IEA Bioenergy
Technology Collaboration Programme

Design of Low Emission Wood Stoves

Technical Guidelines

IEA Bioenergy: Task 32

October 2022

Design of Low Emission Wood Stoves

Technical Guidelines

Authors

Lars SCHWARZER, Anne Mette FREY, Morten Gottlieb WARMING-JESPERSEN

Acknowledgements to

Øyvind SKREIBERG, Hans HARTMANN and Thomas NUSSBAUMER

Edited by

Morten Tony HANSEN

IEA Bioenergy: Task 32 Biomass Combustion

October 2022

ISBN 979-12-80907-18-9

Published by IEA Bioenergy

Index

Introduction

SCOPE

Wood stoves are popular as a primary or complimentary heat source. However, unwanted by-products are formed and emitted during combustion of wood logs. These emissions continue to be a concern for the environment and for public health. Correct operation and proper design are key to minimize harmful emissions. While both are equally important, these guidelines focus on technological measures (e.g., stove design, flue gas cleaning and automatic control systems).

Low emissions require that more than just the stove itself is optimized. Downstream equipment, such as particle filters and flue gas fans will influence draft in the stove, while (automatic) control systems can adjust air flow to the different phases in the combustion process. The guidelines cover both primary and secondary measures. Primary measures aim at controlling combustion so that unwanted reaction products are either prevented or burned out. Secondary measures include the removal of emissions downstream of the combustion chamber (e.g., at the chimney). The recommendation is always to ensure proper installation and operation of the wood stove and to optimize the stove as much as possible with primary measures before applying secondary measures. Secondary technologies are thus meant to reduce the remaining levels of pollutants.

Research and development have led to significant improvements in the design of stoves and auxiliary systems, allowing stoves to meet ever stricter emission requirements. A number of activities were carried out under the ERA-NET project *Wood Stoves 2020*, the results of which are summarized especially in two reports: *Guidelines for Low Emission and High Efficiency Stove Concepts* [1], and *Guidelines for Automated Control Systems for Stoves* [2]. These sources are used as starting point for this review, connecting their main results to other (mainly European) projects that have been carried out in the field. Only wood stoves are considered here, although it is likely that much of the advice will be helpful for emission reduction in slow heat releasing stoves (masonry heaters). This has however not yet been verified in systematic studies.

These technical guidelines should be regarded as an overview or a reference work, and not as an in-depth review of available technologies or stove designs. Several guidelines on stove construction and design have been published in recent years (see list of references), and the reader is advised to consult these for more detailed information.

STOVE TECHNOLOGY: A BRIEF OVERVIEW

Wood stoves are operated intermittently and with a fuel of varying properties and can thus be challenging to optimize. The fuel, wood logs, is loaded and combusted batch-wise. A single charge will burn within a few hours. Longer heating periods require recharging, i.e., fresh logs are added to the embers. Typical operation cycles will therefore consist of an initial ignition phase, one or more recharges, and a final burnout. Sufficient oxygen for complete combustion during all phases is crucial to avoid harmful emissions. This not only means the overall amount of oxygen, but also the distribution of oxygen in the stove.

Modern stoves are based on a staged-air combustion principle, where the combustion air is split into different streams (Figure 1). Typically, ignition or primary air, window purge air, and secondary air flows are distinguished in wood stoves.

Ignition or primary air flows through the grate or the bottom of the stove into the combustion chamber. This air flow is in direct contact with the wood logs. It serves two main purposes, corresponding to the phases of wood combustion: Following the evaporation of residual moisture, the logs pyrolyze/devolatilize. In this phase, combustible gases are released. Partial oxidation of these gases supplies the necessary heat to maintain pyrolysis reactions. The solid pyrolysis residue, carbon-rich char, is then oxidized in the final phase. As the individual wood logs, and even parts of them, are at different stages in the combustion cycle, there will be substantial overlapping of pyrolysis and char burnout phases on a global stove scale. Frequent reloading of the wood stove widens the overlap.

Window purge air serves several purposes, depending also on the air control possibilities and strategy during operation: as purge air to prevent deposition on the glass caused by tars, soot and other particles; to partly oxidize the pyrolysis gases flowing from the wood logs; and to contribute to the char burnout. Depending on the stove design, window purge air can act as primary air (in some publications, no distinction is made between primary air and window purge air). Window purge air is delivered to the stove through downward-facing nozzles or slots at

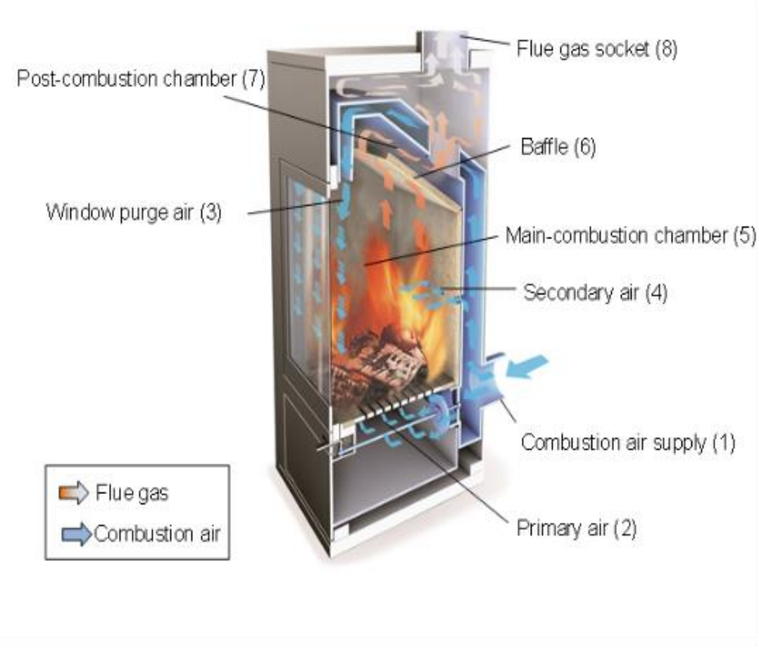


Figure 1: Wood stove layout and focus points for optimization [1].

the window top. It is preheated to a higher temperature than secondary air, and it flows quickly down in front of the window, turns towards the wood logs and mixes with pyrolysis gases above the fuel bed. Here, it acts as primary air after the ignition stage, and contributes with oxygen to the char burnout. Oxidation of pyrolysis gases and formed soot releases heat and causes visible flames in the stove.

