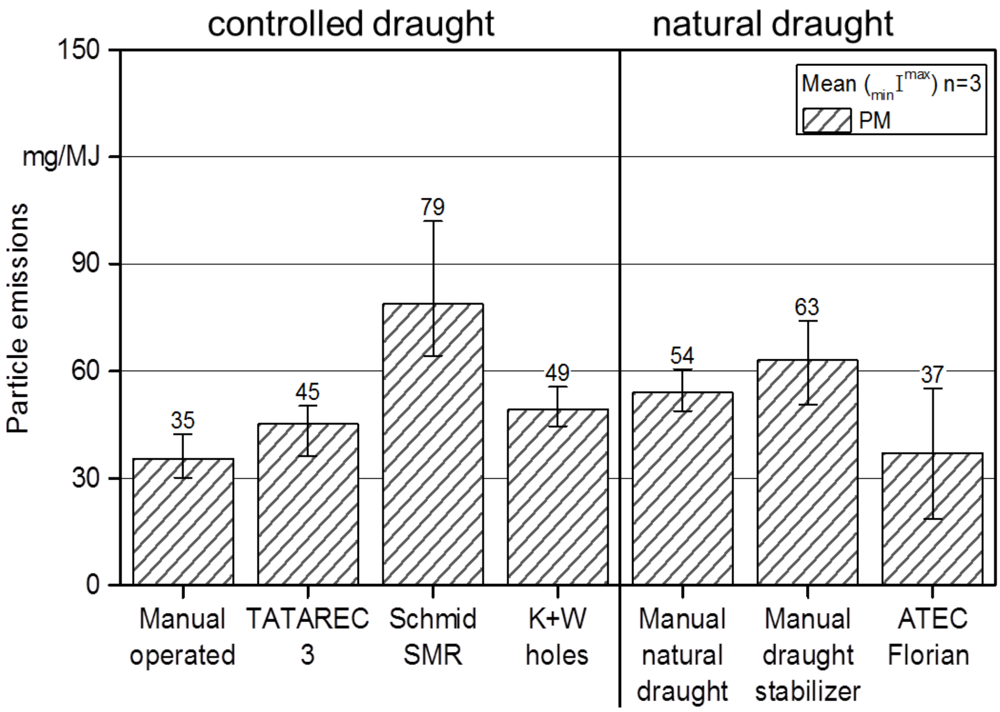


Figure 13: Comparison of particle emissions using several retrofit semi-automatic controllers compared to completely manual log wood stove operation

Figure 14 shows the efficiency impact using the selected retrofit controllers on the tested stove. At controlled draught the tested controllers increasing the efficiency by 1.5 to 4.6 %. The largest influencing parameters are the tightness of the air flap (q_cool) and the adaption of the air supply over the batch (q_a). It was also observed that the amount of charcoal that remains in the furnace after stove operation increases by using a controller; this effect is depending on the tightness of the air flap. These charcoal residues are claimed as losses in the common type testing standards. In future it might be meaningful to instruct the user in the stove manual to use these residues when starting the next stove operation. Then these losses from such residues could be ignored, which would lead to an efficiency gain of another 0.4 to 1.5 percentage-points, compared to a manual stove operation (without closing the flaps of the stove after heating).

At natural draught the efficiency is increased by about 6.2 % when using the ATEC Florian and by about 9.9 % when using the draught stabilizer. This is due to the efficiency losses at higher chimney draughts that are illustrated in WP2. The losses by charcoal residues are slightly higher than for the manually operated stove. But in contrast to the combustion air controlling systems there is less potential to avoid standing losses when using a flue-gas-integrated system as the ATEC Florian.

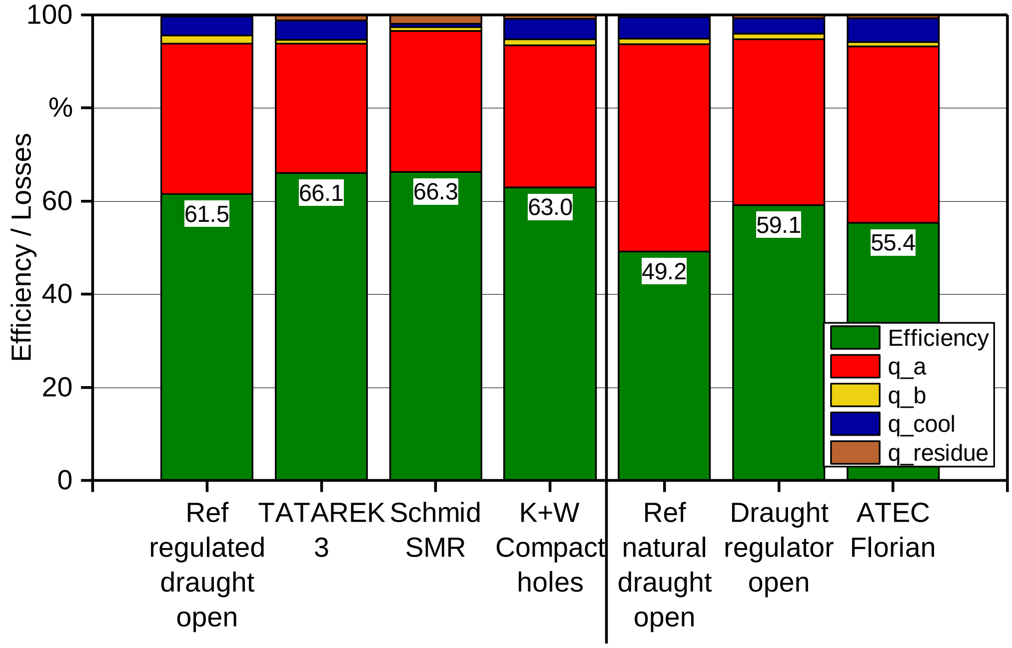


Figure 14: Comparison of efficiency using several retrofit controllers. Ref: reference case

The possible fuel savings by prevention of standing losses and efficiency increase when using a combustion air controller with an air tight flap is shown in Figure 15, which displays the example of the Schmid SMR. Considering a realistic number of 100 heating cycles annually, the price for the saved air dried beech wood by preventing standing losses and by creating the efficiency increase as reported above amounts to about 48 €/a. With an end costumer price of approximately 1,100 € the controller needs about 23 years of pay-off-period. To become economically interesting the price for a retrofit combustion air control unit should be around 250 € (i.e. 5 years pay-off-period).

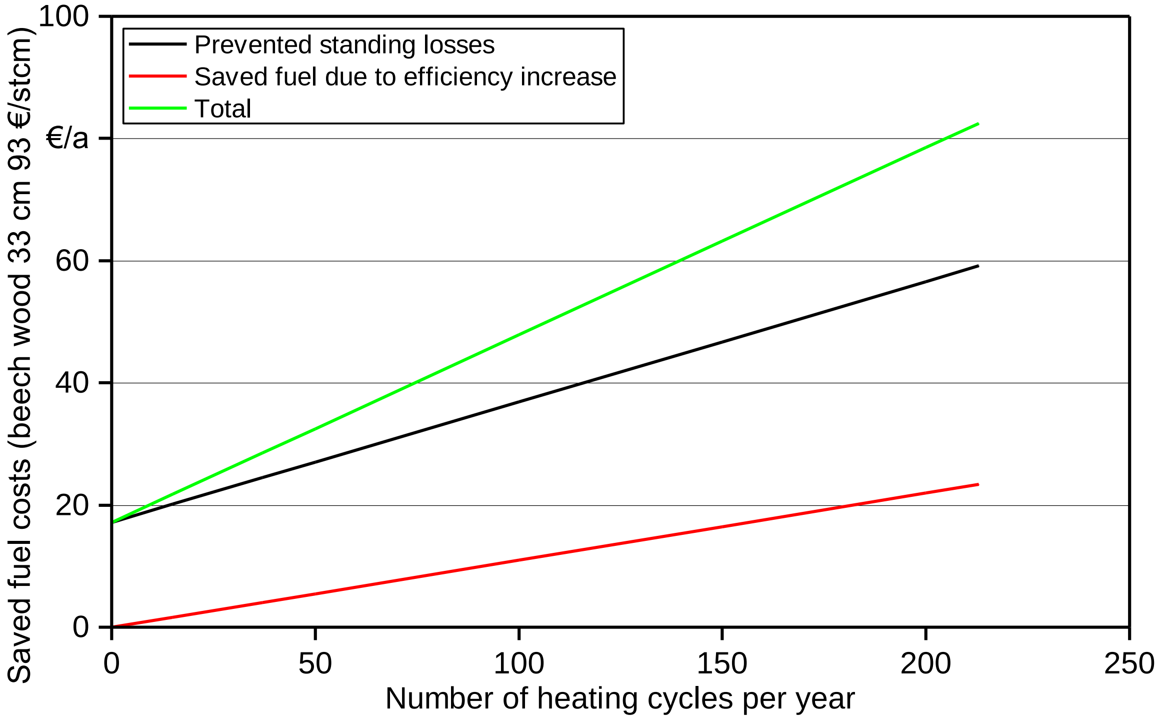


Figure 15: Possible fuel savings by prevention of standing losses and efficiency increase when using a combustion air controller with a completely air tight flap (Schmid SMR). stacked cubic meters of logs. Heating cycle: sequence of several batches in a heating operation

In conclusion it can be stated that combustion air controllers can significantly reduce gaseous emissions from log wood stoves. For PM emissions, however, it was shown that if the adaption of the controller's settings to the individual stove type is performed correctly no improvements compared to a professional manual stove operation can be achieved. But in practise this adaption of the control settings can only be performed by the stove manufacturer or by a specifically trained service person. Without such adaption the particle emissions could be significantly increased when using the retrofit controller (Schmid SMR). Chances for improvements may be given by delaying the refilling signal, but this could counteract with the gaseous emissions which would then be slightly increased. When the controller is installed downstream in the flue gas duct (ATEC) it can reduce both, gaseous and particle emissions. The also tested draught stabilizer (K+W) leads to higher emissions for this particular stove.

The biggest advantages of retrofit controllers may be seen in the prevention of operating failures by the user (e.g. wrong moment of recharging) and the prevention of heating and standing losses. Regarding the standing losses only combustion air controllers have the full potential of minimization; a draught control device in the flue gas duct would not be as effective as it shall never be closed completely.

It is recommended to construct retrofit controllers with fully air tight closure of the flap. The controllers should only be sold for dedicated stoves where the respective parameters were already set. An end costumer price of approx. 250 € should be the target.

1.7 Development of a new temperature based retrofit control concept (K+W)

Pre-test results in chapter 1.6 had shown that the correct adjustment of a retrofit controller is highly important. Correct parameter settings can reduce emissions while wrong adjustments can also increase emissions compared to manual operation. Such adjustment is time consuming and error prone, therefore retrofit controllers with the capability of automatic adjustment to the stove would have clear advantages.

Therefore an adaptive and flexible control concept was developed and implemented on a LabVIEW based prototype. This prototype was tested on four different stove types. Both, efficiency and emissions were evaluated according to the method described in chapter 4.1.

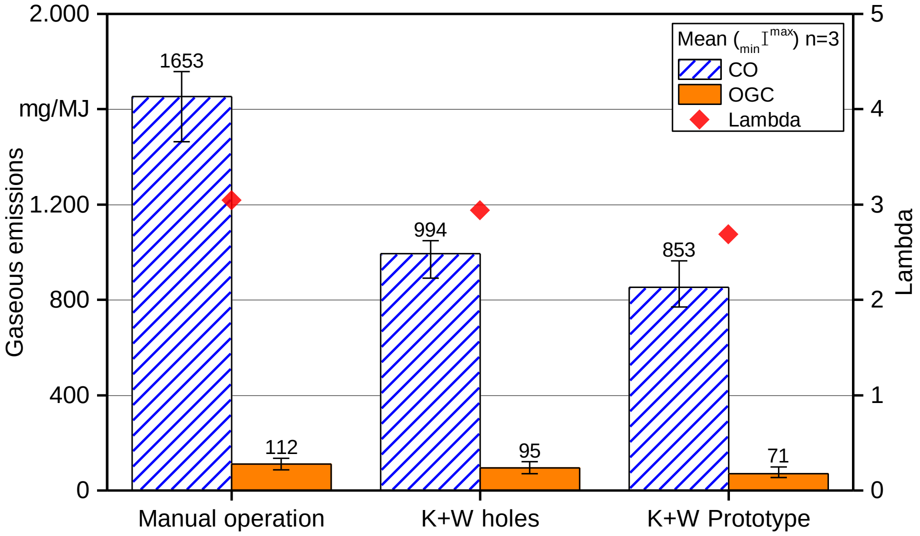


Figure 16: Comparison of auto adaptive (K+W prototype) and standard controller in terms of gaseous emissions. K+ W holes: an automatic air flap with punched holes (9 cm²) was applied to avoid full closure.

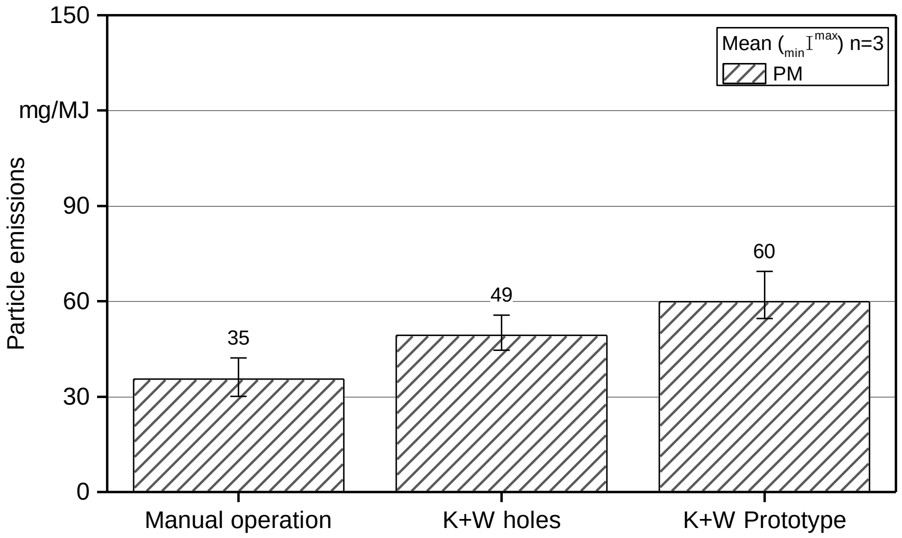


Figure 17: Comparison of auto adaptive (K+W prototype) and standard controller in terms of gaseous- and particle emissions. K+ W holes: an automatic air flap with punched holes (9 cm²) was applied to avoid full closure.

Figure 16 and Figure 17 are comparing the auto adaptive prototype with the K+W standard controller and manual operation. Gaseous emissions could be reduced, but particulate matter emissions were increased.

As described in chapter 1.6 timing of the refilling signal can optimise the gaseous emissions but has also an impact on the PM emissions. This interrelationship is not completely understood but it seems that the refilling time is an important point for reducing PM emissions to a level which is close to manual operation.

The efficiency (shown in Figure 18) was increased about 1 % compared to the K+W standard controller and almost 3 % compared to reference by manual operation.

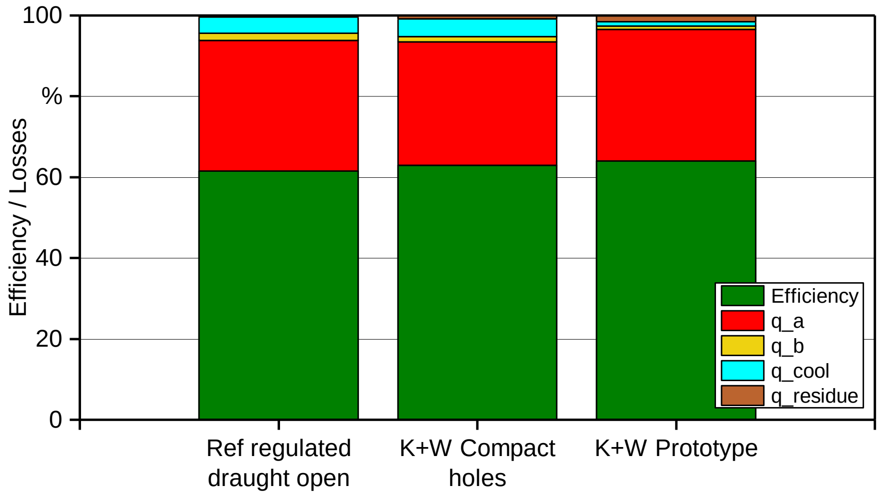


Figure 18: Comparison of auto adaptive (K+W prototype) and standard controller (K+W) in terms of efficiency.

In summary the developed self-adapting concept shows that it is possible to operate the tested stoves at the same emission level as with the K+W standard concept. Optimizing potential is also given and it is required to test the concept on a bigger number of different stoves.

2 WP 2: Measures for emission reduction

To meet the climate targets, CO_2-neutral residential heating by biomass combustion is a meaningful option. But to face the justified increasingly stricter emission limits biomass combustion plants and stoves have to prove their future right to exist by reducing the gaseous and especially the particle emissions drastically compared to the state of the art. WP 2 deals with the question how far the emissions of log wood stoves can be reduced by primary measures such as CFD based optimization of insulation, combustion chamber geometry and air distribution (section 2.1), and by secondary measures such as implementation of oxidation catalysts (section 2.2, 2.3) or foam ceramic filters (section 2.4).

2.1 Low emission high efficiency stove concept (BIOS)

Based on a new stove concept of RIKA a basic design for the new Low-emission wood stove has been developed. Options and constraints for the integration of a heat storage system based on PCM (see section 3.1) have been considered as well. An appropriate insulation of the main and the post combustion chamber is of great importance for an almost complete burnout of the flue gas. Moreover, an efficient mixing of the flue gases with the combustion air and the application of air staging are of relevance in terms of low emissions. Finally, a PCM heat exchanger to maximise the efficiency has been implemented into the stove concept. A scheme of the concept for the new Low-emission and high efficiency stove with integrated PCM heat exchanger is shown in Figure 19.

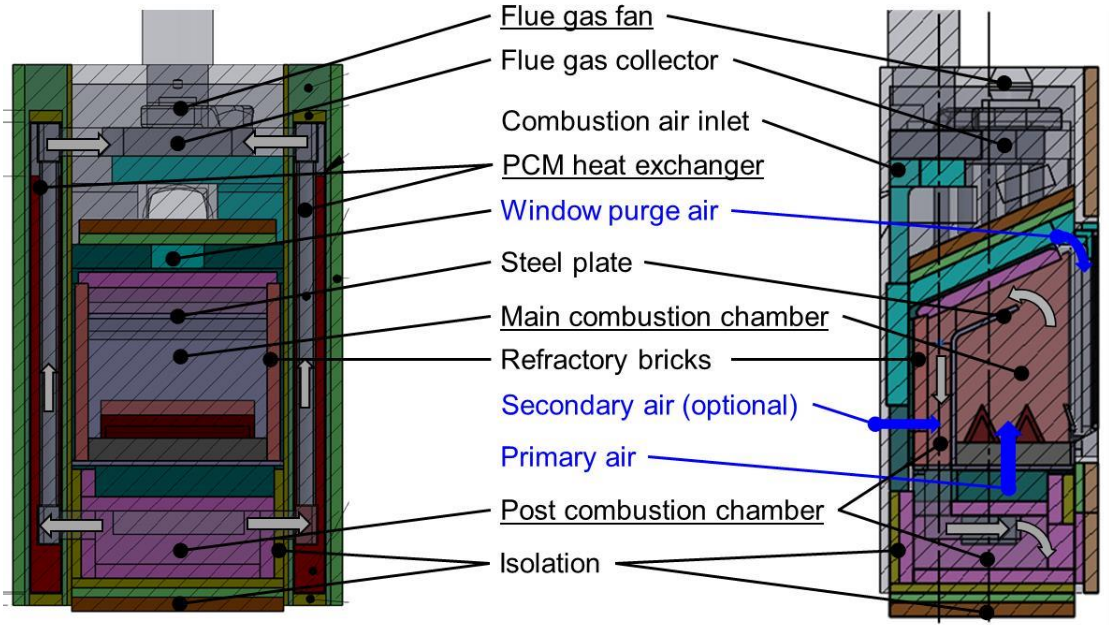


Figure 19: Scheme of the basic concept of the new Low-emission and high efficiency stove with integrated PCM heat exchanger

Explanations: The new stove concept is protected by a patent.

In a next step the geometries of the main combustion chamber and the post combustion chamber as well as the air staging strategy (air distribution between different combustion air flows) were evaluated by means of CFD simulations performed by BIOS. For the simulations an innovative CFD based model for logwood fired stoves, developed by BIOS, has been applied [1]. For the CFD simulations the new low emission and high efficiency stove concept and the PCM heat exchanger have been considered. The simulations are related to the point of a batch where quasi-steady state is achieved (mid of the main combustion phase). In Figure 20 and Figure 21 relevant results of the CFD simulations performed are presented.

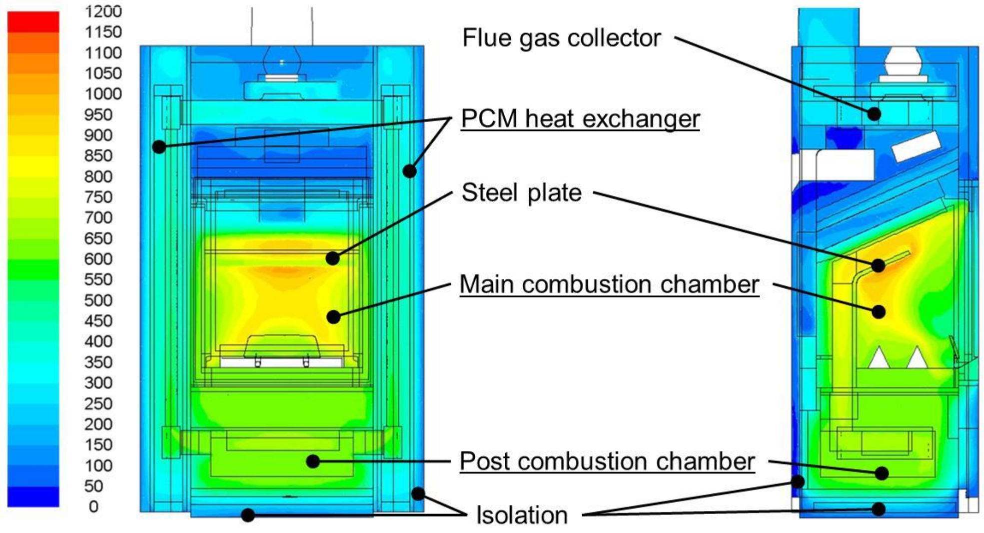


Figure 20: Results from CFD simulations - iso-surfaces of air, flue gas and stove temperatures [°C]

Due to the good isolation of the stove high flue gas temperatures can be achieved in the main and in the post combustion chamber. Figure 21 shows the predicted CO and O_2 concentrations in the flue gas.