Secondary air is often introduced above the fuel bed at the back wall of the stove, or further into the stove after additional preheating. Temperature of secondary air is lower than that of window purge air (compare the air flow in Figure 1). The purpose of secondary air is to ensure complete burnout, which is achieved by efficient mixing of oxygen with the remaining unburnt pyrolysis gases. Secondary air stream volumes are typically smaller than window purge air [1, 2]. Modern wood stoves consist of a main combustion chamber and a post-combustion chamber (Figure 1), where final burnout occurs.

EMISSIONS

Overview of relevant emissions

Emissions considered in these guidelines are particulates or gases that originate from the combustion process and that are considered harmful to human health and/or the environment:

- Particulate matter (PM)
- Carbon monoxide (CO)
- Organic gaseous carbon (OGC)
- Nitrogen oxides (NOx)

Particles are roughly divided into two classes: coarse mode (>1 µm) and fine mode particles (<1 µm). Coarse particles consist of unburnt fuel particles and ash particles. These particles are relatively large, and their fate is affected by gas flow velocities. Flow patterns in the stove, ducts, and the chimney are therefore an important influence on the final emission of coarse particles. High primary air flow rates through the grate lead to more coarse particles released from the grate. Additionally, ducts with long or narrow geometry, coarse surfaces, and/or sharp (or many) bends can retain more particles. Deposition of unburnt particles on surfaces in the duct can in the worst-case lead to chimney fires.

Fine particulate matter consists of soot, organic matter, and inorganic fly ash. Soot consists of carbon and hydrogen and is formed ahead of the flame front from light hydrocarbons/hydrocarbon radicals. Soot formation is typically limited to a temperature window of 1000–2000 K [3]. Soot is also what causes the typical yellow colour of the flame when it is burned out. Condensation of tars can additionally form organic fine particulate matter. Not all sample methods allow to detect this fraction, however – especially ‘hot’ filter techniques will prevent condensation. Inorganic fly ash is formed by vaporization of some inorganic elements, followed by re-condensation, nucleation, and particle agglomerate to provide particles of various compositions and sizes.

Organic gaseous carbon (OGC) includes a wide range of organic molecules, especially hydrocarbons. These molecules are originally formed during pyrolysis of the fuel. They are emitted if the combustion of pyrolysis gases remains incomplete because of insufficient oxygen and/or too low temperatures. This distinguishes OGC from soot, which is formed in the flame (from smaller C_1 and C_2-molecules). Large OGC-molecules may condensate and form tars.

CO is a remainder of incomplete combustion, and is formed by pyrolysis of the wood logs, during char burnout, and from partial oxidation of volatile organic matter. Like OGC, CO is released when temperature and/or oxygen availability are insufficient for complete burnout. Optimizing air flows is therefore a balance between providing enough oxygen and avoiding quenching.

NOx is an umbrella term for nitrogen oxides NO and NO_2. NOx can be formed through the thermal-NO, fuel-NO and prompt-NO mechanisms. Additional NOx is formed in the char burnout stage from nitrogen bound in the char. Thermal-NO requires the breaking of N_2-bonds of molecular nitrogen in the combustion air. This requires high temperatures, typically above 1500 °C [4]. Fuel-NO is formed when nitrogen is present in the fuel itself and is released in the form of gas species (e.g., NH_3 and HCN) or as part of tars. Under (local) oxidizing conditions, these gas species may form NO (or be emitted as is), whereas under reducing conditions, molecular nitrogen (N_2) formation is promoted. While the basic mechanisms of fuel-NO formation are understood, specifics are still a topic of ongoing research, e.g., regarding details of reaction pathways. Prompt-NO is formed by reaction of atmospheric nitrogen with intermediately formed light hydrocarbons close to the flame front. HCN is formed as an intermediate species, which can further react to NO. Of the NOx formation mechanisms, NOx formed from fuel-nitrogen is by far the most important NOx formation mechanism in wood combustion.

Legal requirements

Allowable emissions vary from country to country, and not all countries regulate all the above listed emissions for wood stoves. Some relevant emission limits are listed in Table 1. Additionally, emission legislation in countries with a strong federal structure (e.g., the United States) may be a mixture of national, state, and municipal law. There are attempts to harmonize emission legislation across countries in the European Union, e.g., via the Ecodesign Directive (Directive 2009/125/EC) and its implementation in the Commission Regulation (EU) 2015/1185. In addition to the emission limits, mandatory test procedures are prescribed by various national and international standards. An overview can be found in a recent (2018) IEA report [5].

As a minimum, emissions of particulate matter are limited, while only few regulations place limits on NOx. In addition, there are voluntary, often stricter, emission limits issued by consumer protection organizations. A lack of harmonized standards requires stove manufacturers to consider carefully which market(s) to target. Presence on several markets often requires a new product to be certified according to different standards and limit values.

Emission tests, type approval and real-life emissions

Type tests typically consider quasi-steady operation conditions, i.e., disregarding the ignition period and starting the test with a preheated stove at optimal combustion conditions. An overview of type testing procedures can be found in [5]. For areas where the Ecodesign directive applies, tests are carried out according to EN 13240 (stoves) or EN 13229 (inset appliances). These standards have been updated and combined in EN 16510 (residential solid fuel burning appliances).

Table 1: Emission limits according to different national and international legislation or standards, relevant for log wood stoves. Values given in this document are for reference purposes only and without legal implications.

Regulation	PM	OGC	CO	NOx	Flue gas conditions
Ecodesign (EU 1185) - 2022	40 mg/m³	120 mg(C)/m³	1500 mg/m³	200 mg/m³	13% oxygen, dry, 1013 mbar, 273 K
[Austria] (A) ¹⁾ - 2015	35 mg/MJ	50 mg/MJ	1100 mg/MJ	150 mg/MJ	
Luftreinhalteverordnung (CH)	50 mg/m³	—	1500 mg/m³	—	13% oxygen, dry, 1013 mbar, 273 K
1. BImSchV (D) ²⁾	40 mg/m³	—	1250 mg/m³	—	13% oxygen, dry, 1013 hPa, 273 K
BEK nr 541 (DK)	30 mg/m³	120 mg(C)/m³	—	—	13% oxygen, dry, 1013 mbar, 273 K
EPA (USA) ³⁾ cordwood	2.5 g/h	—	—	—	
AS/NZS 4013:2014 (AU/NZ)	1.5 g/kg (fuel)	—	—	—	

Notes:
1) Austrian regulations are on state level, but harmonized according as “Vereinbarung gemäß Art. 15a B-VG”
2) German municipalities may impose stricter limits on stoves, and/or regulate NOx and OGC.
3) US states or municipalities may impose additional rules, e.g., on smoke opacity, or wholly ban wood stove operation.

Real-life emissions have been found to differ from values obtained in type tests [6, 7, 8]. Emissions generally vary over the combustion cycle [9, 10, 11, 12]. Combustion is especially poor during the ignition phase, when fuel, stove and air are cold. Ignition technique itself also has an influence on emissions, with the major alternatives being ignition at the top or the bottom of the logs [13, 12, 14, 15]. Top-ignition is more frequently recommended due to improved combustion process control and resulting reduced emissions [12, 14, 15]. However, stove-dependent behavior was found in two studies [13, 16], with no clear advantage of the top-ignition technique. The manufacturer should describe the preferred ignition procedure in the manual.

Interest in determining real-life emissions in a comparable and standardized way has increased in recent years. In the European FP7 project "beReal", a new testing method for wood stoves was developed, aiming to quantify emissions comparable to real-life operation. Emissions measured using the beReal-test procedure are generally higher than Ecodesign limits (except NOx) [7]. The procedure also includes ignition of the stove, a steady period at nominal heat output and a low burn period during partial load. The method has subsequently been taken up in voluntary certification and labelling schemes: In 2020 the "Blauer Engel" label (Germany) introduced major requirements from the beReal method as a testing procedure, combined with emission values below Ecodesign requirements (DE-UZ 212) – see

Table 2: Emission limits of voluntary labelling schemes Blauer Engel, Flamme Verte and Nordic Swan label compared to the Ecodesign Directive..

Table 2: Emission limits of voluntary labelling schemes Blauer Engel, Flamme Verte and Nordic Swan label compared to the Ecodesign Directive.

Regulation	Ecodesign	Blauer Engel	Flamme Verte (7 stars)	Nordic Swan Label
PM, mass PM, number	40 mg/m^3 —	15 mg/m^3 $5 \cdot 10^{12}$ /m^3	40 mg/m^3 -	2 g/kg -
OGC [mg(C)/m^3]	120	70	-	100
CO [mg/m^3]	1500	500	1500	1250
NOx [mg/m^3]	200	180	200	-
Efficiency [%]	-	-	75	76
Flue gas conditions, for all schemes	13% oxygen, dry, 1013 mbar, 273 K			
Method	EN standard	Blauer Engel method	EN Standard	NS 3058

Stove Design

PRIMARY EMISSION CONTROL MEASURES

Particulate matter, CO, OGC and NOx are all originally formed in the combustion chamber. Inhibiting the formation of these pollutants or ensuring their burnout (as opposed to removing them from the flue gas at a later stage) is referred to as primary emission control. This can be achieved by controlling combustion process parameters such as temperature, mixing of reactants (gas/gas and gas/solid), residence time, and fuel quality. Primary emission control measures can be permanently built-in (e.g., combustion chamber geometry), or rely on specific operation patterns (e.g., refuelling or air-staging). This report will focus on those measures that are implemented and/or need to be considered in the design phase. Fuel considerations largely fall outside the scope of this report and will therefore only briefly be addressed here.

Fuel quality and user instructions

Wood stoves should only be operated with the fuel they were designed for (wood logs or wood briquettes). This excludes chemically treated wood wastes and other waste materials. Pure bark briquettes should also not be used. Firing other materials in wood stoves typically leads to increased emissions [6]. The wood should be dry (12–20 % moisture, wet basis). Under conditions of natural draft wood stoves, fuel moisture contents of lower than 10 % can lead to severe increases of particle and CO emissions, e.g., due to local lack of oxygen [17, 18]. As wood stoves design and fuel must work together, guidelines for the end-user should be supplied by the manufacturer. These should contain instructions regarding the optimal size of logs, amount of fuel, how to ignite, how and when to re-charge, orientation of logs, air damper settings, procedure for termination of heating and cleaning requirements should be provided by the stove manufacturer. This information should be available in an easily understandable description from the manufacturer (e.g., via a Quick User Guide).