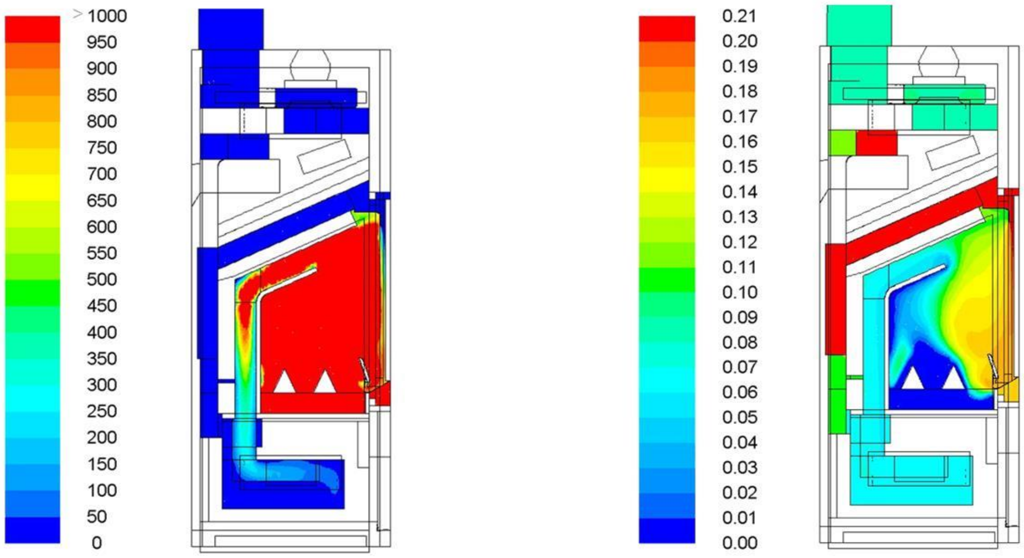


Figure 21: Results from CFD simulations - iso-surfaces of CO concentrations [ppmv] and O_2 concentrations [m³ O_2/ m³ flue gas w.b.] in the flue gas

Air staging and window flushing have been optimized to ensure a clean window and low O_2 contents in the flue gas. The CFD simulations show a good mixing of the flue gas with the combustion air indicated by even distributions of O_2 and CO at the outlet of the post combustion chamber (absence of flue gas streaks). Due to the high temperatures in the combustion chambers and the efficient mixing of the flue gas with the combustion air a very high gas phase burnout quality can be achieved, indicated by very low CO emissions. The optimised positioning and improved insulation of the PCM heat exchanger enable a complete melting of the PCM and thus an efficient heat storage.

The flue gas temperature (according to EN 13240) downstream the stove can be up to 210 °C, resulting in an efficiency of 87 %. This value refers to the steady state operation, in which the efficiency reaches its minimum. At the beginning of a loading cycle (start-up of the stove) the efficiency is significantly higher (> 90 %). Under consideration of the entire loading cycle over 5 batches an efficiency of around 90 % is expected.

Based on the development work a prototype of the stove with integrated PCM heat exchanger has been constructed (see Figure 22).

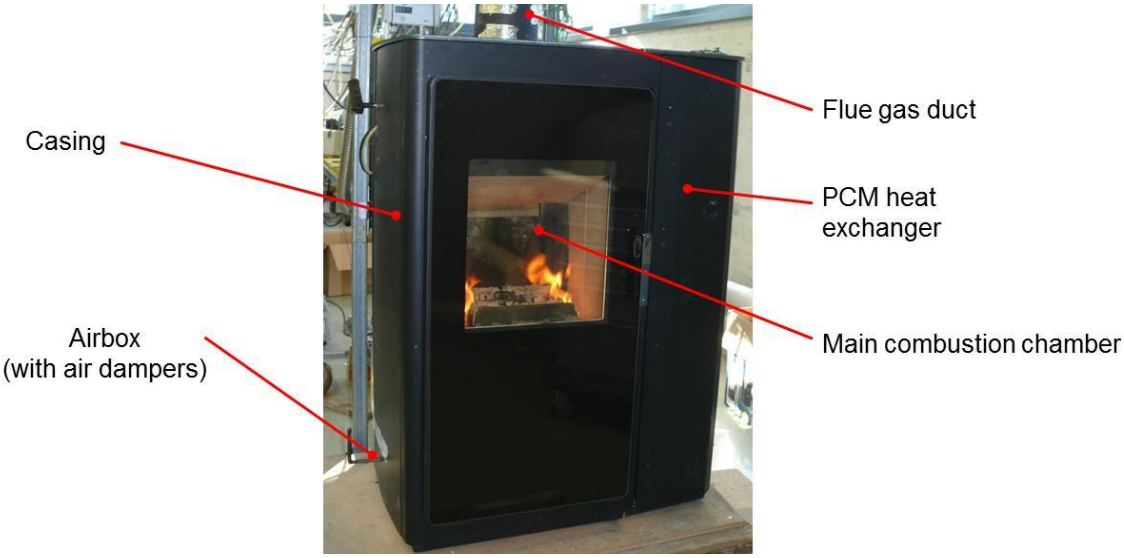


Figure 22: Picture of the prototype of the new Low-emission and high efficiency stove with integrated PCM heat exchanger

Comprehensive test runs with the new Low-emission and high efficiency stove with manual control and with automated control have been performed in order to evaluate the performance of the stove in terms of emissions and to evaluate of the PCM heat exchanger. Based on the test runs the new stove technology has been further developed and stepwise optimised.
The test run series have been performed according to the methodology defined by the project consortium as well as test runs including 1 ignition batch, 4 batches of full load and 1 charcoal burnout batch. The test stand setup applied is shown in Figure 5. In Figure 23 and Figure 24 results from a test run with the new stove with automated control are presented.

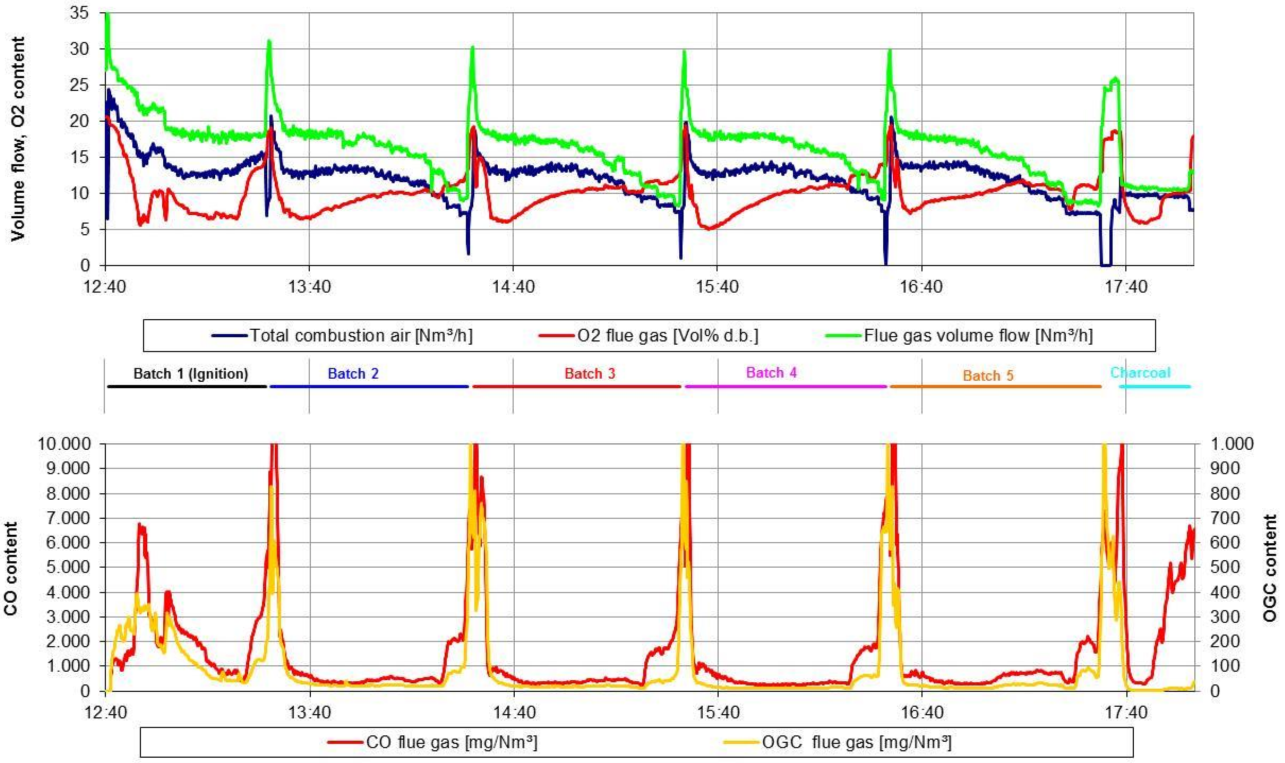


Figure 23: Results from a test run with the new stove with automated control – O_2, air and flue gas flows as well as CO and OGC emissions
Explanations: O_2 related to dry flue gas; emissions related to dry flue gas and 13 vol% O_2

The new stove shows a stable operation behaviour, and very low emission levels can be achieved. It was possible to operate the stove at typical air supply conditions leading to low average O_2 contents in the flue gas over a whole batch of between 10.7 and 12.8 vol.-% (dry flue gas, including the ignition batches).

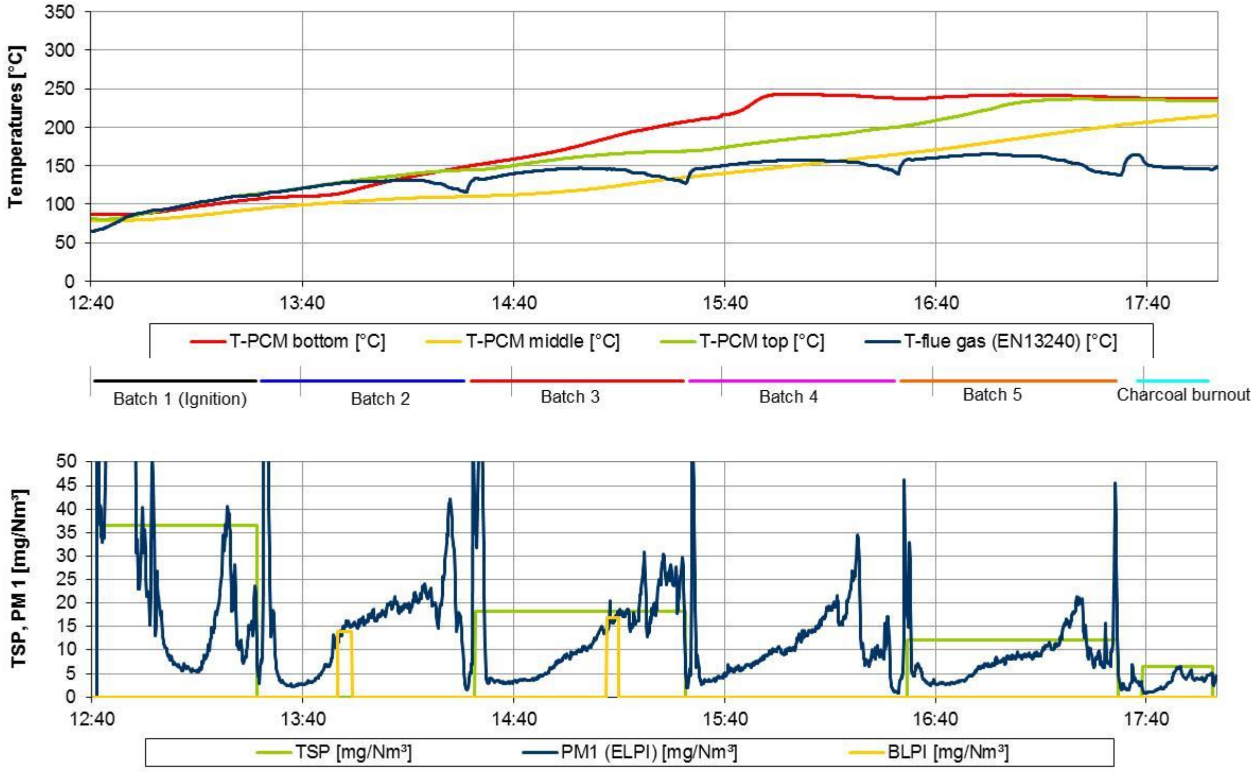


Figure 24: Results from a test run with the new stove with automated control – temperatures as well as PM emissions

Explanations: emissions related to dry flue gas and 13 vol.-% O_2; TSP … Total suspended particles; BLPI ... PM_1 emissions measured by Berner-type low pressure impactor; PM_1 (ELPI) ... PM_1 emissions measured by electrical low-pressure impactor

Due to the high temperatures in the combustion chambers and the efficient mixing of the flue gas with the combustion air a very good gas phase burnout quality can be achieved, indicated by very low CO and OGC emissions during the main combustion phase, and only short emission peaks at the start and the end of the batch occur. The CO und OGC emissions of the stove are well below the relevant emission limits (see Figure 25). In general, compared to state-of-the-art wood log stoves very low TSP as well as PM_1 emissions can be achieved. In this respect the high temperatures in the well isolated combustion chambers reduce soot formation.

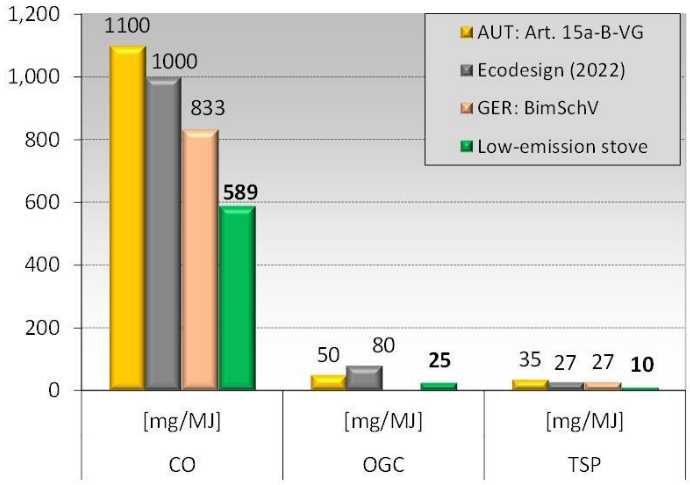


Figure 25: Emissions in comparison to relevant limits for full load operation
Explanations: mean values of averaged emissions over entire batches 3 to 5 (from closing the door until opening the door again for recharging) according to prEN 16510 / DIN EN 13240; emission limits shown according to the respective legislation in Austria and Germany (status 07/2017) as well as according to the planed EU Ecodesign directive which shall get in force in 2022

As shown in Figure 24 the flue gas temperature increased continuously over the test run and the maximum flue gas temperature (according to EN 13240) downstream the stove was up to 170 °C high (full load operation). According to the calculations performed an efficiency of over 92 % could be reached over the whole test cycle (see Table 2). The high efficiency can be achieved due to the integration of the PCM heat storage unit. The achievable thermal efficiency of the new stove technology is considerably higher than in state-of-the-art chimney stoves (on average 82 %).
The PCM heat storage unit is loaded during the operation of the stove. The hot flue gas passes through the PCM heat storage (heat exchanger), sensible heat is transferred to the PCM and the PCM temperature increases continuously. As soon as the PCM starts to melt, also the latent heat can be stored in addition to the sensible heat. Table 2 shows the energy balance of a typical loading cycle of a wood stove with integrated heat storage unit based on PCM (5 batches at nominal load including the ignition batch and 1 charcoal burnout batch):

- Up to 44 % of the total fuel power input and more than 50 % related to the useful heat can be stored in the stove and the PCM heat storage unit, which represents a very attractive value.
- The flue gas losses are low due to the efficient heat storage of the PCM – an efficiency of over 92 % (according to DIN EN 13240) can be reached for the entire loading cycle.

Table 2: Energy balance for the loading cycle of a wood stove with integrated heat storage unit based on PCM.
Explanations: it has been assumed that the entire PCM is molten because the mean temperature of the PCM at the end of the test run was at the melting point; thermal output (through radiation and convection) calculated based on measurements and results of CFD simulations performed.

Energy balance			
	kW	**kWh**	**%**
(1) Fuel power input	10.6	53.5	100 %
(2) Energy storage char coal	1.2	5.9	11 %
(3) Thermal output	3.9	19.9	37.1 %
(4) Energy storage stove	2.5	12.5	23.4 %
(5) Energy storage PCM heat exchanger	2.2	11.0	20.5 %
(6) Heat losses flue gas	0.7	3.7	6.9 %
Total energy storage (stove (4) + PCM (5))		**23.53**	**44 %**
Thermal efficiency (according to EN13240)		92.6	
Duration of test run		5.07 h	

Figure 26 shows a typical unloading cycle (natural convection only) of a wood stove with integrated heat storage unit based on PCM. The air flaps of the stove have been closed at the end of stove operation. During the unloading cycle the stove cools down rather quickly, but the PCM heat exchanger only slowly releases the heat stored, this is due to its improved isolation. After 9 h (i.e. overnight) up to 26 % of the stored energy in total are still available in the stove and in the PCM heat exchanger. The heat release from the stove is reduced and gets discharged over a longer period of time which is of advantage for the comfort of living. By controlling the convective air flow through the heat storage unit the period of heat release can also be influenced.

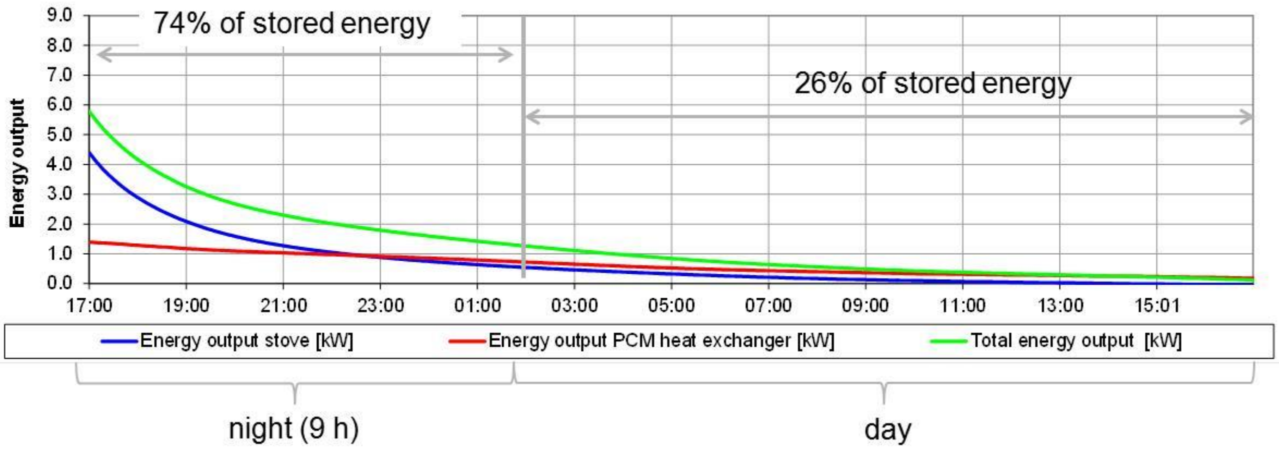


Figure 26: Unloading cycle of a wood stove with integrated heat storage unit based on PCM by natural convection

Explanations: air flaps have been closed at the end of the test run; calculation performed based on energy balances and measurements of surface temperatures during unloading

Conclusions. With the new stove concept with integrated PCM heat exchanger, a renewable CO_2-neutral room heating technology which shows low emissions and significantly increased efficiencies (> 90 %) has been developed. The gaseous and especially the particulate emissions of the new stove are on a very low level compared to state-of-the-art chimney stoves. The integrated PCM heat exchanger developed shows a suitably high heat storage capacity, a compact design and contributes to a better room climate due to its slow heat release. The final design of the new technology is currently ongoing. The market introduction of the new stove technology with integrated PCM heat exchanger is expected for 2018.

References

[1] BENESCH C., BLANK M., SCHARLER R., KOESSL M., OBERNBERGER I., 2013: Transient CFD Simulation of Wood Log Stoves with Heat Storage Devices. In: Proc. of the 21st European Biomass Conference and Exhibition, June 2013, Copenhagen, Denmark, ISBN 978-88-89407-53-0 (ISSN 2282-5819), pp. 578-584, (paper DOI 10.5071/21stEUBCE2013-2CO.7.1), ETA-Florence Renewable Energies (Ed.), Florence, Italy

2.2 Concepts for the optimised implementation of a high temperature catalyst into a low emission stove (BIOS)

Secondary measures like oxidation catalysts are already applied for emission reduction of wood stoves. As these catalysts are usually installed in the flue gas duct downstream the stove the emission reduction potential is limited due to:

- The comparably low temperatures at stove outlet
- The expected slow heat-up of the catalyst at this position.
- Almost no emission reduction during start-up where typically the highest emissions occur.

The main advantages of a catalyst implementation in the stove compared to an installation at stove outlet are:

- Light-off temperature can be reached in short time
- High operation temperatures of the catalysts may support tar and soot reduction
- At high operation temperatures a better VOC reduction is expected (since the VOCs are long-chain compounds and methane)

Based on this approach different high temperature catalysts have been integrated into a low-emission stove concept at different positions and their basic suitability has been evaluated.

Materials and method. As a first step catalysts available on the market and the experiences of test runs already performed have been carefully assessed. Based on the evaluation performed the two following different types of high temperature catalysts have been selected and investigated:

- Three different metal based honeycomb catalysts (active metals: Pt, Pd)
- Catalytically coated foam ceramics (active metal: Pt)

The catalysts applied have been tested at different positions of a specially adapted low emission logwood chimney stove with 2 flue gas pathways downstream the post combustion chamber (see Figure 27). The two flue gas pathways allow for the implementation of a catalyst and of a dummy (substrate without washcoat and catalytic coating), and it enables parallel measurements downstream of both elements. The metal based honeycomb catalysts have been installed at the outlet of the post combustion chamber (mounting position I). The foam ceramics with and without catalyst have been installed at the outlet of the main combustion chamber (mounting position II).

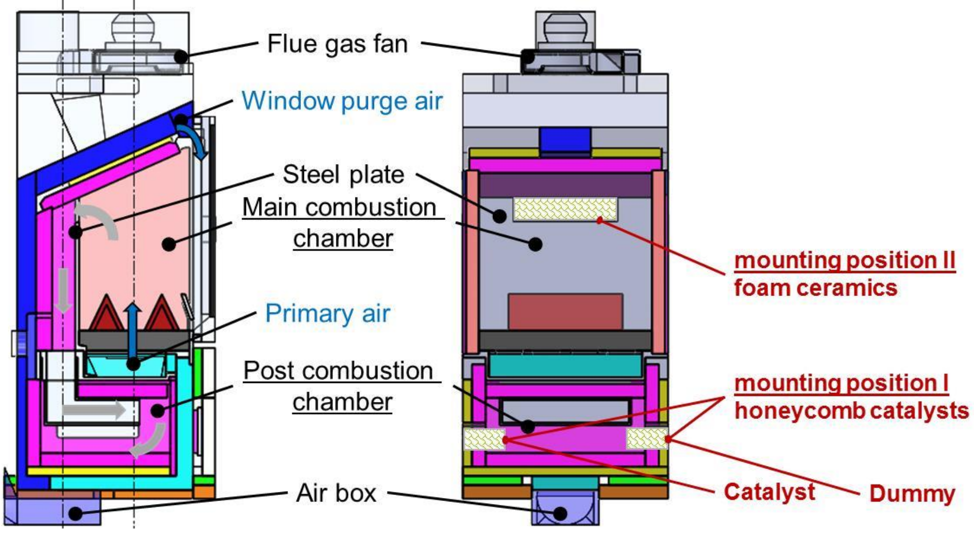


Figure 27: Schemes of the Low-emission wood stove used for catalyst testing

Long-term (2 or 3 weeks) operation of the stove with each catalyst including dedicated testing campaigns with emission measurements have been performed according to the test protocol commonly developed from all partners in the project (see section 4.1).

Results of long-term testing of honeycomb catalysts (mounting position I). Three metal based catalysts with different material properties and different active metal mixtures have been tested (see Table 3). The evaluation of the stove operation data showed, that all test runs have been performed under well comparable and representative combustion conditions. The catalysts showed only a negligible effect on the PM emissions and no effect on the efficiency of the stove.