Air supply and air staging

Local oxygen concentration and temperature can be controlled by air supply and air staging. Air staging is a well-known emission-abatement measure in large-scale combustors, and was found to reduce gaseous and particulate emissions also in small-scale applications [19, 20, 21, 22].

Excessive primary air leads to high burning rates, reduced gas residence time, and higher ember temperatures. These factors increase particle emissions [23], especially soot and black carbon. For the same reason, primary air should not be preheated. Lower temperatures and oxygen deficiency in the primary combustion zone suppress release of NOx-precursors as well as some organic and inorganic PM-precursors, which are then retained in the char. Therefore, primary air from below the grate should be avoided and preferably only be used during the ignition phase. Such primary air used exclusively during start up is also referred to as pilot air or ignition air and can also be supplied through a separate air intake in the lower back of the combustion chamber, e.g., when the stove has no grate. Primary air should be supplied as window purge air after the ignition period. During one fuel batch, devolatilization and gasification of the wood fuel switches from an initially endothermal process to an autothermal process, which relatively fast becomes an allothermal process, with heat provided to the wood fuel by flames in the combustion zone.

Secondary air and window purge air provide oxygen for complete burnout. These reactions occur mainly in the gas phase, but the air also ensures burnout of combustible particles and contributes to the char burnout (purge air). Thorough mixing of air and combustible gas and sufficiently long residence time at high temperatures support burnout. Opposed to primary air, air streams to window purge air and secondary combustion chamber must be pre-heated to avoid cooling of the gas atmosphere in these zones. The preheating also contributes to higher air flow speeds, enabling good mixing conditions and effective window purging.

Attention should be given to the placement and direction of the window purge air: injected at too high air speeds, the purge air can act as primary air. Injected at too low air speeds the purge air hardly reaches the fuel bed and becomes uncontrolled secondary or tertiary air. Higher emissions may then result from the too low window purge air as the primary zone lacks air. Also, if the direction of the window purge air is too high above the fuel bed, and worsening if the air flow speed is too low, the residence time in the stove becomes shorter. This reduces the combustion efficiency. Hence, a proper division of the air supply to secondary and windows purge air is needed for optimal combustion conditions, in addition to proper air flow speeds and directions. This will depend also on the furnace design.

Wood Stove construction

General guidelines for stove construction have been developed in the past years in collaboration between stove manufacturers and research institutions [1, 2, 24, 25, 26, 23]. Designs for stoves that match Ecodesign requirements can vary widely (Figure 2), and the appearance of the stove is often influenced both by aesthetic and technological considerations. Results of the above-mentioned studies are briefly summarized here.

Splitting the stove into a main and a post-combustion chamber aids the separation into primary and secondary combustion zones. Post-combustion chambers are therefore a typical feature of modern stoves. Wood stoves are designed to heat the room they are located in. The headspace downstream of the post-combustion chamber typically acts as heat exchanger (see Figure 1), where the heat is dissipated to the surroundings via the stove walls. To achieve complete combustion, it is necessary to maintain high temperatures up to this point. Therefore, walls of the combustion chamber (sides, back and ceiling) should be insulated to achieve high temperatures. Heat from the main combustion chamber is conserved by an insulation layer of clay, chamotte or vermiculite. Refractory lining is used to preserve the temperature in the post combustion chamber.

Windows contribute significantly to heat loss from the stove [25]. Their size should therefore be as small as possible. This technical recommendation may however conflict with design consideration for the outward appearance of the stove. Heat loss via the window is also influenced by the choice of glass material. Coated glass can reduce heat loss by radiation.

Dimensioning of the combustion chamber should be based on the desired heat output. Too large combustion chambers result in higher specific heat loss, leading to cool gases and incomplete combustion. Furthermore, a high and slim geometry of the main combustion chamber improves flame dispersion and results in more homogeneous residence pattern of pyrolysis gases in the hot zone. Wide/deep and low combustion chambers should be avoided. Figure 2 shows stove designs investigated in [23].

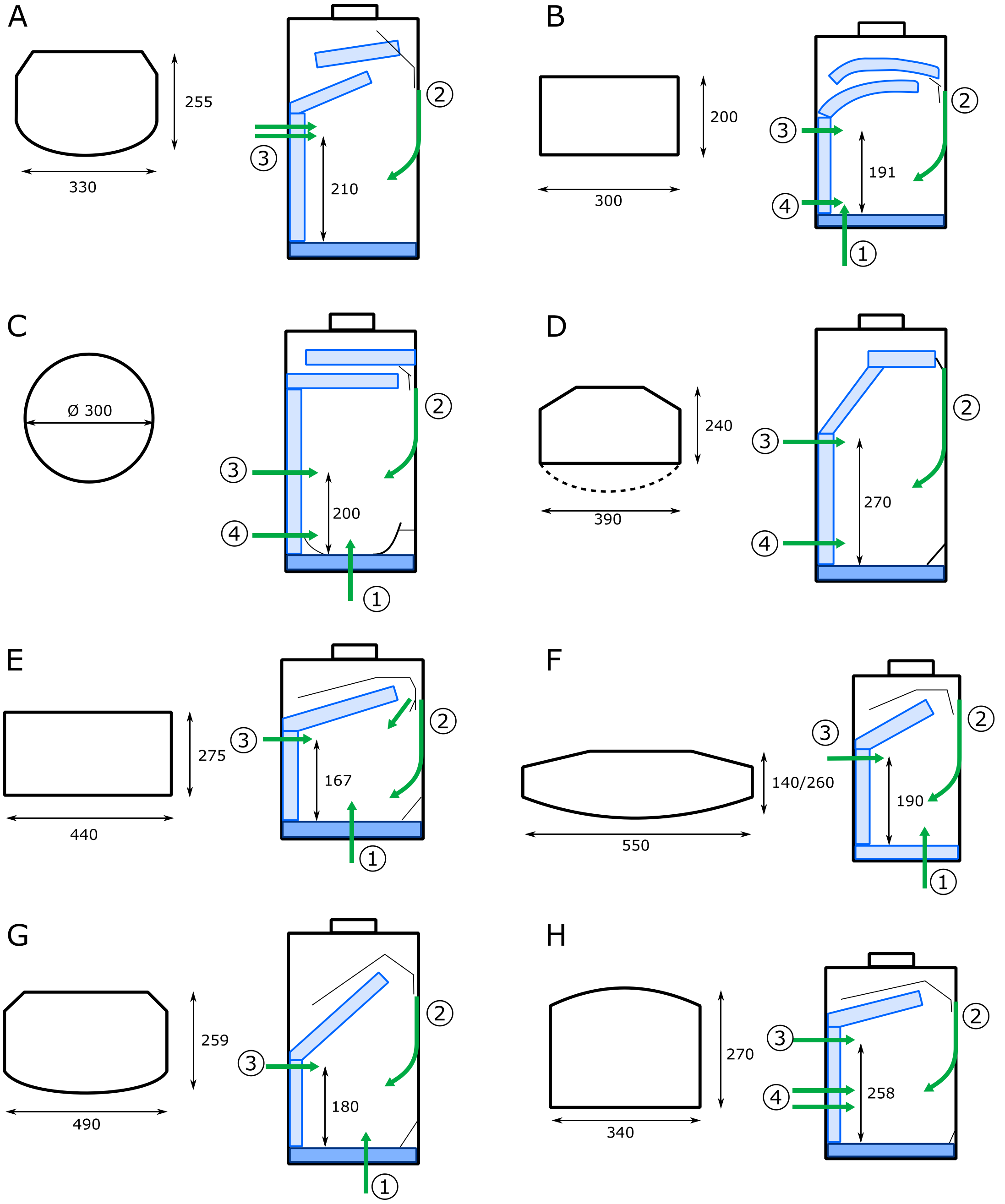


Figure 2: Designs for stoves that match Ecodesign requirements can vary widely. Numbers (1) – (4) are air streams, where: (1) primary air, (2) window purge air, (3) secondary air, (4) pilot air. Pilot air acts as primary air but is only used during ignition. Adapted from [23].

Grooved surface patterns, as well as baffles in the post combustion chamber increase local turbulence, reducing elementary carbon emissions and ensures proper burnout [23]. When baffles are used, they should be spaced in a way that they do not excessively increase flow resistance. Three baffles were found to be a good trade-off between increased turbulence and low flow resistance [23].

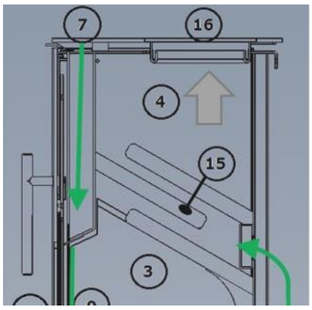


Figure 3: Example of three baffles in the post combustion zone

As formation of pollutants depends highly on local oxygen concentration, local temperature and flow patterns, computational fluid dynamics (CFD) is gaining importance as a design and optimization tool for low emission stoves.

Chimney and flue gas duct

Chimney draft is decisive for the air flow rate through the stove. Insufficient draft causes lack of oxygen, leading to incomplete combustion and increased emissions [27]. While a minimum pressure difference is necessary in all cases, the optimal pressure difference depends on the stove: In a study [27], a controlled variation of draft between 12 Pa and 48 Pa showed different trends for different stoves. Particle emissions appeared unaffected in this range, while emissions of CO and OGC could increase or decrease with pressure difference, depending on the stove design [27]. Similar findings are reported in [13], where limited effect of draft conditions on gaseous emissions were seen. Customers should in any case be advised on the minimal draft necessary to operate the stove in order to achieve low emissions while keeping thermal losses at a low level. The draft should be monitored by the installer, or a chimney sweeper prior to the installation and measures taken to improve the draft if not satisfactory.

Flow resistance in chimney and flue gas ducts should be minimized, e.g., by limiting the number of bends and generally avoiding sharp angles in the flue gas duct. Furthermore, draft depends on the temperature difference between flue gas and surroundings, draft increasing with larger temperature differences. Modern stoves have lower flue gas outlet temperatures (typically around 150 °C), which can lead to problems when a new stove is fitted to an existing chimney. Modern chimneys are insulated to ensure a sufficiently high flue gas temperature and draft. This also helps to avoid flue gas condensation. Insulation can also be retrofitted. Older brick chimneys can be retrofitted with an inner liner.

Installing a fan in the chimney/flue gas duct can additionally improve chimney draft. Fans are typically coupled to automatic control systems (see following section).

AUTOMATIC CONTROL SYSTEMS

Incorrect stove operation by the user may lead to significantly increased emissions [6, 27]. Control systems are also able to react instantaneously to changes in the fuel batch and to reduce standing losses between operation periods. All of these contribute to an increased thermal efficiency.

Automatic control systems can determine the optimal time for refuelling (typically when the previous fuel batch is nearly combusted and the fire almost extinguishes, but temperature is high enough to start the next batch) and notify the user. Optimized refuelling was found to significantly lower gaseous emissions over the combustion cycle [25].