Table 3: Overview over the honeycomb catalyst tested
Explanations: 1) Cells per square inch (1 CPSI ~ 645 mm²); 2) Temperature that marks start of reactions

No	**1**	**2**	**3**
Name	EnviCat®2520	Tailor-made catalyst I	Tailor-made catalyst II
Supplier	Clariant AG (DE)		
Substrate	metal	metal	metal
Structure	honeycomb	honeycomb	honeycomb
CPSI 1)	50	50	50
Dimension (HxWxL)	32 x 160 x 50 mm	30 x 160 x 50 mm	30 x 160 x 50 mm
Washcoat	Al_2O_3		
Active metal	**Pt, Pb**	**Pt**	**Pt, Pd**

Light-off temperature 2)	200°C	not defined yet since the catalysts are prototypes	not defined yet since the catalysts are prototypes
Max. operation temp	650°C	650°C	650°C

Catalyst 1 and Catalyst 3 showed about the same initial pressure drop (<10 Pa) while the initial pressure drop of Catalyst 2 was higher (13.1 Pa, in average for full load operation on day 1). For all 3 catalysts the pressure drop increased with operation time. The increase of the pressure drop could be correlated with the optically determined degree of fly ash deposit build-up on the catalysts inlet surface. Manual cleaning decreased the pressure drop again. For catalyst 1 not all deposits could be removed (the initial pressure drop was not reached again after cleaning). For catalyst 2 and 3 a complete removal of the ash deposits was possible and thus the initial pressure drop could be reached after cleaning.

All 3 catalysts showed high CO emission reduction efficiencies during the first day of operation. Catalyst 1 was with about 94 % (at full load) slightly more efficient than the other two catalysts (about 90 %). The emission reduction efficiency considerably decreased for all three catalysts over time, and cleaning respectively purging with hot air (regeneration) showed no positive effect as shown for catalyst 2 in Figure 28. The CO reduction efficiency at the end of the testing periods decreased to 50 % for catalyst 1, to 60 % for catalyst 2 and to 40 % for catalyst 3 respectively.

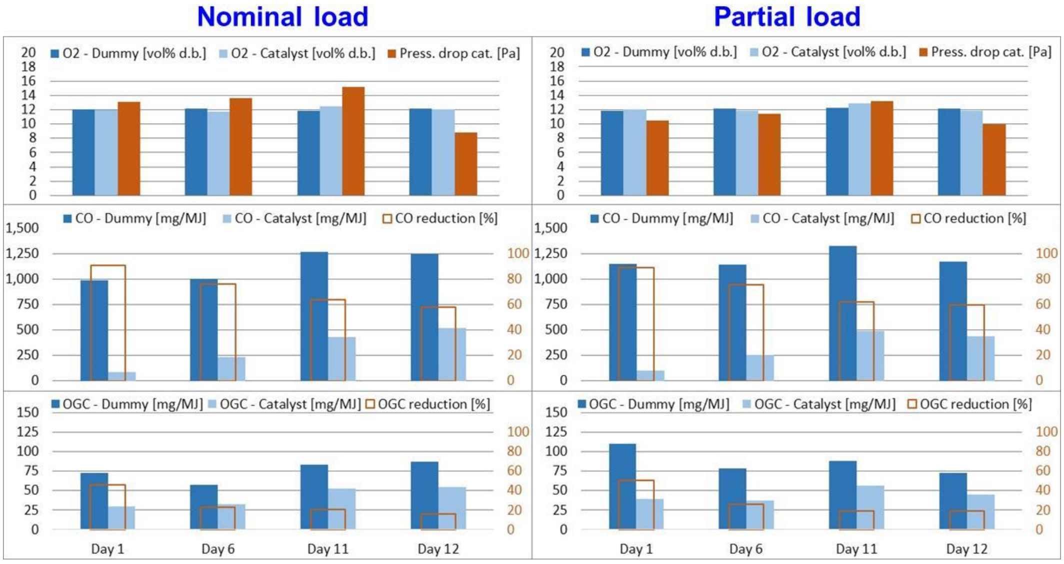


Figure 28: Long term performance of honeycomb catalyst 2 regarding emissions and pressure drop
Explanations: manual cleaning of the catalyst with compressed air after 11th day of operation

All 3 catalysts showed moderate OGC emission reduction efficiencies during the first operation day. Catalyst 2 was with about 46 % (at full load) significantly more efficient than the other two catalysts (19 % and 29 % for Catalyst 1 and 3). The emission reduction efficiency significantly decreased for catalyst 2 (down to 16 %) and 3 (down to 22 %) while it surprisingly increased for catalyst 1 (up to 33 %). Cleaning respectively purging with hot air (regeneration) showed no positive effect. The higher Pt-content of catalyst 2 in comparison to catalyst 3 seems to improve the initial OGC-emission reduction efficiency but after 2 weeks almost no differences occurred. Unfortunately, the exact composition of the catalytically active material of Catalyst 1, which showed the best OGC emission reduction efficiency, is not known. The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90 % as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction under the consideration that CH_4 is not converted by the applied metal based catalysts.

A deeper evaluation of the 3 catalysts investigated has been performed in order to clarify why the catalysts get partly de-activated so quickly and cleaning does not improve their activity anymore. Therefore, wet-chemical analyses of selected deposit samples as well as SEM/EDX analyses of the catalyst surface have been performed in order to probably understand the reasons for deactivation. The performed chemical analyses as well as the SEM/EDX analyses clearly indicated that the catalysts have been deactivated by aerosol deposits (condensation), mainly K_2SO_4 and KCl, which have partly blocked the active centres of the catalysts. Therefore, manual cleaning of the dust did not show an effect on the regeneration of the reduction efficiency.

After an intense discussion together with the manufacturer it has been decided to design a new catalyst (based on a foam ceramic) which can be applied at higher temperatures (up to 800 °C) and which shall be mounted at the outlet of the main combustion chamber where aerosol condensation should not occur or be of minor relevance.

Results of long-term testing of foam ceramics (mounting position II). Test runs with a non-coated and two catalytically coated foam ceramics (Tailor-made catalyst I and II) as well as a test run with the stove without integrated foam ceramic have been performed (see

Table 4). The evaluation of the stove operation data showed, that all test runs have been performed under well comparable and representative combustion conditions. The foam ceramics showed no effect on the efficiency of the stove (as expected). The non-coated foam ceramic showed no emission reduction efficiencies regarding CO, OGC and TSP and showed no relevant influence on the stove operation (except the increased pressure drop).

Table 4: Overview over the foam ceramics tested
Explanations: $^{1)}$ cells per square inch (1 CPSI ~ 645 mm²); $^{2)}$ Pt content of tailor-made catalyst II higher than Pt content of tailor-made catalyst I

No	**1**	**2**	**3**
Name	Non-catalytic foam ceramic	Tailor-made catalyst I	Tailor-made catalyst II
Substrate	SSiC	SSiC	SSiC
Structure	Foam ceramic	Foam ceramic	Foam ceramic
PPI $^{1)}$	10	10	10
Dimension (HxWxL)	380 x 50 x 50 mm	380 x 50 x 50 mm	380 x 50 x 50 mm
Active metal	No active catalyst	Pt $^{2)}$	Pt $^{2)}$

The catalytically coated foam ceramics showed a higher initial pressure drop (+8.7 Pa at full load) compared to the non-coated foam ceramic due to the coating of the foam ceramic with the wash coat and the catalyst (free cross-section of channels somewhat reduced). For all three foam ceramics the pressure drop increased with operation time. For the non-coated foam ceramic only a slight increase of the pressure drop could be observed (from 17.0 to 17.5 Pa). For the catalytically coated foam ceramics a slightly higher increase of the pressure drop was measured (from 26 to 29 Pa after 2 weeks for catalyst 1 and from 24 to 27 Pa after 2 weeks for catalyst 2 respectively). The increase of the pressure drop seems most likely to be due to the optically determined fly ash deposits built-up on the surface of the foam ceramics. Manual cleaning decreased the pressure drop again. The ash deposits could be successfully removed and the initial pressure drop could be reached after cleaning. Manual cleaning of the foam ceramic at least every two weeks of operation would be necessary in order to stabilise the pressure drop (based on the test run results so far).

Both catalysts showed high CO emission reduction efficiencies during the first days of operation (of about 90 %). The emission reduction efficiency considerably decreased for both catalysts, and manual cleaning showed no positive effect as shown for catalyst I in Figure 29. The CO reduction efficiency decreased to 73 % for catalyst I and to 69 % for catalyst II respectively. However, the reduction efficiencies have been still sufficiently high after 3 weeks of operation.

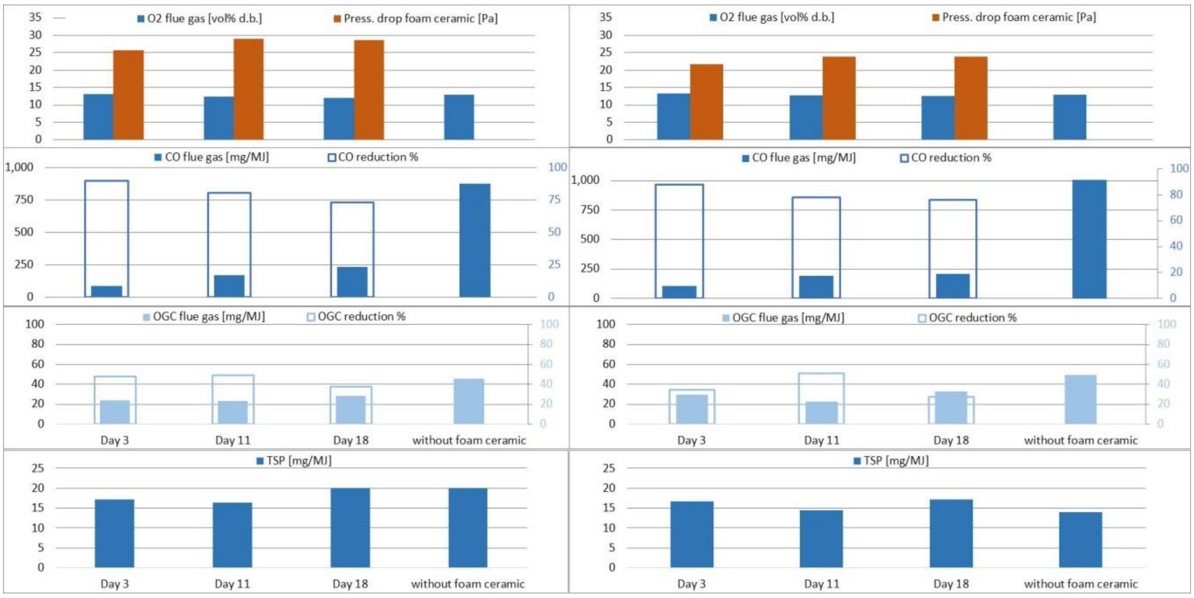


Figure 29: Long term performance of the foam ceramic catalyst I regarding emissions and pressure drop
Explanations: manual cleaning of the catalyst with compressed air after 11th day of operation

Both catalysts also showed good OGC emission reduction efficiency during the first days of operation. Catalyst II was with about 52 % (at full load) slightly more efficient than catalyst I (about 48 %) probably due to the higher Pt doping. The emission reduction efficiency significantly decreased for catalyst II (down to 27 %) while it only slightly decreased for catalyst I (down to 38 %). Manual cleaning of the foam ceramic showed no positive effect. The higher Pt-content of catalyst II in comparison to catalyst I seems to improve the initial OGC-emission reduction efficiency but after 3 weeks the reduction efficiency of catalyst II was considerably lower than for catalyst I.

In conclusion, the catalytically-coated foam ceramic I showed sufficiently high and rather stable emission reduction efficiencies regarding CO and OGC, and therefore this catalyst seems basically to be suitable for logwood fired stoves. Tailor-made catalyst II will not be further considered (also due to the higher costs regarding Pt doping). However, the pressure drop over the coated foam ceramic is quite high and it moderately increased after two weeks of operation due to fly ash deposits on the surface of the foam ceramic. Although the performance of the catalyst seems to be satisfactory so far, the pressure drop of the foam ceramic is currently too high for natural draft systems and has to be considerably reduced. By changing the geometry of the ceramic structure or by applying a foam ceramic with wider pores the tailor made catalyst I seems to be suitable for the implementation into logwood fired stoves in principle.

Conclusions. The implementation of a high temperature catalyst at the outlet of the post combustion chamber (temperature range of about 500 °C) is not recommended as tests showed unstable reduction efficiencies. The decreasing reduction efficiencies over time can most likely be attributed to catalyst deactivation as a consequence of blocking of active centres caused by aerosol condensation. Therefore, the mounting position of the catalyst has to be carefully evaluated in terms of existing flue gas temperatures in order to minimize risks of aerosol depositions (due to condensation).

High temperature catalysts, which are mounted at the outlet of the main combustion chamber (temperature range 600 – 800 °C) showed sufficiently high emission reduction efficiencies regarding CO (69 – 73 %) and OGC (27 – 38 %) and seem basically to be suitable for logwood stoves. However, the emission reduction efficiency decreased for the catalysts over the testing period of about 100 hours of operation and manual cleaning showed no positive effect (e.g. the CO reduction efficiency decreased from 90 % (first day) to 73 % within the testing period).
Tests over a complete heating period would be needed to enable an evaluation of the long-term performance of catalysts in wood stoves as well as the possible need of cleaning. Furthermore, catalysts need enough surface area to achieve sufficient reduction efficiency. This is usually provided by narrow channels which cause a certain pressure drop. The pressure drop is usually too high for an operation of the stove with natural draught only. Therefore, either a flue gas fan is needed if a catalyst should be integrated or the dimension of the catalyst needs to be increased. In general, the mounting position of integrated catalysts has to be carefully evaluated in terms of operating conditions (existing temperature), materials used and the availability to clean the catalyst.

2.3 Concepts for the optimised implementation of a mesh catalyst into a low emission stove (RISE/Nibe)

Choice of catalyst and evaluation procedure. The mesh catalyst type was selected with regard to promising test results in a previous study and therein specified advantages such as easy adaption to an existing or new stove design, low space requirement, good mechanical durability, easy cleaning procedure and the aim of generating only little flow resistance. The evaluated catalyst has a high temperature steel mesh base, with a mesh diameter and opening of about 0.5 mm resp. 1.24 mm, and a total cross section 0.2 m^2, split into 8 pieces at ø 180 mm. The active material was a mixture of stabilized Ce-Oxide and stabilized platinum. Size and coating properties were chosen in consultation with the manufacturer on the basis of expected flue gas conditions regarding volume flow, emissions, etc. and the available space in the catalyst test rig.

The evaluation was divided into two parts, at first a comprehensive study in a catalyst test rig on catalyst properties itself and secondly test runs with a stove integrated catalyst. The set-up of two test stands and the mesh catalyst itself are shown in Figure 30. The catalyst test rig comprised a traditional stove as emission source, a heated flue gas tract to adjust the gas temperature at the catalyst and two identical measuring sections up- and downstream a catalyst box, where the test object was placed. This set-up allowed for simultaneous measurement of gaseous components and particles at adjustable catalyst conditions. The mesh catalyst was studied at different temperatures and over a longer time period of about 150 hours in total including the check of light-off conditions and the impact of aging and cleaning. Additionally, tests with reduced area (fewer mesh) and comparison with commercially available catalysts have also been performed. For the second part of the evaluation the catalyst was tested within a stove to study the impact of catalyst integration on overall stove operation. The test set-up comprises a traditional stove modified with a new socket for holding the catalyst mesh. The stove was operated according to the project's “close-to-real-life” test method without the catalyst (reference case) and with two catalyst alternatives. The test run with the first catalyst alternative, i.e. "Catalyst (2)", where two mesh pieces (equalled about 18 % of original catalyst area) were placed directly above each other, was operated with the same stove settings as in the reference run. The test run with the second catalyst alternative, i.e. "Catalyst (4)", where four mesh pieces (about 35 % of original catalyst area) were placed with 3 mm spacers in between, was operated with adjusted damper settings in order to match the air flow of the reference case.

Figure 30: Catalyst test rig (left); mesh catalyst (new, in test rig, aged), new stove socket and stove integrated catalyst test set-up (right) including placement of mesh pieces (right, below)

Result evaluation in catalyst test rig. The ability of the mesh catalyst for a significant reduction of gaseous emissions was demonstrated. The light-off temperature for CO conversion was around 250 °C, with nearly complete elimination of carbon monoxide at temperatures above 300 °C, independent of CO level or other boundary conditions. The reduction rate for hydrocarbons was in range 25 – 50 % for moderate hydrocarbon contents, reaching up to 70 – 80 % at high hydrocarbon levels. An example for the catalyst performance in the test rig is shown in Figure 31 with the trends for temperature and gaseous components up- and downstream the catalyst. A significant reduction of particles could also be observed. The reduction rate was usually in rage 20 – 50 %, further increasing at batches with large hydrocarbon levels and reduction rates. In large part the particle reduction is based on minimizing particle forming hydrocarbons, but to some extends as well on particle deposit on the catalyst surface. The reduction rates for gaseous emissions and particles seemed to remain unchanged during the evaluation period, indicating no impact of aging or cleaning procedures. Due to the mesh properties (low free cross sections) and the catalyst size and positioning (8 mesh pieces stacked above each other) a noticeable flow resistance (pressure drop) has been measured. This pressure drop even further increased “temporarily” and “permanently”. The temporary increase occurred when running over a long time at low catalyst temperatures. It could reach large numbers and was based on increased catalyst blockage due to particle deposits. When reaching higher catalyst temperatures this blockage was dissolved again, due to the starting carbon conversion in the deposit, a sort of self-cleaning. The permanent increase in flow resistance summed up to doubling the pressure drop within the aging period of about 120 h (where the catalyst was operated at varying temperature levels) and was based on permanent catalyst blockade by ash particles. The removal of this deposit through cleaning restored initial flow resistance conditions.

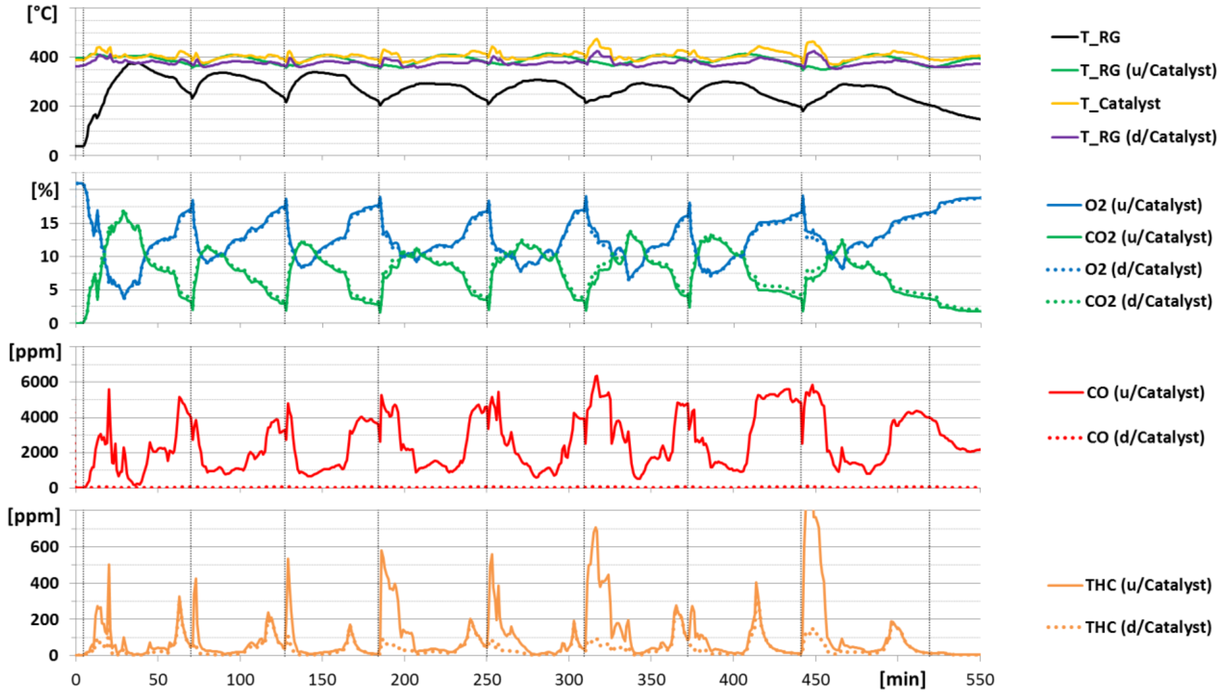


Figure 31: Example for a test run in catalyst test rig, initial test run at 400 °C

Reducing catalyst area by reducing the numbers of mesh pieces had a clear effect on the flow resistance. To put it roughly, by cutting the area in half (4 mesh instead of 8 and so on) the pressure drop was also reduced by half. This is an indication for the benefits of a larger catalyst cross section when aiming for lower flow resistance without having to lose reduction capacity (at least for particles there also could be a negative impact of that measure). Observing the reduction capacity for gaseous emissions and particles the effect of catalyst area decrease mainly became obvious when tests were performed with large area reduction (>= 75 % reduction). There was, for example, still a nearly complete elimination of CO at 50 % area, while at 25 % area CO conversion had only decreased to 90 – 95 %. This means the catalyst seems to be somewhat oversized for exposed flue gas volume and emission levels.

Result evaluation of stove integrated catalyst. Integrating the catalyst into the stove had a significant impact on the combustion conditions in the stove itself. The catalyst’s additional pressure drop will cause a lower air flow when damper settings are not modified. That results in worse conditions for wood ignition at recharge and longer batch duration. Therefore the damper settings were modified for the Catalyst (4) test run. Another noticeable impact is the increase in CO_2 (CO conversion) at the end of a batch, which delays the recharge time (when following the test method’s CO_2 recharge criteria) and thus resulting in lower combustion chamber temperatures and less depth of char bed at recharging.

It could also be observed that the chosen location of the catalyst was not optimal. The catalyst temperature dropped below the light-off value at recharging, resulting in a decrease in reduction at the beginning of each batch. This prevented the catalyst to operate to its fullest potential, especially since the time after recharging is usually the time with the highest hydrocarbon emissions. Due to the chosen location the catalyst did not operate longer times at higher temperatures, thus neither an eventual conversion of short-chain hydrocarbons (e.g. methane) nor a proper self-cleaning could be accomplished, probably leading to faster blockage and shorter cleaning intervals.

Despite the stated negative impacts of catalyst flow resistance and non-optimal placement, a significant improvement on emissions could be observed comparing to the reference test run and even more when comparing to emission values upstream the catalyst. Regarding carbon monoxide a reduction of almost 60 % for Catalyst (2) and 90 % for Catalyst (4) could be achieved when comparing final numbers to the reference run. Comparing to upstream catalyst values the CO conversion for the Catalyst (2) run is even higher at around 65 %. And an altered catalyst location would have given even better results. The same is true for hydrocarbon emissions, for which there is almost a 30 % reduction for the Catalyst (4) test run compared to reference, despite the flaws in catalyst placement. In contrast the Catalyst (2) test run shows a more than 10 % increase for hydrocarbon emissions compared to reference, but a 20 % reduction compared to upstream values. According to the particle samples for the complete test runs the Catalyst (4) test showed a clear 40 % reduction, which seems to be at least partly caused by the reduced air flow during the first batches – compared to reference. And looking at the single batch samples, there is even an indication for reduction potential of the Catalyst (2) alternative. Finally, due to the decrease in chemical (CO conversion) & thermal losses (mainly due to reduced air flow during first batches) there is also an increase in test run efficiency when using the catalyst. A comparison of emissions and efficiency for the reference run without catalyst and the two catalyst alternatives is shown in Figure 32.

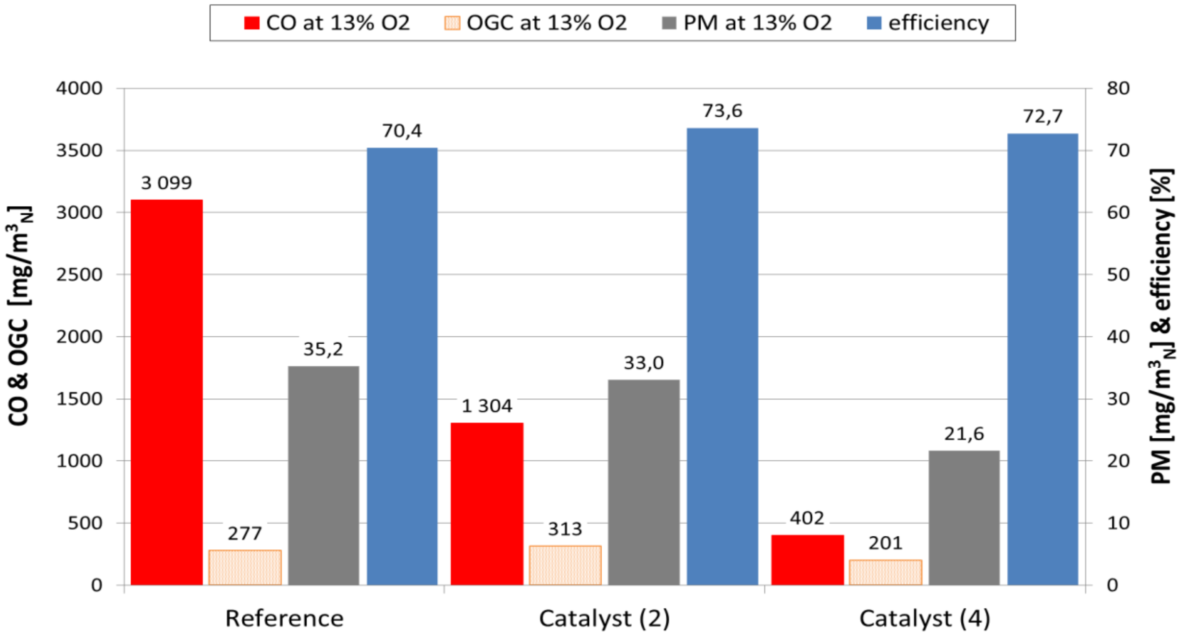


Figure 32 Comparison of performance data for reference run & two catalyst alternatives

Conclusion. The thin metal mesh form of the catalyst provides large design opportunities for integration into a stove. The evaluation has demonstrated the significant reduction capacity for gaseous emissions and particles. The catalyst will also act as a safety device for severe combustion phases, since reduction rates even increase at times with bad combustion & high emissions (for example after user induces errors in operation). During the first 200 hours of operation no signs of deactivation have been observed and a simple cleaning procedure restored initial flow resistance conditions. Most importantly, catalyst positioning is crucial. The catalyst has to be placed to enable fast heat-up and an operation at required temperatures. In particular a drop below light-off temperature at recharging has to be prevented. Nevertheless preventedan easy access has to be given for the stove operator to enable cleaning and/or replacement. Keeping the catalyst area as minimal as needed, i.e. the prevention of oversizing, will be beneficial regarding catalyst costs. This will also help to lower the flow resistance, which can additionally be influenced by finding a location where a large cross section is possible.

2.4 Evaluation of foam ceramic filters or their replacement by a catalyst insert (TFZ)

In the following the performance of catalytic and non-catalytic foam ceramic elements for insertion into existing stoves is evaluated.

Materials and method. To verify if the operation time of foam ceramic filters in stoves has a significant influence on the emissions, three foam ceramic filters (Figure 33) with a different amount of passed batches (0, 200 and 550) were provided. The three filters are made of the same raw material, they had a porosity of 35 ppi.

Figure 33: Foam ceramic filters applied: unused element (left), 200 batches (middle), 550 batches (right)

An other foam ceramic with acts as a ceramic catalyst (Figure 34) was provided by Linder Katalysatoren GmbH, Germany. The carrier material is a open porous (30 ppi) foam ceramic ($SiC - SIO_2 + 3C \rightarrow SiC + 2\,CO$ and Al_2O_3). The manufacturer declares the catalytic coating as a mixture of platinum, rhodium and palladium. The exact ratio of the catalytic components is undisclosed.

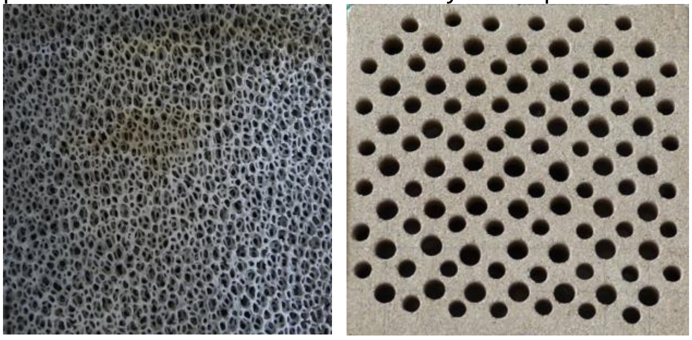


Figure 34: Catalytic foam ceramic (left), “Dummy”-element for achieving equal flow conditions in the test rig (right)

To compare the influence of a foam ceramic filter resp. a foam ceramic catalyst on the emissions a “dummy”-element (Figure 34) causing a similar pressure drop was manufactured from a 30 mm vermiculite plate. The reason for also using a "dummy" in the trials was to prevent that any possibly positive effect on primary combustion and on gas flow characteristics as caused by the flue gas barrier of the catalyst could falsely be interpreted as catalytic effect. For the validation of the dummy having the same flow characteristics as the catalyst element, a test rig was built to determine the pressure drop over both elements. The vermiculite plate was then drilled with 8 and 10 mm holes until the pressure drop was almost equal to the foam ceramic elements and the catalyst (Figure 35).

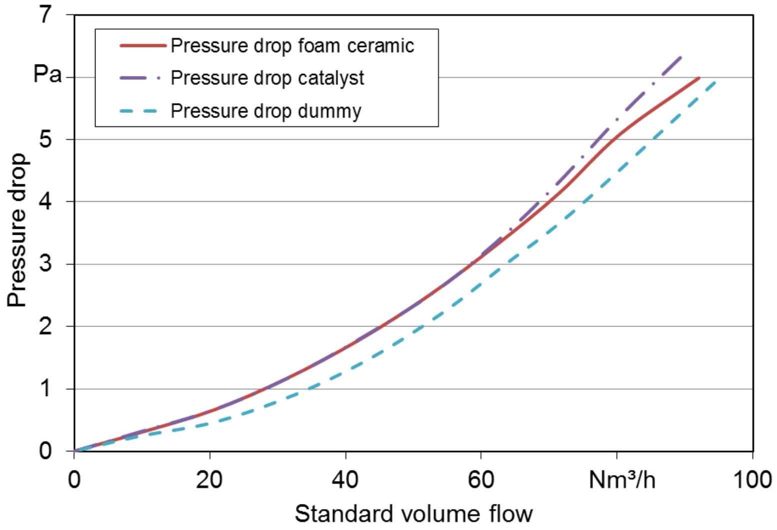


Figure 35: Validation of similar pressure drop achieved with all build-in components used

The appliance used for the combustion test was a state of the art log wood stove with a nominal heating power output of 8 kW and a room independent combustion air supply. When supplied to the customer, the appliance is provided with a non-catalytic foam ceramic filter. The combustion air can be controlled by a primary and a secondary air flap. Furthermore, there is a diverting flap which allows to by-pass the foam ceramic elements; however this flap was closed for all test runs.

All measurements were performed at the combustion test stand of TFZ in Straubing. Figure 36 shows the applied test rig on which all measurements were performed.

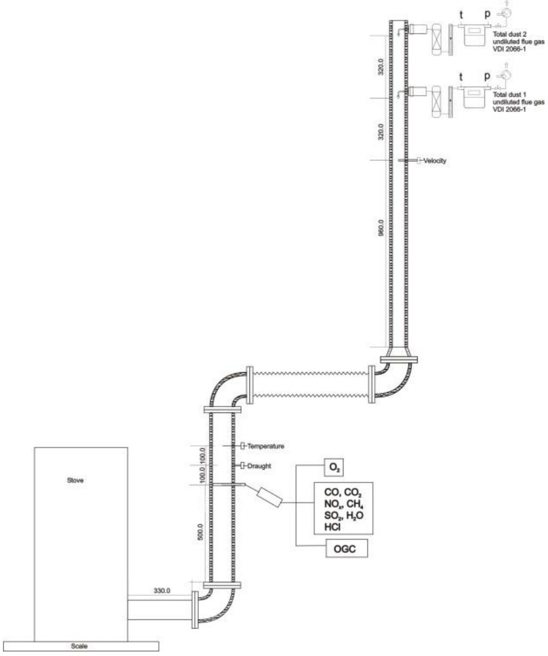


Figure 36: Test stand with flue gas tract for flue gas emission measurements

The combustion appliances were placed on a scale in order to record the mass loss continuously during combustion. Flue gas temperature was measured with a suction pyrometer in accordance to DIN EN 13240 (and with an additional centrally placed thermocouple) it was combined with the gas sampling [1]. The flue gas tunnel for dust sampling was reduced to an effective inner diameter of 64 mm in order to increase the velocity for a reliable isokinetic PM sampling. Gas temperature and velocity near the total dust sampling were continuously recorded for volume flow calculations. The particle sampling was performed following the VDI-Guideline 2066 [2].

For the real life reflecting testing procedure the test protocol as commonly developed for all partners in the project was followed (see chapter 4.1).

Pre-testing of air flow in stove. To test the flow behaviour in the stove and through the foam ceramic elements, pre-tests were executed, they were inspired by tests performed by Aigenbauer et al. [3]. The stove was set under a constant negative pressure of 12 Pa, and the flow rate through the stove as well as the pressure drop over the foam ceramic was logged. Then the leakages were tightened up in 4 steps using air tight tape: Step 1 initial state, Step 2: foam ceramic masked (Figure 37, left), Step 3: all leakages masked and Step 4: cutting the tape from the foam ceramic (Figure 37, right).

Figure 37: Pretesting of the flow behaviour: Step 2 (left), Step 4 (right)

Results on flow behaviour through the stove and foam ceramic. The results from the pretesting (Table 5) show that it is not ensured that the complete flue gas will stream through the foam ceramic while the stove is operated. By comparing Step 2 and Step 4 it becomes apparent that the flow rate and pressure drop over the uncovered foam ceramic (Figure 37, right) is nearly the same as for the foam ceramic masked with air tight tape (Figure 37, left). Therefore it may be assumed that the flue gas is streaming in approximately equal parts through the foam ceramic and through the gaps in the ceramic facing of the stove.

Table 5: Results from pretesting of air flow in stove

Step	Draught	Flow rate	Pressure drop
	Pa	Nm³/h	Pa
1: Initial state	-11.8	35.4	3.2
2: Foam ceramic masked	**-11.9**	**33.9**	**3.8**
3: All leakages masked	-11.8	21.2	9.1
4: Only foam ceramic cut free	**-12.0**	**33.9**	**3.9**

Results on long-term behaviour of non-catalytic foam ceramic elements. In comparison the gaseous emissions for the three foam ceramic filters used (Figure 38) are slightly different but are showing no clear trend relating to the operating hours, neither for full load nor for partial load. The CO emissions are in average around 11 % and the OGC emissions around 13 % higher in partial load operation.

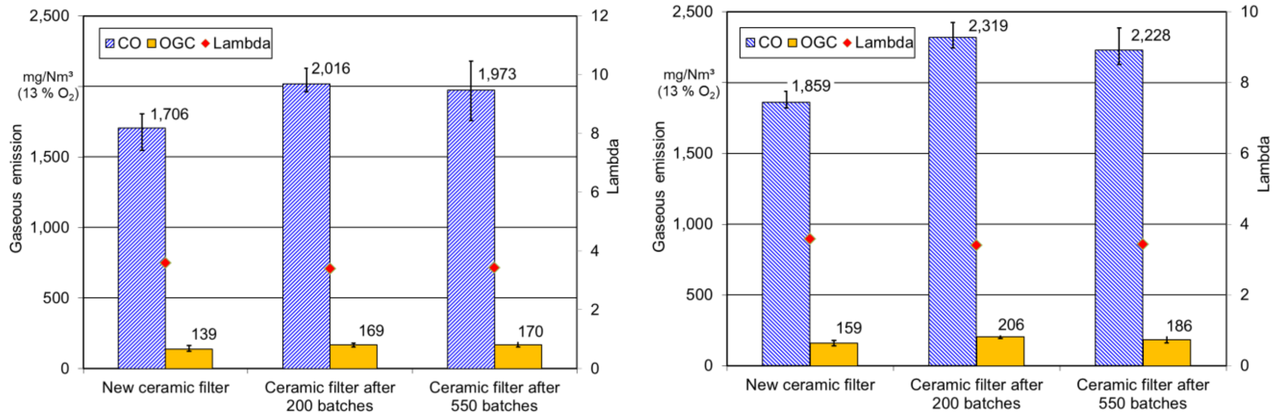


Figure 38: Gaseous emissions using three differently aged foam ceramic filters for full load operation (left) and part load operation (right)

The particle emissions (Figure 39) are slightly different but are showing no clear trend relating the operating hours just as for the gaseous emissions. The particle emissions are in average approx. 6 % higher in partial load operation.

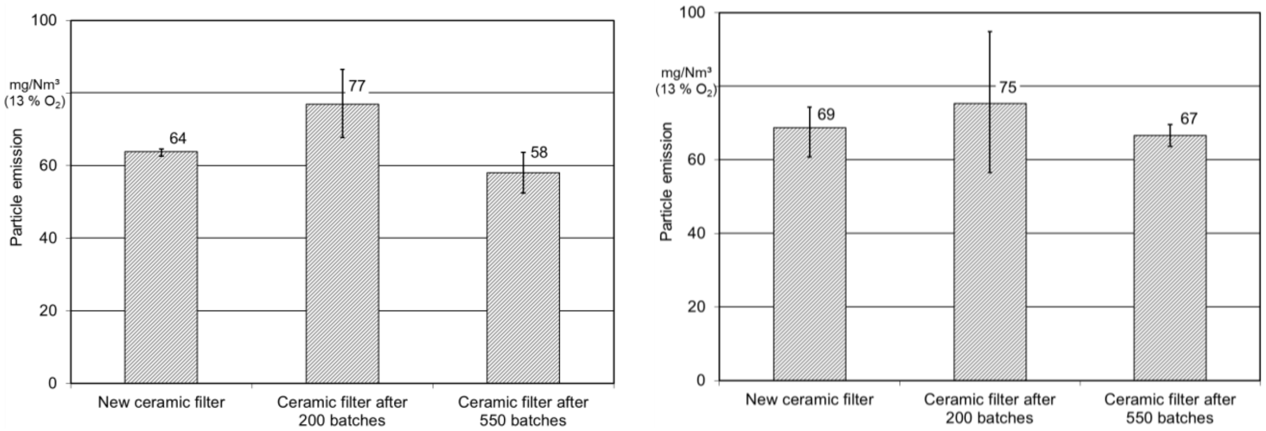


Figure 39: Particle emissions using three differently aged foam ceramic filters for full load operation (left) and part load operation (right)

Generally it can be stated that gaseous and particle emissions measured with the “close to real life” testing cycle (see chapter 4.1) are much higher than the type testing results given on the inspection plate. Thus, the use of a non-catalytic foam ceramic element cannot secure that the strict emission thresholds for type testing will also be met in practical use in the field. This is true for both, particle and gaseous emissions, and it applies particularly when the stove is operated at partial load which happens during transition times or at mild winter temperatures, particularly when the stove power does not fit to the heat demand of the room.

Results using catalytic foam ceramic elements. The catalytic foam ceramic reduces the CO emissions (Figure 40) by about 46 % at full load and by about 47 % in partial load operation, in average. The non-catalytic foam ceramic shows no mentionable reduction of CO emissions.

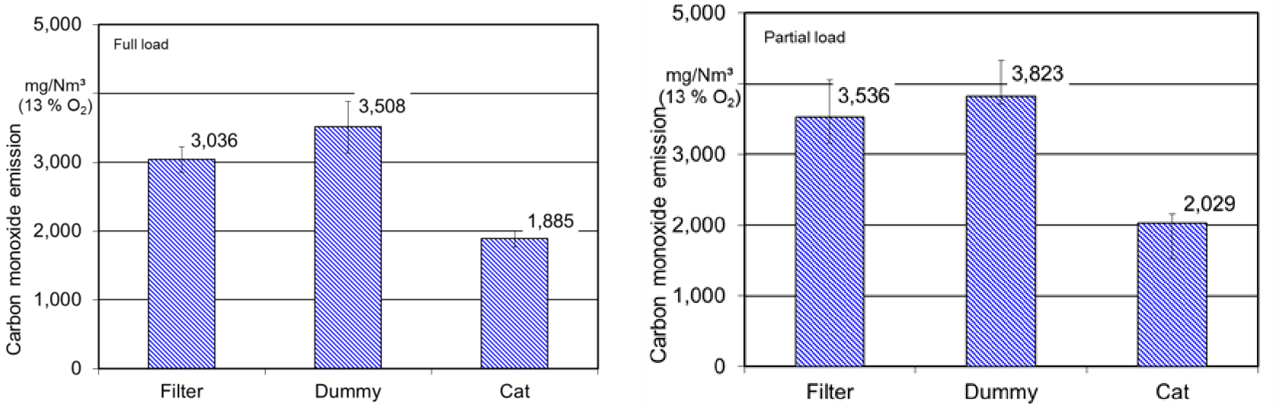


Figure 40: Comparison of the CO emissions for the foam ceramic filter, the catalyst and the dummy at full load operation (left) and part load operation (right)

When using the catalytic foam ceramic the non-methane OGC (FID signal minus CH_4 from FTIR) emissions are reduced by 21 % at full load and by 23 % at partial load (Figure 41). The non-catalytic foam ceramic filter shows no significant reduction of non-methane OGC emissions.

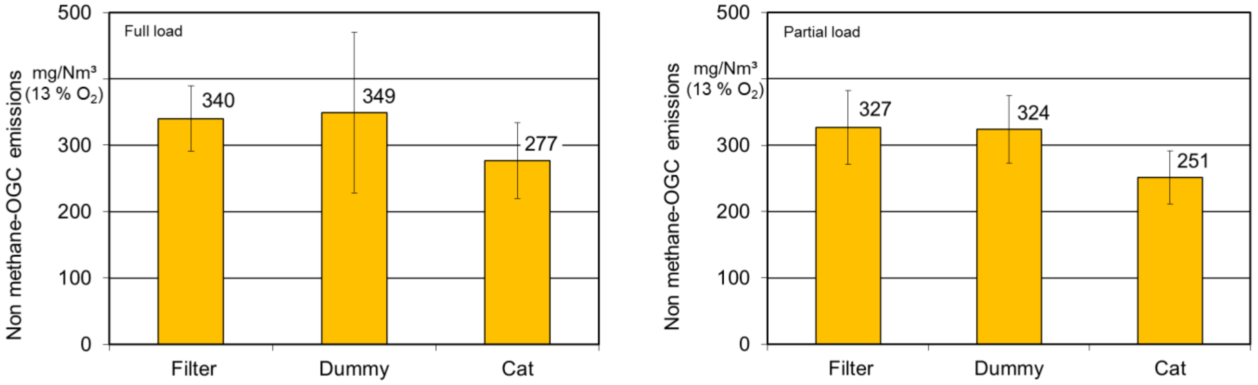


Figure 41: Comparison of the non-methane OGC emissions for the foam ceramic filter, the catalyst and the dummy at full load (left) and part load (right)

As expected, no significant reduction of the CH_4 emissions could be observed because methane behaves very stable at catalyst temperatures below 650 °C [4]. The same applies for the NO_x emissions, for which the catalyst manufacturer had also claimed some reduction potential.

Total particle emissions (Figure 42) were slightly reduced by 10 % for full load and by 12 % for partial load operation when using the catalytic foam ceramic elements, but the differences may partly also be attributed to measurement uncertainties. This is illustrated by the distinct min-max-bars given for "Filter" and "Dummy".

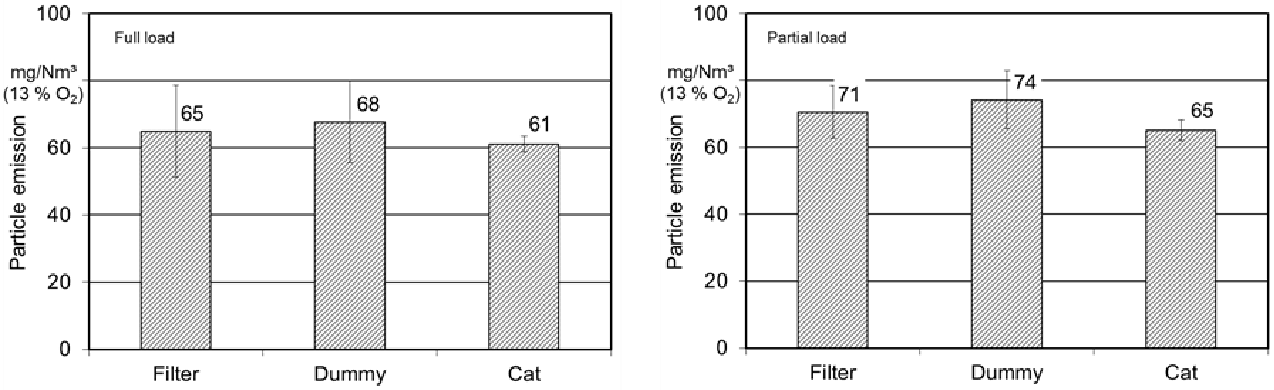


Figure 42: Comparison of the particle emissions for the foam ceramic filter, the catalyst and the dummy at full load operation (left) and part load operation (right)

The temperatures at the catalyst surface are on average 431 °C for full load and 399 °C at partial load. The average maximum temperature (after refilling) is 543 °C and the average minimum temperature (ignition batch or end of batch) is 264 °C at the catalyst surface. For CO conversion the “light off” temperature

(temperature from where a conversion becomes visible) lies between 200 °C and 350 °C, depending on the mixture of noble metals, the flue gas composition and the age of the catalyst [6][7][8]. These temperatures could easily be reached and they could be sustained almost over the complete measuring cycle of the 8 batches. For methane the "light off" temperature lies between 500 °C and 650 °C [4][8]. In the test runs these high temperatures could only be observed during a very short time frame (for only few minutes after each refilling). The "light off" temperature of total organic carbon lies approx. between 300 °C and 400 °C [4]. But the conversion rate rises with the surface temperature from the "light off" until 800 °C and then may be higher [4]. This means that at an average temperature of 431 °C for full load and 399 °C for partial load the catalyst is just becomes active for OGC-reduction, but the conversion may be optimized by realizing higher temperatures at the catalyst surface.

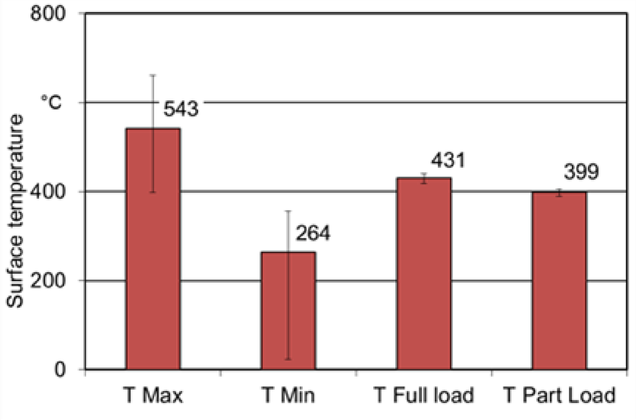


Figure 43: Minimum, maximum and average temperatures at full load and partial load measured at the surface of the catalytic foam ceramic element.