Automatic controls can be built-in or retrofitted to existing stoves. Retrofitting stoves requires special attention, as a poorly installed control system may also increase emissions [27]. For retrofit systems it is crucial that the stove manufacturer is involved in the process, to ensure that controlling algorithms are suitable for the stoves.

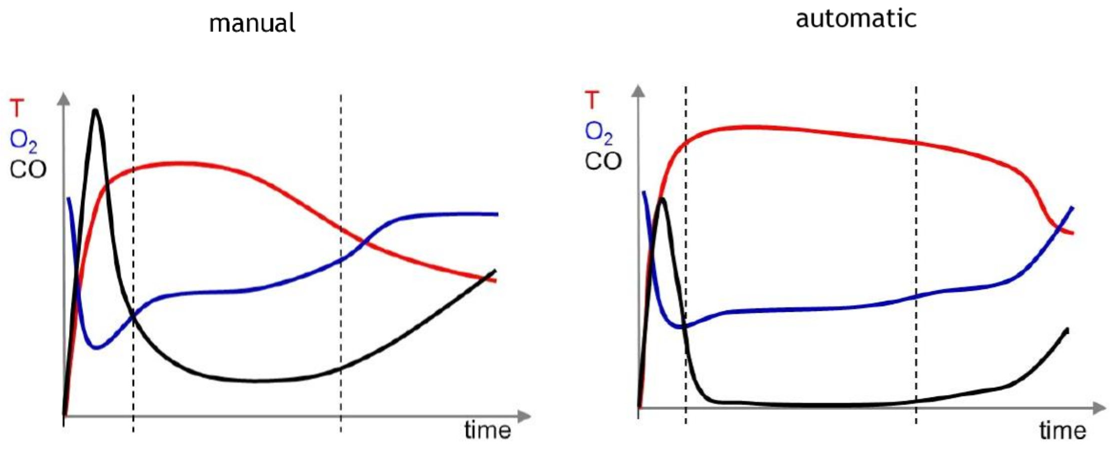
Advantages of automatic control systems

In Figure 4, typical qualitative patterns of flue gas temperature, O_2 and CO are shown for a conventional, uncontrolled stove (left) and the same stove with automatic control (right) [2]. The temperature is higher and more stable for the automatically controlled stove. Furthermore, the level of O_2 is more even and lower during the second phase (main combustion phase) and the CO level in significantly lower as well. By automatic closure of the air flaps after heating operation, it is also possible to increase the overall efficiency. Hot and cold standing losses will otherwise easily reach magnitudes of 750 kWh annually [28] unless the stove receives its combustion air directly from ambient air via a floor duct or a ventilated chimney.

Control concepts

Combustion in the stove can primarily be influenced by the total amount of air and its distribution. A very simple control can be achieved by thermo-mechanically operated air-flaps. This makes use of (different) thermal expansion coefficients used in the actuators, also known as bi-metallic control devices.

Electronic, sensor operated control concepts are not yet common, but are a very efficient way



manual

automatic

Figure 4: Flue gas temperature, CO and O_2 time series (qualitatively) without and with automatic control [2].

of controlling the combustion. Temperature measurements in the combustion chamber and/or oxygen concentration in the exhaust gas are typically used as input parameters [2]. The signals are used to position air flaps/vents with the aid of electric motors. Draft stabilizers or flue gas fans are additional elements of automatic controlled stoves – either as part of the original installation or as retrofit.

Stove control based on temperature or flue gas components

The different combustion phases can be identified by changes in temperature, which can be used to regulate the combustion air [2]. This can be controlled either by bi-metallic actuators or electronic devices, i.e., a combination of sensor and motor.

- Ignition phase: mainly primary air is needed to facilitate quick ignition and fast increase of the temperature in the combustion chamber
- Main combustion phase: primary air is reduced to avoid excessive burning rates and increased black carbon (a soot constituent) and other particle emissions. Simultaneously, secondary air and window purge air are increased to maintain constant oxygen levels.
- Char burnout: secondary and window purge air flows are reduced to keep the temperature high and excess oxygen levels low. Recharge should happen as soon as the flames extinguish to avoid increased CO and OGC emissions.

Greater accuracy can be achieved by combining temperature measurements with flue gas sensors, especially by monitoring the oxygen content. The control strategy for air supply during the different phases is, the same as above. However, such systems are believed to behave more independently from fluctuating draft conditions and can thus also more easily adapt to variable chimney lengths. Furthermore, they usually allow implementation of partial load operation, where air settings need to be automatically adjusted to the reduced fuel loading. Additionally, a lower susceptibility towards too low fuel moisture contents (e.g., 5 to 8 %) is expected, particularly when fuels are delivered after artificial drying.

For retrofit stoves, it is in practice only possible to adapt air flap controllers on the central air inlet, i.e., primary, secondary and window pure air cannot be controlled independently. This allows only for a rudimentary control of primary air and can lead to reduced stove performance concerning emissions [27]. In retrofitted stoves, sensors can only be located behind the stove in the flue gas pipe, as changes to the stove invalidate the type-approval. At such sensor position the dynamic of temperature changes is low and delayed, and consequently does not allow a sound and rapid response to changes in the combustion cycle. In that case data techniques to ensure rapid response is needed.

Avoidance of maloperation

To reduce the impact of the stove user on combustion and air quality is becoming a major goal in stove development. The implementation of an automatic control system is here considered as a key technology which can provide feedback to the user concerning both operational failures or unsuitable fuel mass or fuel moisture. Furthermore, the automatic control unit should also directly avoid false air settings. A manually operated stove would, for example, easily create 5 times higher CO- and particle emissions when the user fails to shut the primary air supply after the first batch [29]. With an automatic air control, such erroneously open flaps are easily avoided, given that primary air is adjusted separately. Furthermore, the re-ignition process after fuel reloading can be optimized automatically by short-term re-opening of the primary air inlet (e.g. for 1 minute). Thus, longer smouldering phases are avoided, particularly when placing new fuel onto a low ember bed. Such operational improvements can already be realized when applying a simple temperature control system with a thermocouple positioned in the combustion chamber.