To figure out the long-term performance of the catalytic foam ceramic some long term testing was performed according to the method described in WP 4. The results of these long term testing's are shown in Figure 44. There is a significant decrease of the reduction rate within 11 days of operating time (each day 8 successive batches). A cleaning of the catalytic foam ceramic with pressurized air (between day 11 and 12) could not restore the initial reduction rate regarding CO, PM and OGC (not shown).

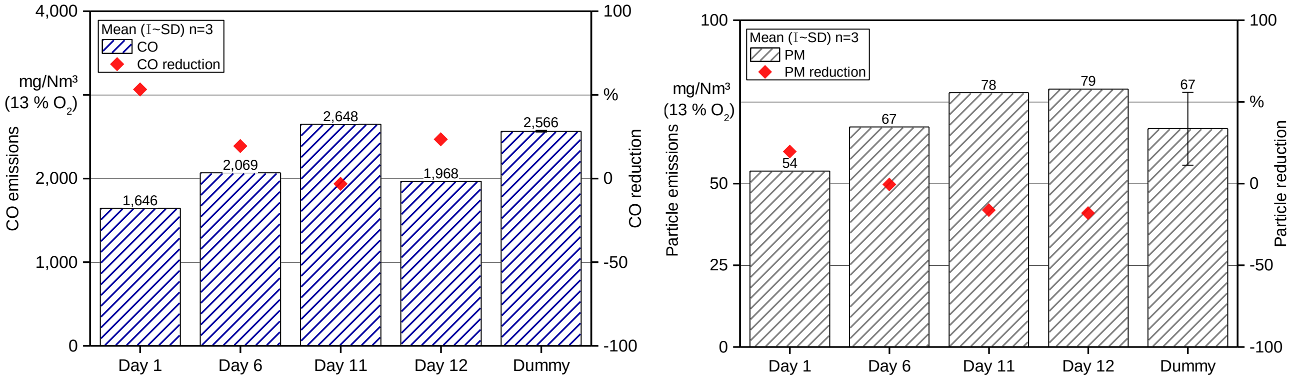


Figure 44: Long-term performance of the catalytic foam ceramic regarding CO emissions (left) and particle emissions (right)

Conclusions. To apply (non-catalytic) foam ceramic elements in a log wood stove has no relevant potential for reducing gaseous and particle emissions. The aging of the foam ceramic does not matter anyway. But the reduction potential of foam ceramic elements (catalytic and non-catalytic) may be optimized by ensuring that the complete flue gas will flow through the foam ceramic and not through gaps in the ceramic lining of the furnace.

The catalytic foam ceramic element reduces CO emissions effectively as the temperatures in the combustion chamber are sufficient to allow high CO conversation rates. To improve the OGC and perhaps also the CH_4 reduction, higher temperatures at the catalyst surface are required. This can be achieved by optimizing the combustion chamber geometry and by insulation or by choosing a better suitable position for catalyst integration.

The long-term stability of the catalytic foam ceramic has to be improved possibly by choosing another mixture of novel metals to ensure a stable reduction over at least one heating season. However, the decrease of the reduction efficiency over the operation time has to be investigated. After this heating season it should be possible recover the catalyst by cleaning. Otherwise this technology is not of interest for use in log wood stoves.

A detailed report about catalysts is available for download on the website.

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3 WP 3: Increasing efficiency and applicability

Common log wood stoves show a thermal efficiency of approx. 80 % during type testing and an average nominal heat output of approx. 8 – 12 kW. But in new and well insulated or renovated houses the heat demand of the room where the stove is integrated is usually much lower and partial load operation happens frequently. Tests in the EU-project "beReal" had shown that in practice the efficiency is largely lower and the heat output is even higher than determined during type testing. To increase the applicability for log wood stoves in future buildings, a heat exchanger based on phase change material (PCM) was developed, in order to reduce the nominal heat output and to improve the user comfort (see section 3.1). Furthermore, it was the aim to prove that higher efficiencies could also be achieved with conventional stoves in practice, this potential was evaluated by determining the avoidable standing losses (section 3.2) as well as the influence of too low and too high draft on efficiency and emissions, the corrective technologies were therefore also evaluated (section 3.3 – 3.5).

3.1 Concept for the integration of a heat storage system based on a phase change material into a low emission stove (BIOS)

As a first step a detailed evaluation of PCMs available on the market based on literature reviews and data from manufacturers has been performed. Promising PCMs have been summed up in a short-list and have been further evaluated in terms of costs, thermodynamic properties, heat capacity, density, toxicity, flammability and temperature degradation. Primarily, a high density and heat capacity of the PCM is important as the heat storage unit should be realised in a compact way. The evaluated PCMs have to be suitable for the application in a heat storage unit (e.g. flue gas heat exchanger) of wood stoves. Accordingly, some basic criteria limit the applicability of these PCMs. These criteria were defined as follows:

- Melting temperature: 150 – 300 °C
    - Should be determined in a way that complete melting can be achieved within a representative number of batches. This can be evaluated by CFD simulations.
- Degradation temperature: > 600 °C
    - Maximum achievable temperature of stove materials can be evaluated by CFD simulations and depends on the isolation applied (see chapter 4).
- The price should be as low as possible in order to be economically competitive.
- The material should not be corrosive or toxic under operation conditions.

Based on the evaluation performed promising PCMs (salt mixtures) have been selected for the PCM heat exchanger. In a next step an appropriate heat exchanger for heat transfer from the flue gas to the PCM (loading cycle) and for heat transfer from the PCM to convection air (unloading cycle) has been designed and integrated into the low emission stove concept developed within WP 2 (see section 2.1). The PCM heat exchanger should be integrated into the stove concept in a way that a large share of the energy produced is transferred to the PCM in order to ensure high storage efficiency. The basic concept of the PCM heat exchanger is shown in Figure 45.

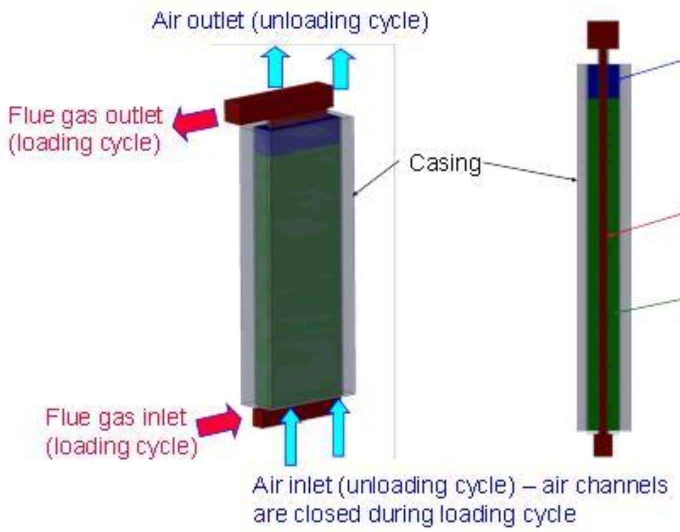


Figure 45: Scheme of the PCM heat exchanger concept with convective air channels

The release of the heat stored (unloading cycle) can be realised

- via convection air channels which are opened at the end of operation of the stove. Thus, the stored heat can be distributed even to different rooms (see Figure 45).
- via slow natural convection over a larger time duration which is of advantage for the comfort of living.

The development of the PCM heat storage device has been accompanied and supported by CFD simulations in order to evaluate the performance of the heat storage device. By applying CFD simulations the stove including the heat storage geometry can be optimised more effectively than by trial-and-error test runs.

BIOS has developed an innovative CFD model for wood log fired stoves operated in batch mode consisting of an empirical model for wood log combustion and CFD models for the turbulent reactive flow and heat transfer in the stove [1]. However, the combustion of wood logs in small-scale stoves is a highly transient and complex process, as a wood log stove is operated in batch mode with every batch consisting of a starting, a main combustion and a burnout phase. The transient character of the operation of wood log stoves becomes even more important, when a heat storage system is included. In this case, steady-state conditions do not apply, as the operation of a heat storage device is divided into 3 phases: heat-up, heat storage (without charging) and heat release (discharge). Therefore, BIOS has developed an innovative CFD simulation methodology including a transient simulation of the system [2]. Thus, it is possible to derive and discuss the thermal behaviour of a heat storage device coupled to a wood log fired stove during the heat-up and discharge phase. Moreover, the influence of the air-flow in the discharging channels and the flue gas flow in the charging channels as well as material properties on the charging/discharging processes can be evaluated.

In Figure 46 the surface temperatures of the PCM heat storage unit (similar to Figure 45) and in Figure 47 the flow conditions through the PCM heat storage unit, laterally coupled to the new Low-emission stove (on both sides), are depicted as examples.

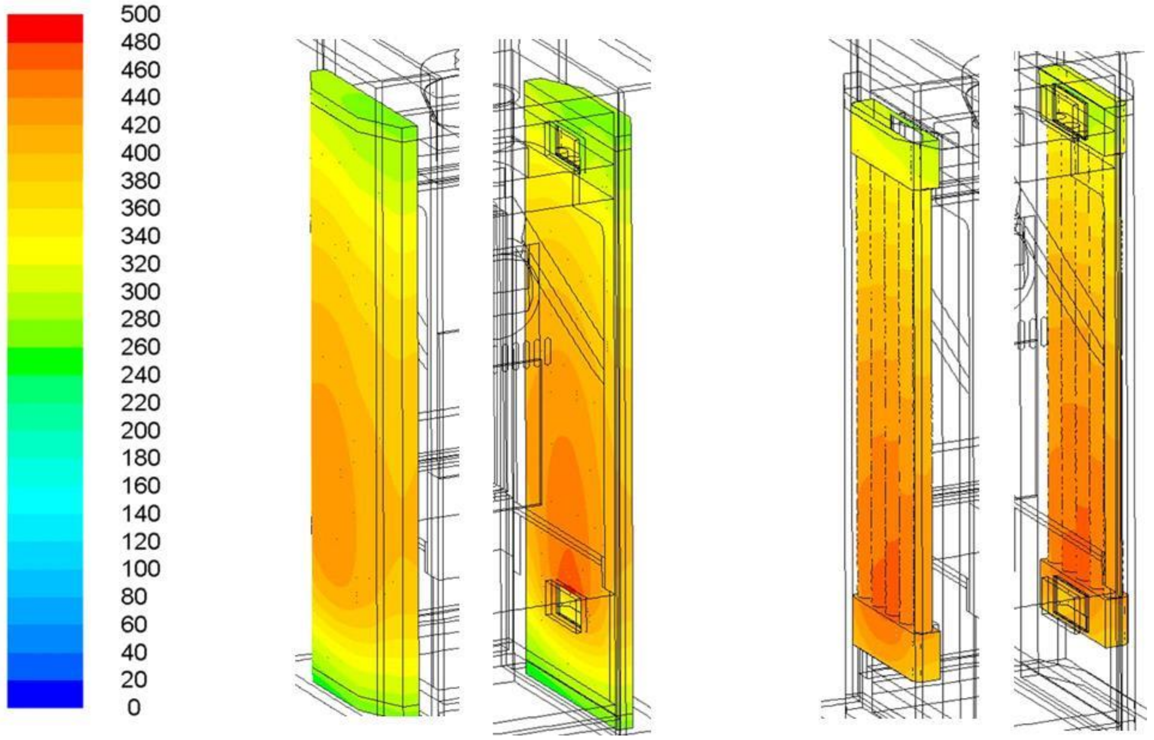


Figure 46: Iso-surfaces of material temperature [°C] in the PCM heat storage unit (steady state after complete charging); 3D view from the left and right hand side of the air channels

The CFD simulations show a rather even flow of the flue gas through the heat exchanger modules indicating a good utilisation of the heat exchanger. The maximum temperature of the PCM achievable is close to 480 °C, which is significantly lower than the degradation temperature of the selected PCM. The highest temperature occurs at the flue gas inlet into the tubes. In the bottom and top of the heat exchanger modules the temperatures are lower. The minimum temperature of the PCM can be up to 260 °C which is well above the melting temperature of the selected PCM, indicating that complete melting of the PCM is possible.
The evaluation of the heat storage potential as well as of the efficiency of a stove with integrated PCM has already been discussed in section 2.1. The results show that more than 50 % of the useful heat can be stored in the stove and the PCM heat exchanger and efficiencies above 92 % are achievable.

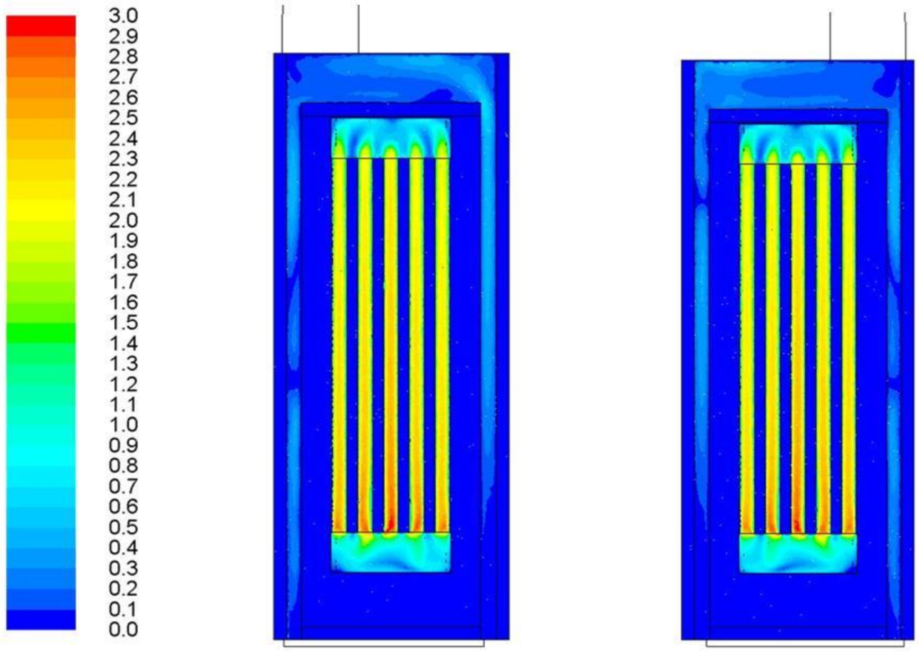


Figure 47: Iso-surfaces of the flue gas and convection air velocities [m/s] in the PCM heat storage unit (steady state after complete charging)

Conclusions. A concept of an appropriate heat exchanger for heat transfer from the flue gas to the PCM (loading cycle) and for heat transfer from the PCM to the surroundings (unloading cycle) has been developed and integrated into the new low emission stove. The PCM heat exchanger concept has been developed by means of CFD simulations. Based on the development work a prototype of the stove with integrated PCM heat exchanger has been constructed and tested. Due to the optimised positioning and improved insulation of the PCM heat exchanger a high efficiency of the stove (> 92 %) and an efficient heat storage in the PCM heat exchanger can be achieved which has also been proven by test runs performed.

References:

[1] Scharler R., Benesch C., Neudeck A., Obernberger I., 2009: CFD based design and optimisation of wood log fired stoves. In: Proc. of the 17th European Biomass Conference, June 2009, Hamburg, Germany, ISBN 978-88-89407-57-3, pp. 1361-1367, ETA-Renewable Energies (Ed.), Florence, Italy

[2] BENESCH C., BLANK M., SCHARLER R., KOESSL M., OBERNBERGER I., 2013: Transient CFD Simulation of Wood Log Stoves with Heat Storage Devices. In: Proc. of the 21st European Biomass Conference and Exhibition, June 2013, Copenhagen, Denmark, ISBN 978-88-89407-53-0 (ISSN 2282-5819), pp. 578-584, (paper DOI 10.5071/21stEUBCE2013-2CO.7.1), ETA-Florence Renewable Energies (Ed.), Florence, Italy

3.2 Determination of standing losses of stoves and their prevention (TFZ)

In stove combustion the chimney draught still remains active over a long time after termination of combustion. This is due to the fact that both, stove and chimney still remain warm for several hours. Furthermore, the temperature gradient between the inside of the building and ambient air persists even though stove and chimney may both have cooled down completely. As a result, a certain chimney draught is sustained throughout the complete heating season even if the stove is not used at all. If air supply is then not shut down – as given for most stoves – continued heat losses are inevitable as the building remains heated (e.g. by central heating).

Two types of standing losses were investigated: heat losses though the chimney without any heating operation (cold standing losses) and the post heating losses (losses during chimney cool down).

Equipment used. Three log wood stoves were chosen for measurements of cold standing losses, all were equipped with a central air inlet socket. Stove A was a room sealed stove Hark 44 GT ECOplus with 8.0 kW nominal heating power. It was equipped with an integrated foam ceramic element for particle emission reduction. Three dampers allowed for manual adjustment of either primary or secondary air, or enabled the opening of a bypass around an integrated foam ceramic filter element; this was to ensure a safe ignition and an operation during phases of low chimney draught or filter clogging.

Stove B was a log wood stove Scan 85 2013, type 85-2, with 8.0 kW nominal heating power. Air dampers were adjusted by a single-lever mechanism for combined primary and secondary air adjustment.

Stove C was a log wood stove Buderus Blueline, type No. 10, with 8.0 kW nominal heating power. Air dampers were adjusted individually for primary and secondary air supply.

All 3 stoves were mounted to a chimney of 130 mm inner diameter. It was made of stainless steel and had a total height of 12.5 m with 1.7 m in outdoor environment. The chimney was equipped with several sensors (Figure 48).

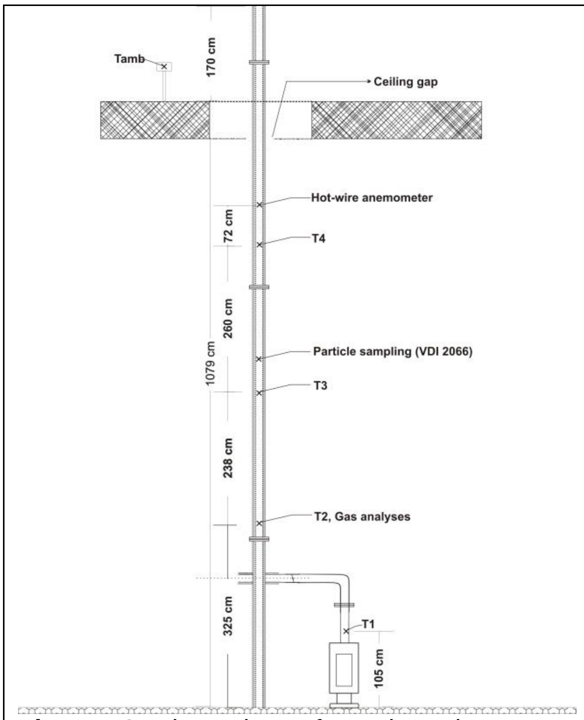


Figure 48: Dimensions of test rig and sensor positions in chimney

Procedure for cold standing losses. Stove A was monitored over several weeks on a cold natural draught chimney. Four different damper positions of the stove were applied sequentially:

1 = Primary air: max; secondary air: max; bypass open

2 = Primary air: min; secondary air: max; bypass open

3 = Primary air: min; secondary air: max; bypass closed

4 = Primary air: min; secondary air min; bypass closed

During this time the usual fluctuation of the natural draught conditions was accepted. A recording of the conditions during the monitoring phase is presented in Figure 2. It shows, that ambient temperatures were usually between 0 and 10 °C and wind velocity fluctuated between 0 and 4 m/s. As consequence the natural chimney draught was largely determined by these factors, while it hardly fell below -4 Pa it could easily reach peaks of -40 Pa, particularly during periods of elevated wind speeds. As a result the measured volume flow though the cold chimney follows the same pattern as given for the chimney draught (Figure 49).

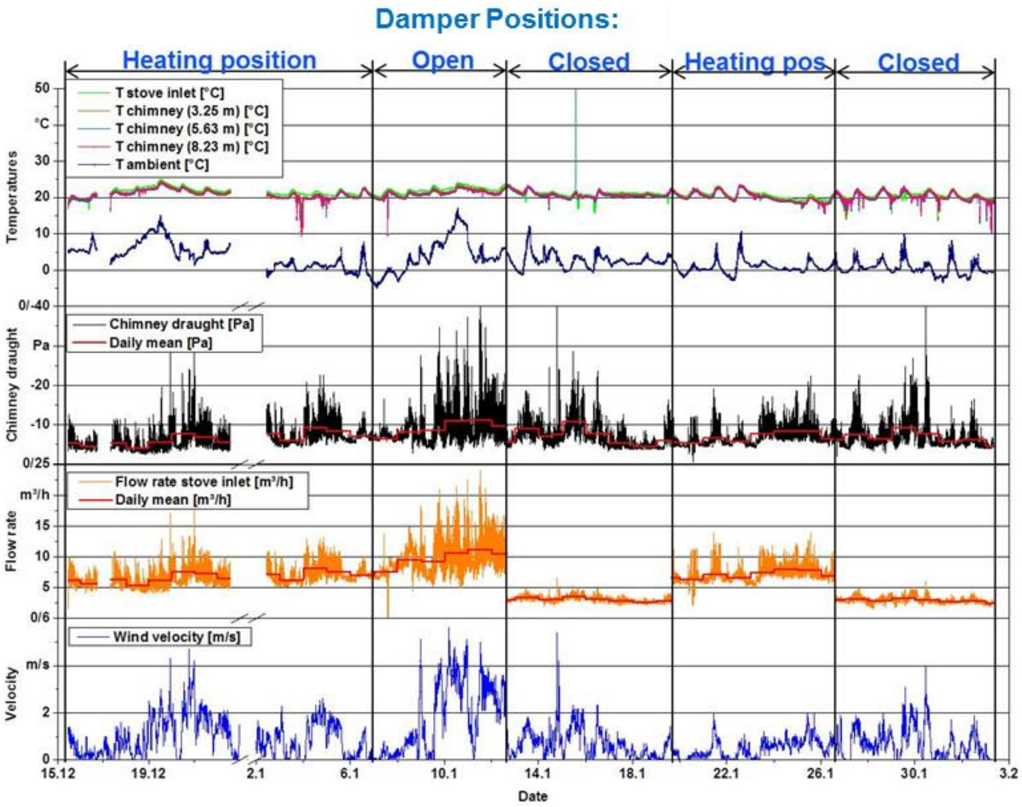


Figure 49: Measured parameters during monitoring program for cold standing loss estimation at the four damper positions applied with Stove A

With the two other stoves the procedure was similar. For Stove B three different damper positions were chosen:

1 = fully open,

2 = intermediate position (normal combustion),

3 = fully closed.

And for Stove C the damper positions were:

1 = Primary air: max; secondary air: max,

2 = Primary air: min; secondary air: max,

3 = Primary air: min; secondary air: min.

The duration of each test is given in Table 6. All monitoring periods were conducted under quite similar climatic conditions during mild winter days in 2015.

Table 6: Monitoring duration of cold stoves at natural draught chimney (duration in days)

Stove A		Stove B		Stove C	
Damper position	Duration	Damper position	Duration	Damper position	Duration
1	4.0	1	30.1	1	8.8
2	4.2	2	5.0	2	3.1
3	5.8	3	8.6	3	2.5
4	2.8	--	--	--	--

Procedure for losses during chimney cooling. For these tests the same setup was used but tests were executed with only one log wood stove (Stove A). A heating cycle of 5 full load batches followed by 3 partial load batches was applied. This heating cycle was repeated over 13 testing days. At the end of each such heating cycle the air flaps were either fully closed (in 6 tests) or they remained in the last heating position (in 7 tests). The monitoring period of the cooling phase lasted over 12 hours (i.e. overnight).

Calculation. Mean chimney temperature $\bar{T}_{chimney}$ was calculated as mean value from the three sensor positions T2 to T4 as indicated in Figure 1. Cold standing losses via chimney were calculated according to the following equation:

$$\dot{Q}_{chimney} = \dot{V}_{air} * \bar{\rho}_{air} * \bar{c}_{p_{air}} * \left(\bar{T}_{chimney} - T_{ambient}\right)$$

where $\dot{Q}_{chimney}$ is the calcuated heat loss rate through the cold chimney (in W), $\dot{V}_{air}$ is the air volume flow in the chimney (in Nm³/s), $\bar{\rho}_{air}$ is the mean density of air (in kg/m³) calculated at given temperature (calculated as mean value of $\bar{T}_{chimney}$ (i.e. the mean chimney temperature) and $T_{ambient}$ (i.e. the ambient air temperature measured at the rooftop) in °C.

The calculation regarding the standing losses for the hot chimney are made using the same equation.

Results on cold standing losses. During the relatively mild winter period 2015 the measured the average cold standing losses of the log wood stoves via the cold chimney was between 19 and 75 W (Stove A) or it was between 27 and 56 W for Stove B. For Stove C the range was from 17 to 44 W. This is shown in the results presented in Table 7.

Table 7: Cold standing losses using Stoves A, B and C without heating operation, calculated over full the measurement duration (n.a. = not available)

Stove/damper position	Chimney draught [Pa]	Flow rate $\dot{V}_{air}$ [m³/h]	$\bar{T}_{chimney}$ [°C]	$T_{ambient}$ [°C]	$\dot{Q}_{chimney}$ [W]	Monthly heat loss (calculated) [kWh]
A/1	-4.5	13.9	19.0	2.8	74.7	53.8
A/2	-5.8	11.5	19.4	3.5	60.7	43.7
A/3	-6.0	11.9	21.3	4.2	68.3	49.2
A/4	-6.2	4.3	21.8	8.4	19.0	13.7
B/1	-9.7	10.1	21.4	5.0	55.5	40.0
B/2	-6.8	7.0	20.5	4.4	37.6	27.1
B/3	-9.6	4.5	20.6	2.5	27.1	19.5
C/1	n.a.	8.3	20.2	4.3	44.0	31.7
C/2	n.a.	4.4	21.2	7.1	20.9	15.1
C/3	n.a.	2.8	21.3	3.2	16.7	12.0

Maximum heat loss flow was recorded when all dampers were kept open (see A/1, B/1, C/1 in Table 7). For Stove A differences were low when either primary or secondary air were kept open (Positions 2 and 3); only when all dampers were closed there was always a significantly reduced air flow which created only low loss rate of between 17 and 27 W in average.

Calculated on a monthly basis this lowest loss rate of Stove A would amount to a heat loss of approximately 14 kWh. An equivalent of about 4 kg of wood fuel would be required to compensate for this monthly loss. For the highest loss rate (Stove A at damper position 1) an aggregated monthly cold standing loss of 54 kWh is calculated, it would be compensated by the use of about 16 kg of wood fuel.

Results on losses during chimney cooling. If the stove is operated occasionally, additional heat losses will occur. This was tested by the use of Stove A only. In Figure 50 from two testing days are displayed, it shows the differences between an operational mode with and without a closure of both air dampers after the last batch. When both dampers remain in the same position as during combustion, the temperature of both, stove and chimney, rapidly declines (see dotted line) while a closure of dampers will immediately reduce the flow through the chimney (continuous line) and as a consequence this will prevent convection losses. In Table 8 the results from all 5-h-cooling phases observed during 12 testing days are compiled and sorted in ascending order of the respective chimney draught. It shows that the range of climatic conditions during the tests were quite similar for both settings; they are thus reflecting a typical range of heating days in Germany. It is also shown that the level of mean chimney flow velocity is drastically reduced by about 60 to 70 % when all dampers are shut after combustion.

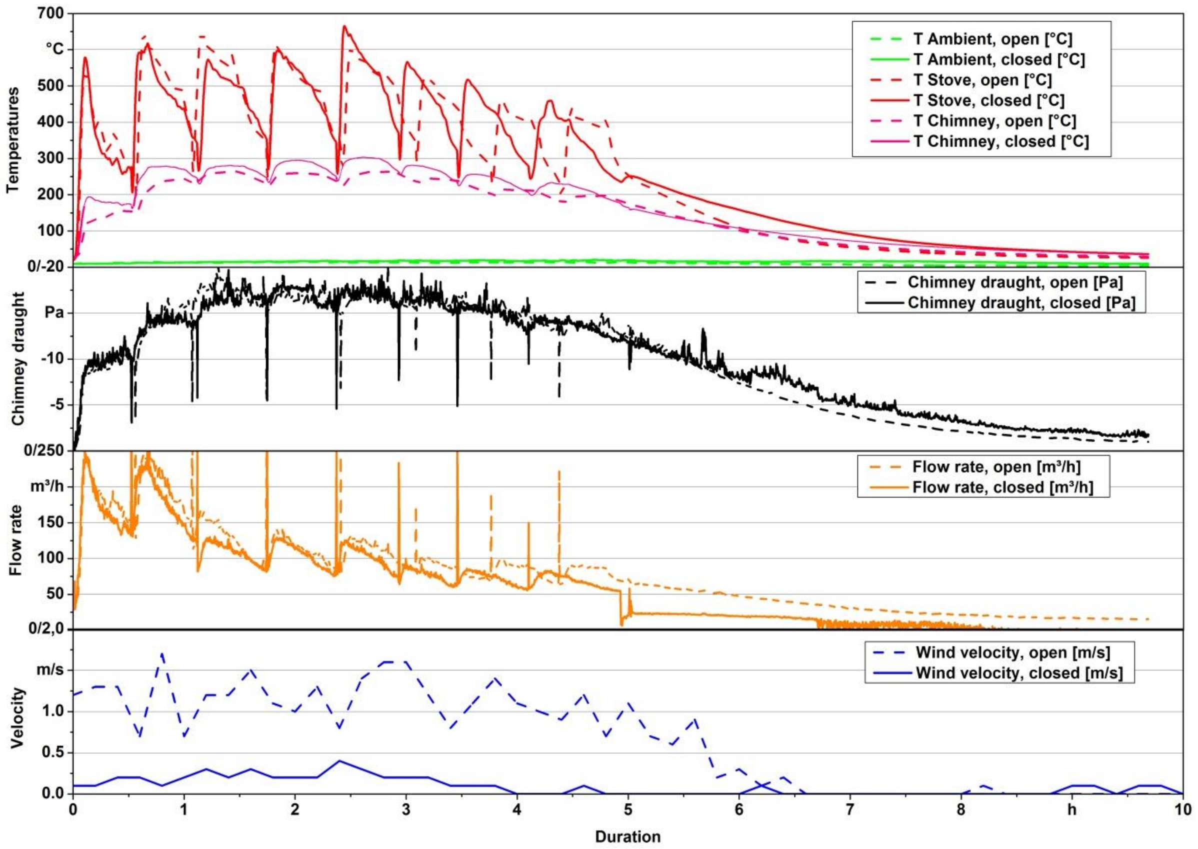


Figure 50: Cooling performance of Stove A at operational mode "closed" (= both dampers are closed after batch 8) and "open" (both dampers are left open after batch 8)

However, there is still a remaining flow, which is either a deliberately realised flow (for safety reasons) or it can be attributed to leakage air intake from an untight stove construction. The post heating losses within the assumed 5-h-cooling phase are shown in Figure 51 as a function of the respective chimney draught. There is a clear correlation which follows a similar pattern as also given for the correlation between chimney flow velocity and chimney draught (see data in Table 8). The fact that the heat losses in Figure 51 did not follow a steady linear increase can be attributed to chimney draught fluctuations which are not easily reflected by the calculated mean value over the 5 h observation period. Additional sources of variation could be either an inconsistency of stove tightness or of the damper positions at closure.

Table 8: Operational conditions and measurement results with Stove A on heat losses during cooling phase (5 h) after combustion (trials sorted by natural chimney draught under given climatic condition)

		Damper settings after heating operation: **"open" (O)**						Damper settings after heating opera **"closed" (C)**				
		O1	O2	O3	O4	O5	O6	C1	C2	C3	C4	C5
Mean heating power losses in post heating phase (5 h)	kW	0.6	0.8	1.0	0.9	1.1	1.1	0.2	0.3	0.3	0.4	0.4
Total of post heating losses	kWh	2.8	4.0	4.9	4.7	5.6	5.4	1.1	1.5	1.5	2.1	1.9
Mean ambient temperature while cooling (5 h)	°C	6.6	24.3	13.8	16.7	4.8	10.7	14.3	14.6	17.4	11.2	17.9
Mean chimney temperature while cooling (5 h)	°C	62.1	96.3	92.3	88.6	82.5	79.8	74.6	85.2	94.5	96.0	93.4
Mean stove temperature while cooling	°C	64.4	120.9	121.2	110.1	95.7	85.1	99.8	106.5	140.8	155.1	132.1
Mean chimney flow velocity	m/s	0.63	0.8	0.92	1.0	1.09	1.24	0.19	0.26	0.2	0.3	0.4
Mean chimney draught	Pa	-3.9	-20.3	-23.3	-27.7	-33.1	-42.5	-5.3	-6.9	-21.3	-26.3	-29.3
Mean atmospheric pressure	mbar	974	978	991	988	970	962	984	969	985	994	987

From Table 8 the mean post heating losses are 4.6 kWh (damper settings "open") and 1.9 kWh (damper settings "closed"). Thus, with Stove A the total directly avoidable post heating losses are around 2.7 kWh. It can be assumed, that there is a high potential for further reducing the avoidable post heating losses. Such reduction could be achieved by applying fully tight air flaps on a central air intake socket while at the same time the stoves should also be highly airtight towards the heated room.

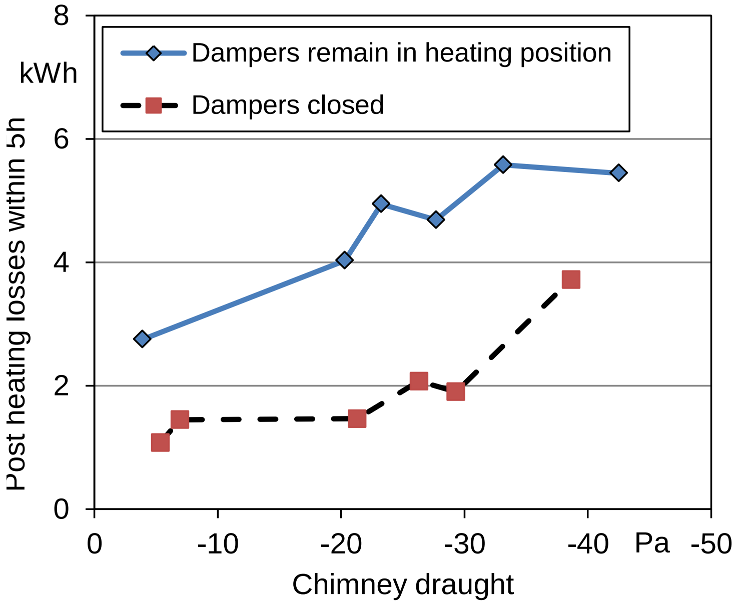


Figure 51: Post heating losses as a function of respective chimney draught

Techno-economic evaluation of standing losses. A model calculation was performed using the measured post heating losses as presented above. It was assumed, that the heating period will last from October until April (i.e. 213 days). For Stove A the usual damper position after a heating cycle would be Position 3 (see equipment used). In this position cold standing losses of 68.3 W were determined (see Table 7) and post heating losses are 4.6 kWh per heating cycle (average of damper setting "open" in Table 8). In an operation with air dampers closed (Position 4) after terminating the heating cycle, a cold standing loss flow of 19 W was assumed while the mean post heating losses were 1.9 kWh per each heating cycle.

With these input data the total standing losses were calculated as shown in Figure 52.

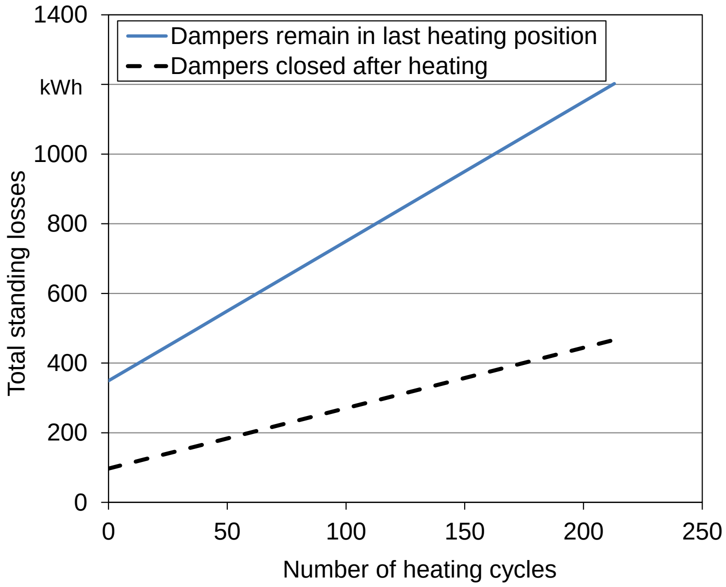


Figure 52: Aggregated total standing losses as a function of the number of annual heating cycles (calculated on measurement results for Stove A)

Figure 52 shows that, given the assumption of the air dampers remaining in the last heating position (which may be regarded as a highly probable case in practice), and with an estimated number of 100 heating cycles per year, the annual heat loss using Stove A amounts to 750 kWh. The heat loss in this example corresponds to approximately 0.5 m³ of staked hard wood logs. If this heat loss shall be replaced by an ordinary heating oil boiler, having an annual efficiency of 85 %, Stove B would then cause additional heating costs in the order of around 62 €/a due to leakage flow through the chimney (at an assumed oil price of 0.66 €/l).

Significant reduction of two thirds of these losses were demonstrated by closing the air dampers after heating operation (Figure 52), although this closure seems to be rather unlikely in practice as the stove burnout usually happens overnight. But even then some losses would remain, they must be accounted to a non-air-tight stove construction and to the fact that even with fully closed air dampers some air may be allowed to enter the stove via the air inlet socket (e.g. for complete coal burnout). Thus, further reduction potential is given by a fully automatic shutdown of the air supply. This could be performed by control systems or also be realized by retrofit flaps with electronical control (see also WP4).

Conclusions. Both, room heat and such heat which is still stored in a stove can easily be exhausted through the chimney of a log wood stove; this can account for notable heat losses which are usually not evaluated in stove tests. Modern stoves with automatic combustion air inlets can reduce such heat losses to a minimum by closing the air supply or the flue gas connection when the stove has cooled down to a given temperature level.

Heat losses through chimneys after termination of heating operation should generally be regarded in economic viability calculations for additional stove features such as automatic air inlet flaps. However, it should also be clarified if a complete closure of air inlet flaps is compliant with given legal safety restrictions.

References: [1] Rawe, R. et al. (2004): Energieverluste von Gebäuden infolge Luftströmungen durch Abgasanlagen Einsparungen durch Abgasklappen, Fachhochschule Gelsenkirchen

3.3 Evaluated concepts for stove draft stabilization

The results from the evaluation of draught stabilizers are presented together with the semi-automatic stove control devices (see chapter 1.6). This was deemed useful due given functional similarities with retrofit flue gas flow control devices and combustion air control devices.

3.4 Summary on chimney draught impact on emissions and efficiency

Comprehensive investigations on stove performance as a function of chimney draught had been performed in previous projects. The results were comprehensively presented and discussed in the consortium. In the following the main results can be summarised for this report.

As shown in Figure 53 the influence on CO and OGC emissions by applying different chimney draughts is highly stove dependant. Depending on the flue gas flow properties and the air distribution, the gaseous emission increases or decreases with higher chimney draught.

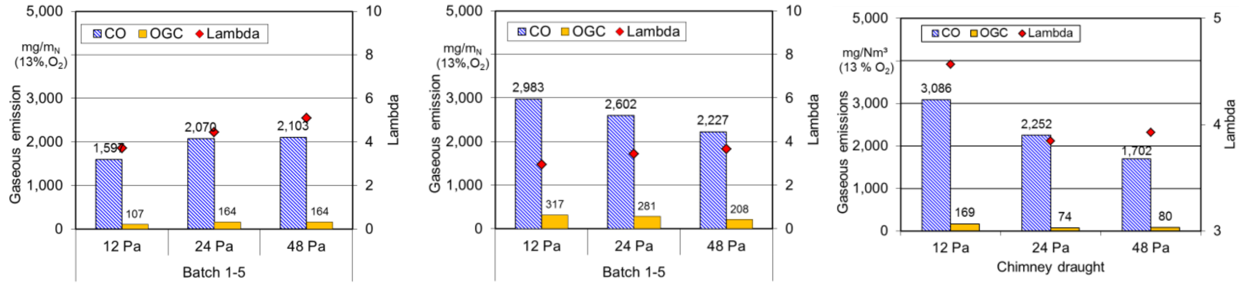


Figure 53: Influence of different chimney draught applied to stove a (left), stove b (middle) and stove c (right) on CO and OGC emissions

The influence of chimney draught on particle emissions follows no clear trend (Figure 54). It seems that the particle emissions rather remain stabile.

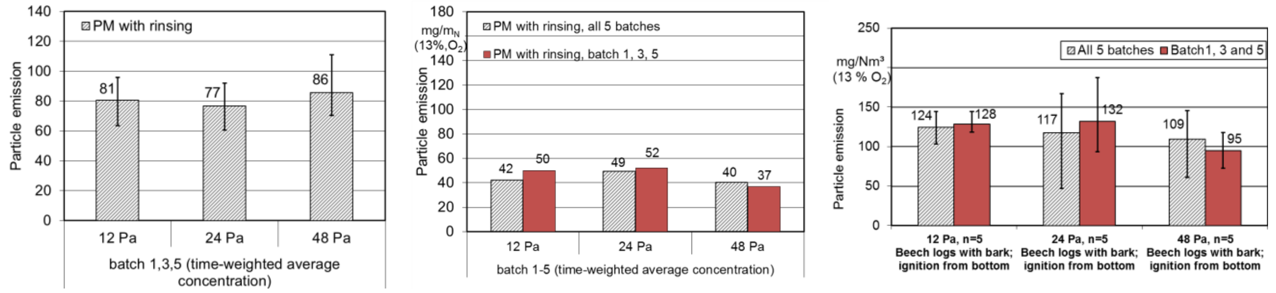


Figure 54: Influence of different chimney draught applied to Stove A (left), Stove B (middle) and Stove C (right) on particle emissions

Regarding the efficiency, all tested stoves are sowing the same trend (Figure 55). The efficiency is decreasing significantly at higher draught pressure levels.

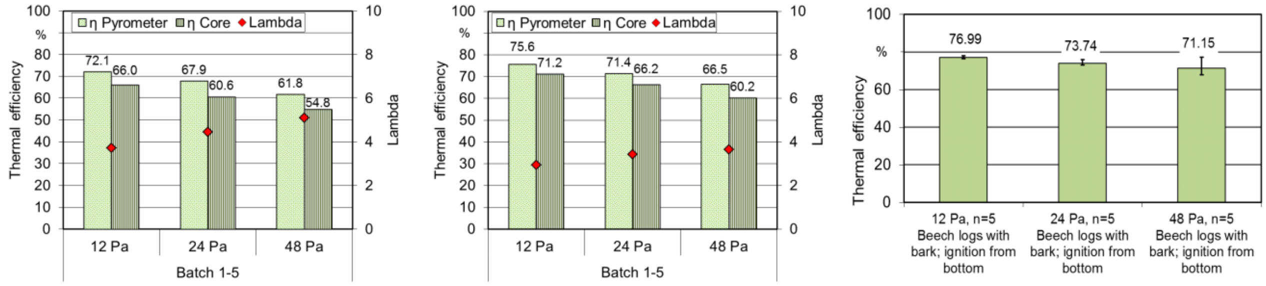


Figure 55: Influence of different chimney draught applied to Stove A (left), Stove B (middle) and Stove C (right) on efficiency

3.5 Potential for fan stabilized combustion (RISE/Nibe)

Insufficient draft at stove operation will result in insufficient air supply to the combustion chamber, which causes incomplete combustion and therefore increases hazardous emissions released into the atmosphere. The most critical timeframe of stove operation is the ignition phase, when stove and chimney are cold. This results in a fast flue gas cool-down which minimizes the natural draft induced by temperature differences to ambient air. This problem has been reported in literature, primary when the stove was connected to an existing large masonry chimney.

Problems with insufficient draft can also occur when secondary measures create a large flow resistance across the stove. As already reported in the chapter before, filters and catalyst can cause such a large pressure drop, which will even increase during operation due to particle blockage. Besides impairment of the general combustion conditions this will lead to another critical moment when the door is opened for recharging. At that time the large air flow into the stove will increase flow resistance across the stove even further, thus minimizing natural draft in the chimney. At insufficient draft conditions there will be a higher risk for flue gas backflow during recharging, which poses as an immediate thread for personal health and effect indoor climate. See Figure 56 as an example for this, where the pressure drop across the catalyst increases to more than double when the door is opened.

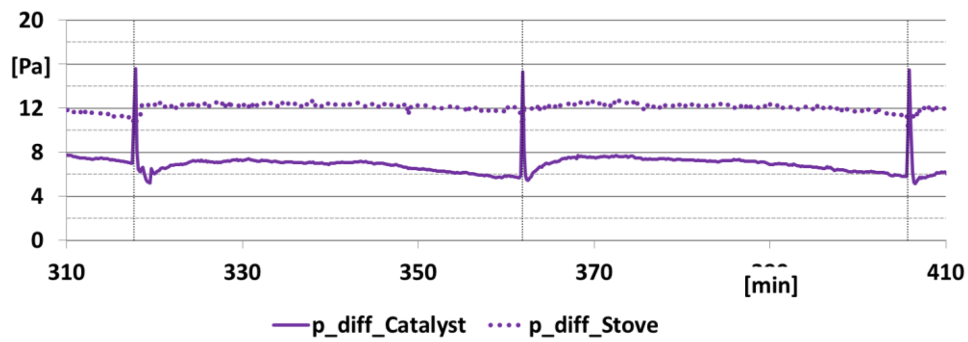


Figure 56: Pressure drop trend across catalyst at recharging

In order to confirm and quantify problems related to insufficient draft at cold start, RISE conducted comparison tests at various draft conditions. The study was done with the same stove at identical boundary

conditions (cold stove; same wood mass, wood condition and placement in stove) and at four different draft levels: 12, 8, 5 and 2 Pa.
The results of the study can be summarized as follows: At the 12 Pa draft level ignition was quick; the combustion was stable with low emissions and a good charcoal burnout. Already at 8 Pa a decrease in performance could be observed and at low draft levels combustion was really bad (see Figure 57). At 2 Pa, for example, CO emissions were twice as high and OGC emissions even seven times as high as at 12 Pa. Large amounts of soot and tar were formed and the fire was several times close to extinction. This is because at low draft levels the oxygen supply is insufficient to generate the heat needed for drying and pyrolysis.