However, the advantages of such improvements are usually not reflected in type testing reports as such critical phases are usually excluded from standard measurement procedures. But new product standards might be available soon, or they are introduced on national level. In Germany, for example, a standard for electrically powered temperature-controlled combustion air devices was recently published (DIN 18843-1), while further standards concerning flue gas sensor-based systems or user feedback systems are on the way.

Safety considerations

In case of power blackout or sensor failure, the stove must revert to a safe state that allows manual control. Pyrolysis gases must not be released indoors from the stove under any circumstances, as this may lead to poisoning. Detection of door opening is important [2].

Sensor technology

Control concepts and sensors are described in more detail elsewhere [2]. A summary is given here.

Thermocouples are both cheap and robust and are therefore widely used in automatic stoves. More elaborate control systems (additionally) include *gas sensors*. This avoids using the temperature as a proxy for the combustion state. Sensors typically used can detect oxygen, CO, or CO_2. Oxygen sensors have good accuracy and little cross sensitivity. They have been found to be durable and reliable in operation. CO sensors may respond to hydrocarbons as well. These sensors are more expensive than oxygen sensors, but their cost has significantly decreased in recent years. Sensors for oxygen and unburned components are sometimes bundled and sold as single unit. A comprehensive testing of gas sensors for wood stoves was performed in the European Project “Wood Stove 2020” [2].

Other sensors used are *pressure sensors*, mainly in connection with draft stabilizers/flue gas fans, as well as flame detectors and sensors that recognize door opening. The latter are especially interesting in connection with air control systems. They can prevent the control system from overcompensating what appears as a sudden but brief surge of air while the door is open.

Main design considerations for sensors are robustness, accuracy, and costs. The added cost of the control and sensor system should be in an adequate relation to the price of the stove and the gain in efficiency. Sensors should ideally last for the entire lifetime of the stove, or sensor failure must clearly be indicated to the user to call for immediate replacement. Additionally, signals should be stable. Especially gas sensors may experience signal drift and may need regular re-calibration.

Sensors near to the combustion chamber should tolerate high temperatures. This is especially challenging for gas and pressure sensors; their cost increases dramatically if hot gas measurements are required. Gas conditioning and/or cooling of the sensors may make them more economically viable.

EMISSION REDUCTION AND POST COMBUSTION MEASURES

It is advisable to reduce emissions as much as possible by optimizing the actual combustion process. Additional devices are necessary to convert or remove the problematic compounds after they have been formed, i.e. downstream of the combustion chamber. Such secondary emission reduction technologies can be an integral part of the stove installation such as a catalyst or be retrofitted in the flue gas duct.

Oxidation catalysts

Oxidation catalysts remove intermediate (unburnt) combustion products, such as CO, hydrocarbons, and soot. Oxidation catalysts are generally most efficient in reducing CO (90-100 % removal), and slightly less efficient with respect to hydrocarbons (50–70 %) [1]. Catalytic CO oxidation can be achieved from 200–300 °C upwards. Oxidation of hydrocarbons typically requires higher temperatures. Additional challenges arise from the large number of different organic carbon species. Oxidation catalysts may also promote the formation of PCDD/F (commonly known as dioxins or furans) [30].

General considerations for oxidation catalysts in wood stoves are their placement, avoiding deactivation, and purity of the catalytic material. Technological requirements for catalysts differ, depending on whether the catalyst is an integrated or a downstream installation. Stoves with built-in oxidation catalysts are commercially available, and catalysts are also available as retrofit. Retrofit catalysts can only be installed downstream of the stove; however, when the stove design aims at achieving a high energy efficiency, flue gas temperature at the outlet will usually stay well below the activation temperature of conventional catalysts. Integrated catalysts are located closer to the combustion zone, and therefore need to withstand higher temperatures. Thermal degradation of the catalysts sets an upper bound for operating temperatures.

Advantages of integrated catalysts compared to downstream catalysts installed at the stove outlet are

- A shorter time to reach temperatures in which the catalyst is active
- Higher operation temperature (600-800 °C) enhances removal of volatile organic compounds, CO, soot, and tar.
- Possibility of applying non-noble active metals, i.e. a cheaper catalyst.

Challenges with applying an integrated catalyst in wood stoves are

- Flow resistance, which can cause insufficient air flow. Pressure drop can be up to 10-15 Pa. Typical values for honeycomb catalysts are 5–10 Pa [31].
- Flue gas backflow
- Catalyst degradation. Degradation varies widely among stove installations.
- Installation of the catalyst at the outlet of the post combustion chamber (~500 °C) should be avoided due to likely deactivation by blocking of the active sites by aerosol condensation.

Heterogeneous catalysts are used. Often the basic structure is an iron-alloy or a ceramic, such as Al_2O_3 or ZrO_2. The structure of the material is either a packed bed, a monolith (honeycomb or foam structure) or network/wire mesh. The substrate acts either as carrier material for a wash coat (to increase the surface area) or directly for the catalytically active component. Normally noble metals are used, where palladium (Pd) is known for good CO oxidation and platinum (Pt) for VOC and CO oxidation. At higher temperature, cheaper metals, such as nickel (Ni) and copper (Cu), are active.