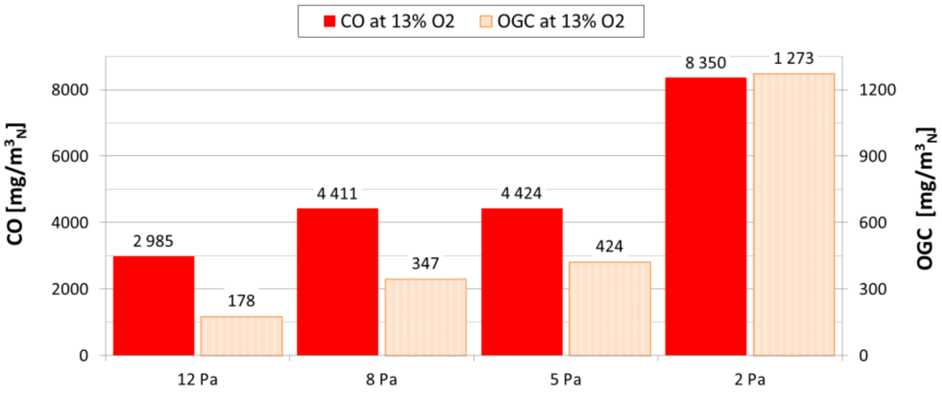


Figure 57: Comparison of CO & OGC for ignition batch at different draft levels

The tests demonstrated that sufficient draft is essential for a stable combustion with low emissions. It is therefore necessary to take draft conditions already into account during installation and use of the stove. The following risk factors should be considered:

- Low chimney height
- Existing large masonry chimney shall be used for newer stoves. Natural draft will improve with operation time when the chimney is warmed up by the flue gas. Since such masonry chimneys have a large heat capacity, this warming period will take longer time than for alternative chimneys. Additionally with installation of modern more efficient stoves, flue gas volume and temperature are lower than with older stoves, thus providing less heat to warm up the chimney.
- Appliances that increase flow resistance have been installed in the chimney, as for example retrofit catalysts or flaps.
- Kitchen fans (in combination with new tight buildings) can lead to a significant pressure decrease in the room, thus preventing the formation of sufficient draft in the chimney.
- Stoves with integrated particle filter or catalyst. In such cases, the manufacturer should give instructions how much draft is needed and how critical operating phases as ignition and recharging should be handled.

If one or several risk factors apply the actual draft conditions at place should be evaluated and cross-checked with the stoves minimum draft requirement. Sometimes an alternative chimney construction, either new or retrofit, could already be enough to eliminate the risk factors and increase draft. If these measures are not applicable or not enough, a flue gas fan could be the solution to ensure sufficient combustion conditions. The following points should be considered when selecting and installing a flue gas fan:

- To avoid overpressure in the chimney and flue downstream the stove, it is advantageous to place the fan on the top of the chimney. This location also helps to minimize noise emissions.
- The size of the fan should be sufficient to generate the required draft at all conditions, this means for example even for full load operation at poor weather conditions.
- The flue gas fan should be capable to withstand flue gas exposure in terms of expected gaseous and particle emissions.
- Fan operation should be controlled to keep the draft at recommended levels. This control can be a stand-alone solution or integrated into an automated stove control system.
-

4 WP 4: Testing and evaluation of the technologies developed

All results from the test runs performed with the respective technologies in WP4 are presented in the respective chapters where the technology and achieved concepts itself are presented in full detail (see chapters 1, 2 and 3).

4.1 Common method for testing of the improved stoves or system components under harmonised conditions

For those developments and devices, which require a close to real-life testing procedure for realistic assessment, a common test approach was developed and agreed in the project. A brief summary of this procedure is described in the following.

Measurement section and equipment. The measurement section should be designed according to good laboratory practice, with regard to required inlet/outlet zones and sufficient tightness of the measuring points. The position of flue gas temperature measurement for efficiency determination should follow DIN EN 13240. It can be performed by using thermocouple or suction pyrometer. If a suction pyrometer is used a flue gas velocity in the free cross section (5±1mm) of 20 to 25 m/s shall be reached as defined in DIN EN 13240. No burning scale is required because log fuel shall be weighted individually.

Testing procedure. The testing procedure should reflect the new devices' and technology's “real life” performance. For this reason the method was defined to be largely in accordance with the "beReal method" as developed in the beReal project, when applicable. Further information can be found on http://www.bereal-project.eu/.

Prior to and after all measurements at one stove a leakage test at 5 Pa, 10 Pa, 15 Pa (3 repetitions) should be performed by applying under-pressure from the flue gas socket while the all air supply ducts remain closed (according prEN16510). The actual combustion tests should then be executed using a constant flue gas draught of (12 ± 2) Pa.

The fuel consumption is determined by weighing the wood charged into the stove. The testing fuel used should be beech or birch, without bark, having a triangle shape. The ash content of the test fuel should be <1 % and the moisture content should be at (16 ± 4) % (sampling and determination without delay).

The test runs are executed by performing 8 successive batches (5 full load + 3 partial load) starting from cold conditions (including 1st ignition batch). The Moment of refilling is reached when the CO_2 content of the flue gas is ≤4 % and ≤25 % of the maximum CO_2 content of the respective batch or if CO_2-max is ≤12 % the refilling should occur at 3 % CO_2 when flames are extinguished. Figure 58 shows a flowchart of a whole test run including all refilling criteria. The mode of refilling is defined by the stove manufacturer or RTD partner in a so called “Quick-User Guide”.

Poking, raking, and levelling-out of the fire bed can be done before recharging or an optional charcoal burnout. At refilling the door opening should last for 60 seconds at maximum.

The air damper settings shall be defined by the manufacturer (in the "Quick-User Guide"). Two to maximum three different damper settings for heating operation can be defined for:

- Ignition batch + (if necessary) 2nd preheating batch
- Heating operation (max. two damper positions)
- Partial load (one additional damper position, if specified by manufacturer)
- Charcoal burnout

If a stove is automatically controlled there can be a build-up of a charcoal bed over the 5 full load batches. In this case the charcoal burnout can be measured in the transient phase to the partial load or at the end of partial load. The automated process control has to display the beginning and the end of charcoal burnout.

Operation during charcoal burnout:

a) Manual stove operation: No additional charcoal burnout should be performed
b) Automatically controlled stoves (either after batch 5 or 8):

After batch 5: End of charcoal burnout is given at recharging signal.

After batch 8: End of charcoal burnout is given at recharging or other adequate signal.

Poking of charcoal shall be made only if the user is called for by the automated control system. Temperature and flue gas volume measurement (hot-wire anemometer or vane wheel anemometer) continues at -12 Pa draught, residues are sampled for carbon content.

An additional PM sampling is made during charcoal burnout, gaseous components are measured as well. The complete residues shall be removed from the stove and the mass has to be documented.

The cool down phase begins when the refilling criterion is reached or when f the controlling system gives the refilling signal at the end of batch 8. The cool down phase ends when a temperature of 50°C at the flue gas socket is reached. The temperature and volume flow measurement shall be continued after the CO_2 target is met (see testing procedure) or when the air flap closure was performed automatically, if applicable.

The heat losses will be evaluated from the end of batch No 8 till 50°C flue gas temperature is reached.

If the air flaps close completely and if the stove shows good air-tightness, an evaluation of the heat losses of the flue gas during the cool down phase does not seem meaningful.

If a heat storage unit is integrated in the stove, partial load operation is not meaningful when the stove is already in steady state operation after full load operation (5 batches) as the heat storage ratio decreases.

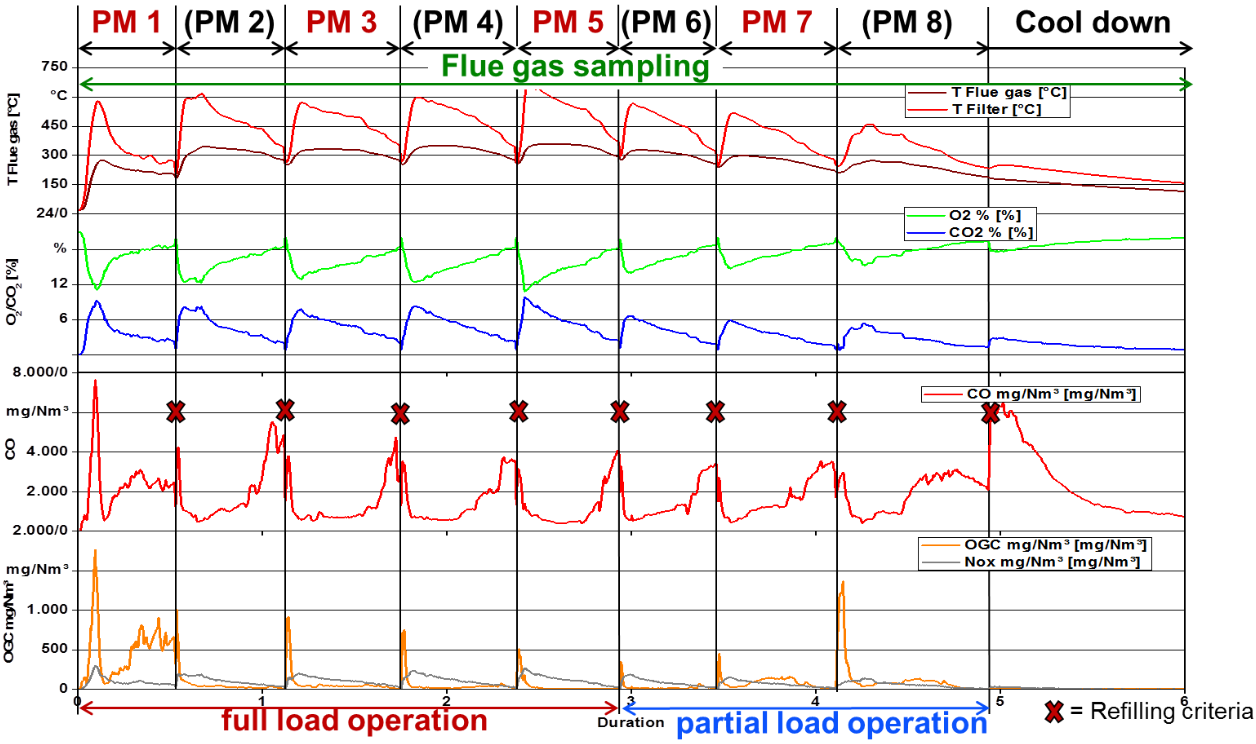
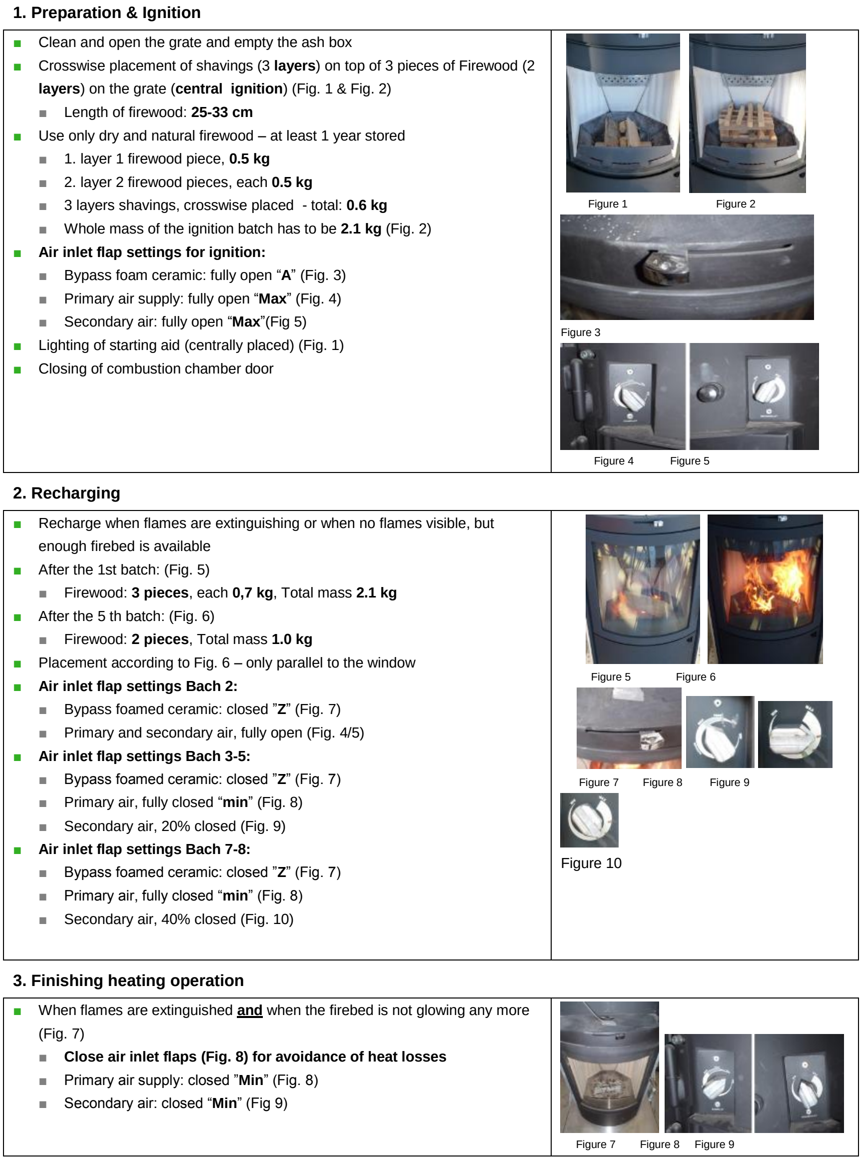


Figure 58: Flow chart of testing procedure for improved wood log stoves

Quick user guide. The appliance is operated according to a Quick-User-Guide (Text & Pictures) shown in an example for Hark 44 GT ECOplus in Figure 59. The information of the Quick-User-Guide is provided by the manufacturer and defines relevant operation characteristics that are specific for the appliance:

- Preparations before heating operation
- Mode of ignition
- Mode of refilling
- Requirements of firewood – dimensions, number of pieces per batch, arrangement of wood logs in the combustion chamber, for full load and part load
- Adjustments of damper settings for combustion air supply (during and after heating operation), for full load and part load



1. Preparation & Ignition

- Clean and open the grate and empty the ash box
- Crosswise placement of shavings (3 **layers**) on top of 3 pieces of Firewood (2 **layers**) on the grate (**central ignition**) (Fig. 1 & Fig. 2)
  - Length of firewood: **25-33 cm**
- Use only dry and natural firewood – at least 1 year stored
  - 1. layer 1 firewood piece, **0.5 kg**
  - 2. layer 2 firewood pieces, each **0.5 kg**
  - 3 layers shavings, crosswise placed - total: **0.6 kg**
  - Whole mass of the ignition batch has to be **2.1 kg** (Fig. 2)
- **Air inlet flap settings for ignition:**
  - Bypass foam ceramic: fully open “**A**” (Fig. 3)
  - Primary air supply: fully open “**Max**” (Fig. 4)
  - Secondary air: fully open “**Max**”(Fig 5)
- Lighting of starting aid (centrally placed) (Fig. 1)
- Closing of combustion chamber door

2. Recharging

- Recharge when flames are extinguishing or when no flames visible, but enough firebed is available
- After the 1st batch: (Fig. 5)
  - Firewood: **3 pieces**, each **0,7 kg**, Total mass **2.1 kg**
- After the 5 th batch: (Fig. 6)
  - Firewood: **2 pieces**, Total mass **1.0 kg**
- Placement according to Fig. 6 – only parallel to the window
- **Air inlet flap settings Bach 2:**
  - Bypass foamed ceramic: closed ”**Z**” (Fig. 7)
  - Primary and secondary air, fully open (Fig. 4/5)
- **Air inlet flap settings Bach 3-5:**
  - Bypass foamed ceramic: closed ”**Z**” (Fig. 7)
  - Primary air, fully closed “**min**” (Fig. 8)
  - Secondary air, 20% closed (Fig. 9)
- **Air inlet flap settings Bach 7-8:**
  - Bypass foamed ceramic: closed ”**Z**” (Fig. 7)
  - Primary air, fully closed “**min**” (Fig. 8)
  - Secondary air, 40% closed (Fig. 10)

3. Finishing heating operation

- When flames are extinguished **and** when the firebed is not glowing any more (Fig. 7)
  - **Close air inlet flaps (Fig. 8) for avoidance of heat losses**
  - Primary air supply: closed ”**Min**” (Fig. 8)
  - Secondary air: closed “**Min**” (Fig 9)

Figure 59: Example for a quick user guide for the Hark 44 GT ECOplus

Additional procedure for stoves with combustion air controllers. If the controller is built-in into the flue gas duct the tests shall be executed on a natural draught chimney otherwise the tests will be performed at a constant draught of -12 Pa. If the controller gives a refilling signal, this signal should be considered as refilling criterion, even if it indicates the time of refilling prior to having met the CO_2 criterion.

To evaluate the effects of the controller compared to a common stove, one test (3 repetitions, each consisting of 8 batches) shall to be executed without using the controller (recharging according to CO_2 criterion).

Flue gas sampling

Measured gaseous components (uncertainties and measurement ranges of instruments):

O2	0 vol.-% to 21 vol.-%, ± 0.4 vol.-%
CO2	0 vol.-% to 20 vol.-%, ± 0.4 vol.-%
CO	0 ppm to 15.000 ppm, ± 10% (0-500 ppm: ± 10 ppm/ 0-3000 ppm: ± 45 ppm)
NOx	0 ppm to 500 ppm, ± 5 %
OGC	0 ppm to 10.000 ppm, ± 5 % of current measurement range

Gaseous components are continuously measured during all test batches. The data measuring and logging interval has to be at least ≤ 10 seconds.

Particle sampling. Particle sampling shall be executed during batches 1, 3, 5 and 7 or during all batches, if two independent sampling tracts are available. Particle sampling starts at cold stove before ignition (i.e. when a match ignites the ignition block), resp. before opening the door when recharging.

The recommended filter materials are a cartridge stuffed with quartz wool combined with a plane filter (or compatible). It has to be ensured that an entire batch can be measured without interruption. The filter pre-treatment has to be at 180 °C, according to individual laboratory practise (i.e. ≥1 h at 180 °C cooling in desiccator for ≥8 h). The filtration temperature should be kept constant at 180 °C (same temperature as for OGC sampling). The filter post-treatment shall be set at 180 °C, according to individual laboratory practise (i.e. TFZ: ≥1 h at 180 °C cooling in desiccator for ≥8 h).

If a diameter of 150 mm is used for the measuring section the nozzle shall be 12 mm diameter. The nozzle orientation shall be upstream. During particle measurement isokinetic or over-isokinetic conditions should be assured at the nozzle.

After the measurement a rinsing of the sampling probe (i.e. the nozzle, elbow and connecting pipe) with acetone has to be performed, as illustrated in Figure 60. The rinsing procedure of the sampling probe shall be repeated 2 to 3 times. Afterwards the acetone shall be evaporated in an appropriate drying oven. The rinsing container should be post-treated like done with the loaded filters (1 h at 180 °C, Cooling down in desiccator ≥8 h). The residues through rinsing shall be proportionally distributed to the load as determined on the filters that were used with the respective sampling probe.

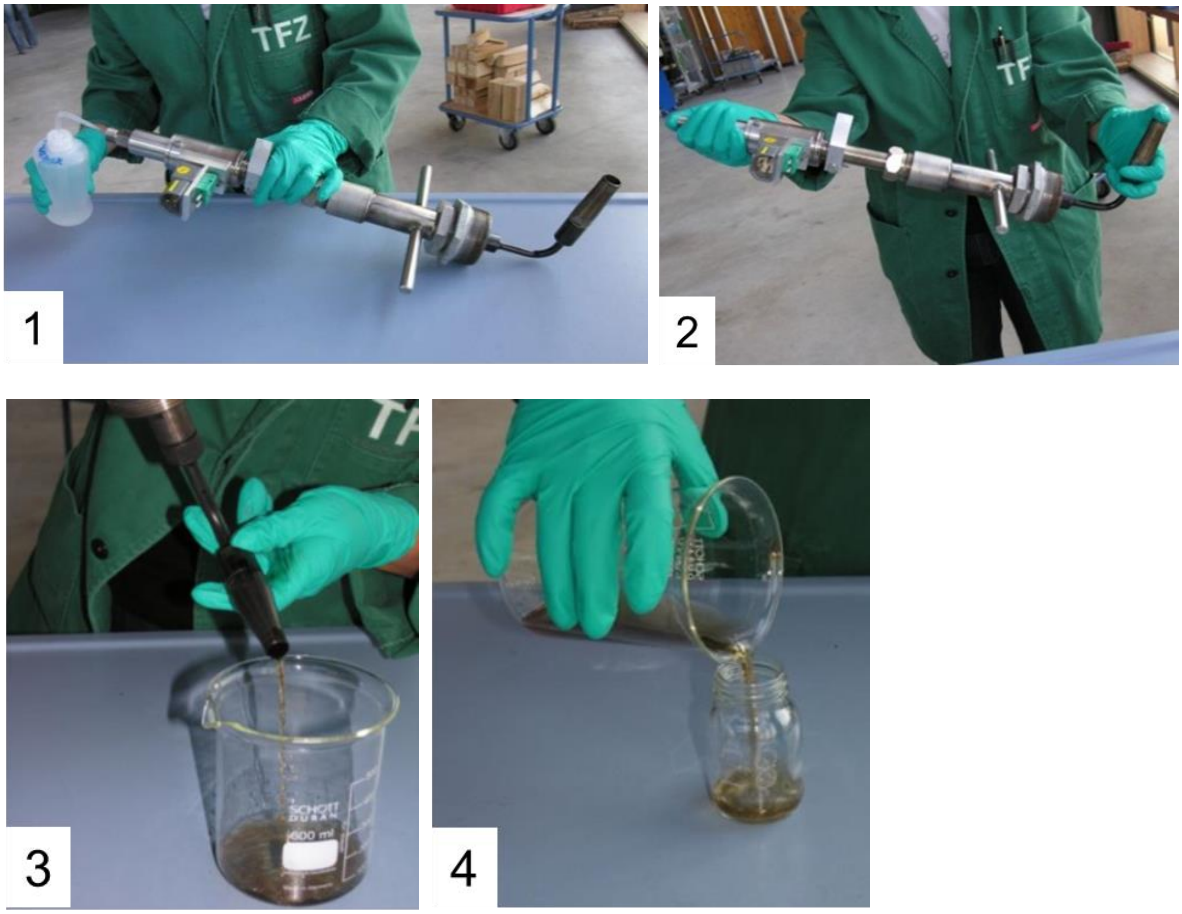


Figure 60: Execution of rinsing of PM sampling tract (source: TFZ)

Data evaluation. The emissions will be evaluated based on the flue gas volume, which means in mg/MJ, derived from dividing the overall mg value by the fuel power input related to the NCV of the fuel mass converted during the batch (beech wood without remaining charcoal and fuel ash Table 9). The overall mg value equals the added sum of measured flue gas volume flow (Nm³ d.b.) multiplied with the measured concentration (mg/Nm³ d.b.) at each time interval (e.g. 10 seconds).

Table 9: Example for calculating the converted net calorific value of the converted fuel

Fuel composition		**Beech wood**[1)]	**Beech wood without remaining charcoal**[2)]
Parameter	**Unit**		
moisture content	[wt.% w.b.]	15.00	15.80
carbon	[wt.% d.b.]	49.1	45.6
hydrogen	[wt.% d.b.]	6.1	6.6
oxygen	[wt.% d.b.]	44.4	47.7
ash content[3)]	[wt.% d.b.]	0.4	0.00
gross calorific value (GCV)	[wt.% d.b.]	19.3	18.7
net calorific value (NCV)	[wt.% w.b.]	15.0	14.2

[1)] fuel composition according to wet chemical analyses;

[2)] fuel composition without remaining charcoal (including fuel ash) at the end of batch; thus this fuel composition is related to the fuel converted during the batch; composition of remaining charcoal (including fuel ash): 92.5 wt.% C, 0.8 wt.% H, 1.5 wt.% O, 5.2 wt.% ash;

[3)] remaining charcoal includes entire fuel ash; therefore ash content of fuel converted during the batch (beech wood without remaining charcoal) is equal to 0

Calculation of thermal efficiency (for the complete cycle) shall follow prEN 16510 / DIN EN 13240, added by losses during cool down phase (q_{cool}) and a determination of the losses from residues (q_r) instead of accepting the suggested standard devault value of 0.5 %.The efficiency will be evaluated as one time weighted average value including all measurements of all considered batches (for thermal (q_a) and chemical (q_b) flue gas losses). Only for automated stoves the charcoal burnout is calculated as an additional batch (i.e. 9 batches in total).

Thermal flue gas losses are calculated over the complete combustion and cool down phase. If the stove closes the air valves completely (measured volume flow below the detection limit e.g. 0.2 m/s) the losses through the cool down phase are set to zero. Chemical flue gas losses are respected from ignition until 18 % O_2-content or until automatic flap closure after batch 8, respectively. The following calculation are followed:

$$\eta = 100 - (q_a + q_b + q_{residue} + q_{cool})$$

$$q_{cool} = \frac{\left((\sum \dot{m}_{air} * \Delta t) * c_{p_{air}} * \Delta T\right)}{m_{fuel} * H_u}$$

$$\Delta T = (T_{flue\ gas} - T_{amb})$$

with:

m_{air} = mean mass flow of air through the chimney [kg/s]; $c_{p,\ air}$ = effective heat capacity of air [kJ/kg*K]; ΔT = temperature difference between flue gas at the standard measuring point and ambient temperature [K]; m_{fuel} = fired fuel mass[kg]; H_u = lower calorific value of the fuel used [kJ/kg]; Δt = time interval for measurement logging [s].

Losses from unburned residues on the grate are calculated as follows:

$$q_r = \frac{m_{residues} - m_{fuel} * a \ * H_{u,C}}{m_{fuel} * H_{u,fuel}} * 100\%$$

Testing procedure for stoves with integrated catalysts. To give an idea of the long-term performance of high or medium temperature catalyst, a ”long-term” operation of the stove (over two weeks) with each catalyst shall to be performed. Within these two weeks four dedicated testing campaigns with emission measurements are performed. CO and OGC emission reduction are determined. In addition the effects of catalyst cleaning after 2 weeks of operation on the emission reduction and the pressure drop caused by the should be detected.

The measurements should be executed according to the method already described above. The catalyst evaluation should be performed either with split flue gas (parallel catalyst and dummy measurement) as shown in Figure 61 (this is the preferable procedure), or by applying catalyst and dummy in sequential test runs. Therefore one testing day (5 full load + 3 partial load batches) with catalyst followed by one testing day (5 full load + 3 partial load batches) with dummy shall be performed. As dummy a catalyst without catalytic coating and identical flow conditions has to be used.

Flue gas temperature measurement before catalyst inlet and online pressure drop measurements over the catalyst needs to be performed, if possible. The duration from ignition until reaching the catalyst's light-off-temperature (i.e. beginning of significant emission reduction) should be determined.

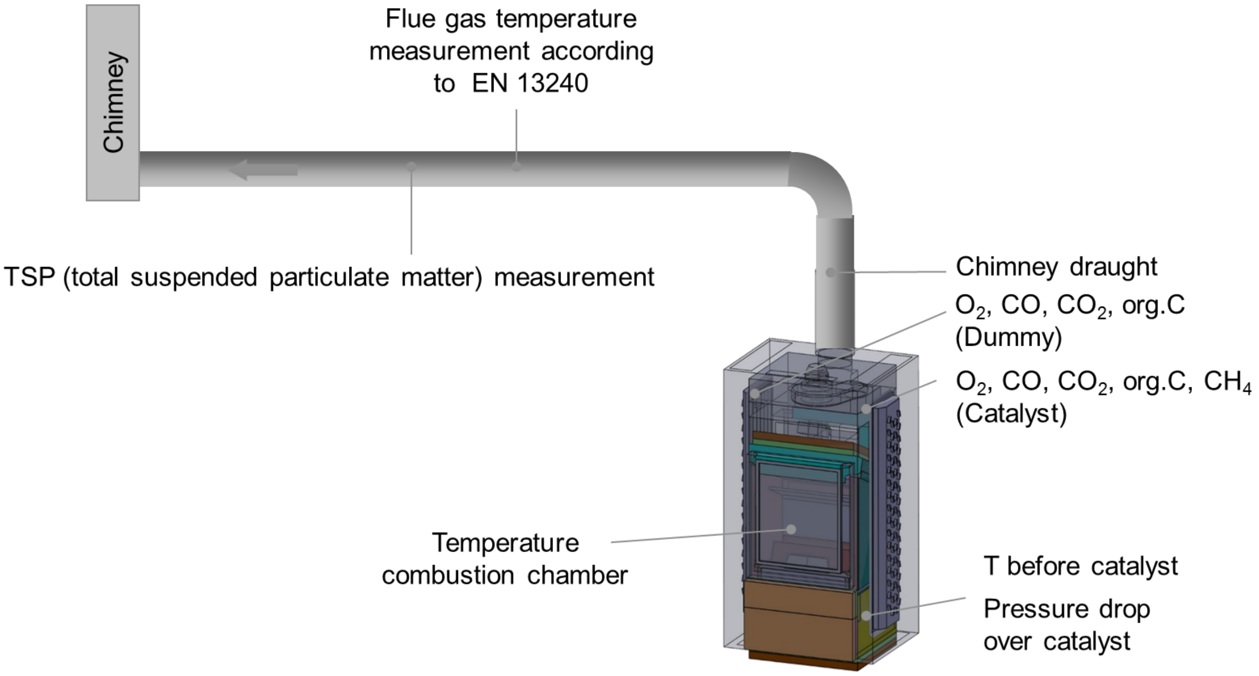


Figure 61: Example for a test stand with split flue gas section (source: BIOS)

Execution of tests. The stove has to be operated over at least 2 weeks (i.e. 10 working days). Within this operation period four dedicated measurement days are included, they are performed as follows:

With split flue gas section:

- 1st day of operation
- after one week of operation (day 6)
- after two weeks of operation (day 11)
- after manual cleaning of the catalyst after 2 weeks of operation (day 12)

Without split flue gas section in sequential test runs:

- 1st day of operation (day 1 with catalyst + 1 test with dummy)
- after one week of operation (day 6 with catalyst + 1 test with dummy)
- after two weeks of operation (day 11 with catalyst + 1 test with dummy)
- after manual cleaning of the catalyst after 2 weeks operation (day 12 with catalyst + 1 test with dummy)

5 WP 5: Elaboration and dissemination of guidelines for the design of future low emission stoves and for the retrofit of old stoves

In the project three guidelines were commonly developed; they compile the achieved knowledge in a compact and structured way to become easily accessible for engineers and developers:
(1) The *"Guidelines for Low Emission and High Efficiency Stove Concepts"* summarizes the outcome of the investigations regarding the improvement of wood stoves with respect to emissions and efficiency. It is

meant to support stove manufacturers concerning the optimisation of their products and the development and design of new products. The recommendations given were worked out based on scientific investigations and comprehensive test runs. The complete document is available for download here (free of costs).

(2) The *”Guidelines for heat storage units based on Phase Change Materials (PCM)”* summarises the outcome of the investigations regarding the development of heat storing stoves using phase Change Materials (PCM) to achieve higher efficiency and heating comfort. It is meant to support stove manufacturers concerning the optimisation of their products and the development and design of new products. Its recommendations had been worked out based on scientific investigations as well as comprehensive test runs. The complete document is available for download here (free of costs).

The *”Guidelines for automated control systems for stoves”* summarises the outcomes of the investigations regarding the improvement of wood stoves by the application of automated control concepts as a primary measure for emission reduction. It is meant to support stove manufacturers concerning the optimisation of their products and the development and design of new products and its recommendations were elaborated based on scientific investigations as well as on comprehensive test runs. The complete document is available for download here (free of costs).

In order to disseminate the project results to a broad public audience, an international project workshop was organised as final project event. Many stakeholders from the participating countries were invited and moreover. All presentations can be downloaded here (free of costs). The workshop agenda is given in the following:

- Welcome and introduction (Hans Hartmann, TFZ)
- Quantification of energy losses during wood combustion in stoves (Hans Hartmann, TFZ)
- Flue gas sensors testing and evaluation (results of RISE and BIOS) (Ingmar Schüßler, RISE)
- Development of integrated stove control systems based on temperature sensors (results of BIOS and Rika) (Christoph Mandl, BIOS)
- Retrofit controlling units and modern draught stabilizers for stoves, results of TFZ and K+W (Robert Mack, TFZ)
- Selection and integration of high temperature catalysts into a stove(Thomas Brunner, BIOS)
- Selection and testing of medium temperature metal based mesh catalysts for stoves (Ingmar Schüßler, RISE)
- Improved high efficiency low emission stove concept including an PCM heat exchanger, results by (BIOS and Rika) (Ingwald Obernberger, BIOS)

6 WP 6: Management and coordination

The consortium agreement has been prepared and signed by all partners till 18th of November 2017. Furthermore within the project one kick-off meeting and 5 additional, semi-annual consortium meetings were organized and held, in cooperation with the respective local partners. This ensured an intensive communication and co-operation between the partners and enabled the successful completion of all tasks, work packages and the project as a whole within the given schedule. The meetings were:

- Kick-off meeting 27th to 28th of October 2014 in Straubing (Germany), TFZ
- 2nd consortium meeting 20th to 21st of April 2015 in Lyngby (Denmark), DTU/HWAM
- 3rd consortium meeting 18th to 19th of November 2015 in Bad Hall (Austria), RIKA
- 4th consortium meeting 12th to 13th of Mai 2016 in Borås (Sweden), SP/Contura
- 5th consortium meeting 21st to 22nd of November 2016 in Graz (Austria), BIOS
- 6th consortium meeting 18th to 19th of Mai 2017 in Maisach (Germany), K+W

Moreover a data cloud for the data exchange between all partners was provided and the distribution of the results and outcomes of the meetings was managed. For the dissemination of results, guidelines and other publications which were produced in the project, a download page was created on the web pages of the coordinator (TFZ). The download of all documents is guaranteed without any expiration of the links.

2. If applicable, problems and changes in objectives *(Describe the difficulties and problems that have hindered the achievement of the planned objectives, if any, and any alternative plan or change with respect to the former proposal)*

There haven't been any problems and changes in the objectives.

3. Collaboration within the consortium *(Describe exchange of personnel, actual share of facilities etc. within the consortium)*

No comments (see answers in section *"How has the ERA-Net made a difference to your research or business?"*)

4. Project-derived exploitation, e.g. patents, publications

*4.1 Publications of single partners (**without** involvement of other partners)*	See below in list of publications: No. 1, 2, 3, 4, 5, 6, 8,
*4.2 Publications **with** the involvement of other partners of the consortium*	See below in list of publications: No. 7, 9, 10, 11, 12, 13, 14, 15
*4.3 Patents of single partners (**without** involvement of other partners)*	No patents were created during the project period.
*4.4 Patents **with** the involvement of other partners of the consortium*	No patents were created during the project period.
4.5 Other exploitation	

Table 10: List of publications and dissemination work

No.	Partner involved	Type	Person	Year	Event or media / Title
1	TFZ	Conference / workshop presentation	Robert Mack, Dr. Hans Hartmann	2015	IEA workshop: Performance of foam ceramic elements in log wood stoves
2	TFZ	Conference / workshop paper	Robert Mack, Dr. Hans Hartmann	2016	EUBCE: Performance of catalytic and non-catalytic foam ceramic elements in log wood stoves
3	TFZ	Conference / workshop paper	Robert Mack, Dr. Hans Hartmann	2016	EUBCE: Standing losses via chimney when using log wood stoves
4	TFZ	Conference / workshop presentation	Robert Mack, Dr. Hans Hartmann	2016	EUBCE: Performance of catalytic and non-catalytic foam ceramic elements in log wood stoves
5	TFZ	Poster	Robert Mack, Dr. Hans Hartmann	2016	EUBCE: Standing losses via chimney when using log wood stoves
6	TFZ	Conference / workshop presentation	Robert Mack, Dr. Hans Hartmann	2016	Abscheider Fachgespräch: Wirkung eines katalytisch aktiven Schaumkeramikeinbaus im Kaminofen
7	TFZ	Conference / workshop presentation	Robert Mack, Dr. Hans Hartmann	2017	Arbeitskreis Holzfeuerungen: Beurteilung nachrüstbarer Verbrennungsluftregelungen für Kaminöfen

8	TFZ	Conference / workshop presentation	Dr. Hans Hartmann, Robert Mack	2017	ECUBE-final-workshop: Quantification of energy losses during wood combustion in stoves
9	RISE/BIOS	Conference / workshop presentation	Ingmar Schüssler	2017	ECUBE-final-workshop: Flue gas sensors testing and evaluation
10	BIOS/RIKA	Conference / workshop presentation	Dipl. Ing. Dr. Christoph Mandl	2017	ECUBE-final-workshop: Development of integrated stove control systems based on temperature sensors
11	NIBE/RISE	Conference / workshop presentation	Johan Furborg	2017	ECUBE-final-workshop: Development of integrated stove control systems based on temperature and flue gas sensors
12	TFZ/K+W	Conference / workshop presentation	Robert Mack, Dr. Hans Hartmann	2017	ECUBE-final-workshop: Retrofit controlling units and modern draught stabilizers for stoves
13	BIOS/RIKA	Conference / workshop presentation	Dipl.-Ing. Dr. Thomas Brunner	2017	ECUBE-final-workshop: Selection and integration of high temperature catalysts into a stove
14	RISE/NIBE	Conference / workshop presentation	Ingmar Schüssler	2017	ECUBE-final-workshop: Selection and testing of medium temperature metal based mesh catalysts for stoves
15	BIOS/RIKA	Conference / workshop presentation	Prof.Univ.-Doz. Dipl.-Ing. Dr. Ingwald Obernberger	2017	ECUBE-final-workshop: Improved high efficiency low emission stove with integrated PCM heat exchanger

5. Other comments *(on procedures or incl. feedback to the funding organisations, e.g. regarding the contract negotiation phase etc.)*

No comments

6. Publishable executive summary of the project and its progress

Please add 3 high resolution pictures with an explanation when you return the report to matté.brijder@rvo.nl

What are the results and the relevance of the project + impact on day-to-day life? *(about 4000 characters or 800 words)*
Please include any relevant information about your project partners as well. *(Max. 1000 characters or 150 words)*

Log wood stoves contribute significantly to renewable heat production in Europe. But new efficiency and emission requirements are challenging. Therefore the project "WoodStoves2020" aimed at investigating and improving complete systems of a wood stove appliances, addressing all major technological aspects, from air supply, stove geometry, heat storage capability, sensors and electronics, up to the chimney and its components (Figure 62). Both, thermal efficiency and flue gas emissions were in the focus.

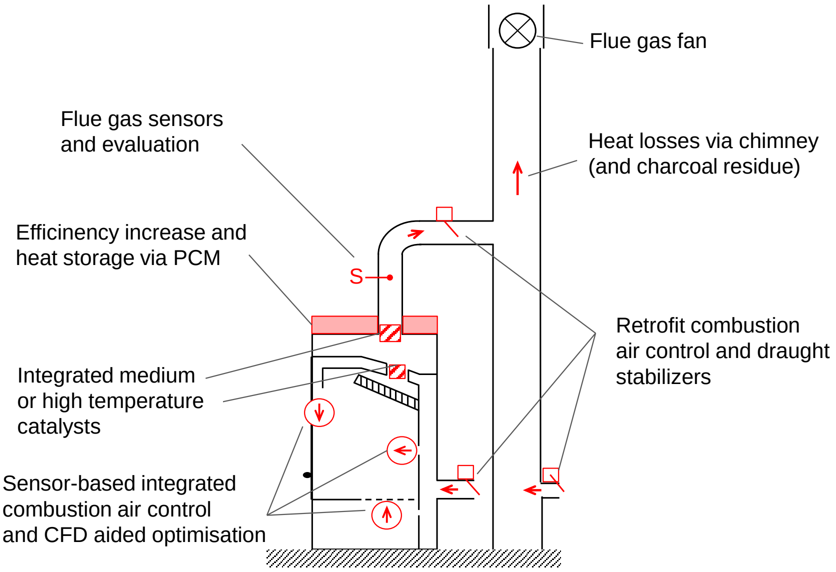


Figure 62: Overview on all system components regarded or optimized in the project. *PCM*: Phase Change Materials. *CFD* Computational Fluid Dynamics (source: TFZ)

Based on a sensor screening four gas sensor models were selected for experimental evaluation in a more than 500 resp. 250 hour long-term stove test; two different types of lambda probes (switching & broadband), a CO/O_2 probe and an O_2&CO combination sensor. The affordable lambda probes demonstrated a highly accurate oxygen determination throughout the whole evaluation, eventual impairment by aging or particle deposit has not been observed. The combination sensor, which also showed accurate O_2 determination, as well as the CO/O_2 probe enabled a reliable detection of CO gradients & overall ranges, thus proving their applicability. However current costs for sensor and electronics are seen as still too high for a broader use in the stove sector.

Within the project, various automated control systems were evaluated; both integrated systems and add-on solutions (retrofit systems). The integrated systems, temperature and flue gas sensor based control systems, consistently improved stove performance compared to manual operation of the same stove (fixed air flow). An example for that potential is seen in Figure 63, where gaseous emissions were reduced (CO: minus 20 – 32 %; OGC: minus 25 – 45 %) and thermal efficiency improved (by 1 – 2 %-points) for the same stove just by operating it with an automated control system (due to lower O_2 levels). Another huge benefit of these systems will be the minimization of user induces errors.

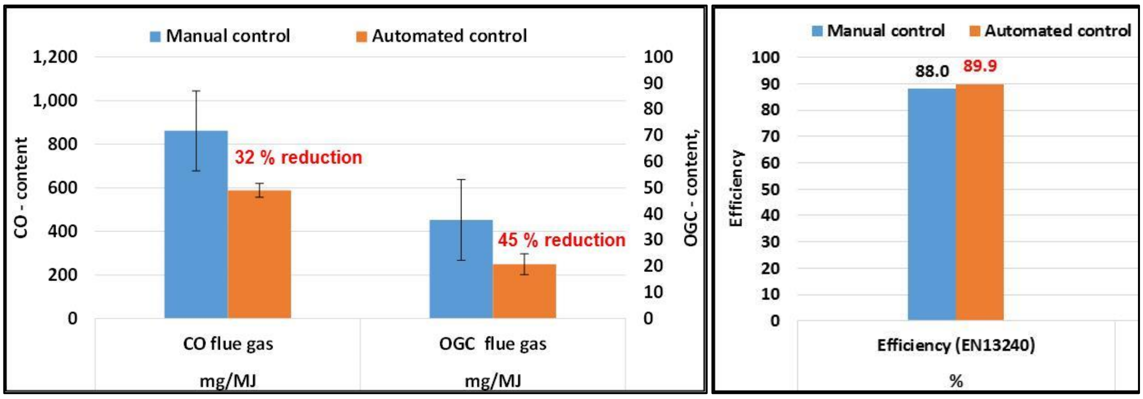


Figure 63: Emission reduction and effiency increase achieved by implementing an automated control system in a newly developed low-emission stove (Source: BIOS)

The evaluation of retrofit control systems showed a significant potential for increasing efficiency (by about 1.5 – 4.6 %-points) and for reducing gaseous emissions (by about 40 – 56 %). However, particle emissions remained largely unchanged or were comparable to good manual stove operation.

A new low-emission stove with integrated PCM (phase change material) heat storage was also developed. Compared to state-of-the-art chimney stoves the new stove technology achieved lower emissions and significantly higher efficiencies (> 90 %). The market introduction of this new technology is expected for 2018.

Experimental evaluation of different types of catalysts (mesh, honeycomb and foam ceramic filters with catalytic coating) was another focus in the project. It could be shown that selection (type & material) and right placement in the stove are crucial to ensure an effective operation with adequate long-term stability. With a proper choice a significant reduction of gaseous emissions and particles can be achieved. Regarding carbon monoxide, for example, reduction rates of more than 90 % (up to nearly complete elimination) could have been observed for some models. Additionally, catalysts will also act as a safety device for severe combustion phases, since reduction rates for hydrocarbon and particles usually even increase at times with bad combustion & high emissions. A challenge in using catalysts will be the increased flow resistance, which is limiting their applicability. Therefore the aim should be to keep the pressure drop across the catalyst as low as possible and/or to use a flue gas fan to increase draft when needed.

However, tests over a whole heating period would be needed to be able to evaluate the long-term performance of catalysts for wood stoves. The assumption that PM reduction could also be achieved by using uncoated (non-catalytic) foam ceramic elements in stoves - as it was recently advertised by several stove manufacturers - couldn’t be proven.

The influence of chimney draught (too low or too high) was also investigated. A draught stabilizer was tested and evaluated. It enabled an increased efficiency by approx. 10 %-points, but at the same time it also raised gaseous emissions (+23 %) and PM emissions (+14 %). Furthermore, recommendations regarding the implementation of flue gas fans to overcome cases of too low chimney draught were developed.

Regarding efficiency improvements, the standing heat losses from stoves through the chimney (i.e. losses after stove operation and cold standing losses) were investigated. For a modern 8 kW log wood stove they can amount to 750 kWh per year, assuming 100 heating cycles annually. The tests showed that these losses can be minimized nearly to zero when using automatically closing and tight air flaps or when automated combustion air control units are applied. But with the current prices of automatically closing air flaps and retrofit controllers the pay-off period is still too high (approx. 14 – 23 years).

Furthermore, a PCM heat exchanger was developed and integrated into a stove. It helps to store a relevant share of heat produced and to release it with delay to the room over a longer period. This improves the living comfort and makes such stoves more attractive for low energy buildings. It was shown that more than 50 % of the heat produced can be stored in the stove and in the PCM material. The heat is then slowly released over night. According to the test runs performed the developed PCM heat exchanger shows a good heat storage capacity and is suitable for the integration in a wood stove (efficiencies > 90 % are possible).

All technologies investigated were comprehensively tested using a particularly developed and harmonized testing method which was closer to a realistic stove operation in practise, compared to today's type testing standards. Thus, all achieved results and performances can be also interpreted as directly achievable in field applications.

As an outcome of the project, three Technical Guidelines which comprise the main outcome of the project for manufacturers and other persons of interest were established. The Guidelines are focusing on optimized stove concepts, automated control systems for stoves, and on heat storage units based on PCM. They can be downloaded here.

How has the ERA-Net made a difference to your research or business?
(“Quotation: about 80 à 100 words)

Intensive exchange during frequent (semi-annual) meetings have created an atmosphere of strong interlinking of tasks and has established fruitful contacts which shall be continued after the project, too. The scientific group had the chance to learn about measuring practises of other scientific partners and to receive feedback on their existing practises in own laboratory and test stands. This exchange has also triggered some investments into infrastructure (e.g. at TFZ, BIOS and RISE). Similar conclusions can be drawn for industry partners (e.g. Kutzner+Weber, RIKA and NIBE), who have also made investments into testing infrastructure, based on the experience gained during collaboration with the scientific partners. Furthermore, the joint development of technology between scientific and industrial partners has also created business opportunities and in several cases a marketing strategy for these specific products was decided. The harmonisation of test methods has created the basis for more meaningful real life performance tests of new appliances, these method shall now be used in future projects and developments.

Within the consortium it was possible to make comprehensive joint development and testing of several different catalysts integrated in different stove designs and in a specific catalyst testing rig. Furthermore different control concepts could be developed and be investigated. This broad approach and the concerted share of burden enabled that a high number of scientific aspects and technical devices could be efficiently considered and general conclusions were made possible.