Deactivation of the catalyst can happen by catalyst poisoning, thermal degradation, and blockage by particles, where the two latter are considered most severe. The catalyst must be placed in such a way that it can be easily removed for cleaning and replacement [1]. Catalyst lifetime can be extended by reducing emissions as much as possible via primary measures. This includes removing dust or particles in the flue gas, which may lead to mechanical blockage of the catalyst.

A major challenge will thus be the catalyst flow resistance, which can cause insufficient air flow under natural draft conditions. Additionally, there is a risk for potentially dangerous flue gas backflow into the room during recharging. Catalyst pressure drops can vary from only a few Pascal up to significant double-digit numbers. The aim is therefore to choose an appropriate catalyst type and size for flow resistance, this is done by applying a large cross section. Otherwise, the implementation of a flue gas fan would have to be considered. Comprehensive results on catalyst performance for wood stoves were compiled in the ERA-NET project *Wood Stove 2020* [32].

Particle removal

Electrostatic precipitators (ESP) are currently the preferred technology for particle removal from the flue gas. Other particle removal methods (e.g., textile filters, cyclones, scrubbers) are normally not used for wood stoves. Ceramic foam filters (similar to integrated catalysts, but without chemically active surface) have been marketed as filters. These however have been found to have no significant effect on particle emissions [25].

In ESPs, particles are ionized by applying a high voltage between an electrode in the gas stream and the grounded flue gas duct. Charged particles precipitate on the grounded surface, where they are collected and can be (mechanically) removed. ESPs have proven to be efficient in removing particle emissions from the flue gas stream: under ideal (laboratory) conditions, removal efficiencies of 87–97% are reported [33, 34]. Similar efficiencies can be achieved in the field as well [34, 35]. Build-up of particles on the electrode and/or the collector surface decreases the efficiency drastically (down to 30% [34]) and can render it useless in extreme cases [35]. This makes regular cleaning (possibly automated) necessary [34, 35]. Failure to clean the filter may also result in re-entrainment of agglomerates [34].

Commercial electrostatic precipitators for wood stoves have recently been developed in e.g., Denmark, Germany, Austria and Switzerland. Different designs for electrostatic precipitators exist, with some being installed directly at the stove, some midways in the flue gas duct, and some immediately at the chimney top. Mounting position does not appear to influence the efficiency of the electrostatic precipitator [34, 35]. However, fuel type [35] and poor flue gas quality [34] may reduce the ESP's efficiency. The latter is especially interesting when retrofitting ESPs to stoves with poor burnout and high soot and organic emissions.

The addition of filters increases the cost of the stove considerably, so that most stoves are currently sold without. Additionally, filters require regular maintenance. Meeting future lower emission limits may however require an ESP [35].

Reduction of NOx

Nitrogen oxides (NOx) can be reduced to molecular nitrogen (N_2) by optimised staged air combustion and/or with the aid of a reducing agent. Targeted NOx-reduction technologies are currently not applied in wood stoves. Staged-air combustion, which is directed at reducing emissions of unburned gases and particles may however also be beneficial for low NOx-emissions.

For efficient NOx reduction through air staging, a clear physical separation between the primary and secondary combustion zone is needed. This means that primary air must efficiently and in the right amount be supplied to the pyrolysis gas flowing out from the wood fuel, a certain time is then needed for the primary air to oxidise the main pyrolysis species to an extent that allows for an effective reduction of the NOx precursors in the now partly oxidised pyrolysis gas to molecular nitrogen. This reduction also takes time, i.e. a reduction zone without additional oxygen supply is needed. Thereafter, secondary air can be supplied to ensure complete combustion. The typical wood stove design, the not so clearly separated air streams and the complexity connected to the batch combustion principle makes controlled NOx reduction by air staging very challenging. However, a large part of the nitrogen in the wood fuel is anyway converted to molecular nitrogen, both in reducing and oxidising combustion zones, while the remaining is mainly emitted as NO, also from the char combustion. Controlled air staging at optimised conditions has the potential to significantly reduce the current NOx emission levels from wood stoves, if the proper stove design, air supply strategy and control possibilities are implemented.

Post-combustion NOx reduction methods are known for large-scale applications (e.g., power plants) and mobile applications (e.g., road vehicles). The cost involved in the additional equipment and reduction media makes post-combustion NOx reduction economically unattractive for wood stoves – especially since current NOx emission limits can be met by primary measures. These limits are today met without optimised staged air combustion for the wood species defined in test standards, as these wood species contain a relatively low amount of nitrogen. The nitrogen content in the wood fuel is a decisive factor influencing both the current NOx emission levels and also the NOx reduction potential by staged air combustion.

Economic Considerations

LIFETIME AND MAINTENANCE

Data on wood stove lifetime is scarce. An online survey [36] of several European countries listed 50% of stoves younger than 5 years, 25% between 6–10 years, 12% between 11–15 years, and the rest older (1183 respondents). An inventory of Danish households [37] showed 15% of stoves younger than 5 years, 23% between 6–10 years, 17% 11–15 years, and 26% 16 years or older (19% unknown or unspecified). A 2017 survey of all German ovens and stoves reported 20 % newer than seven years, 42 % between 7 and 22 years old, and the rest older or unidentified [25]. Differences in these figures may be explained by the way the surveys were conducted, with the European study [36] possibly skewed towards more technology-affine users (and thus newer stoves).[1] Combining these figures tentatively suggests that wood stoves are operated for at least 10–15 years, after which they are gradually replaced.

Reasons for replacing stoves can be both technological/economical (e.g., wear or stove has reached end of its lifetime) as well as regulatory (newer, more stringent emission regulation no longer met by old installations) and incentive strategies from governments introducing replacements of older stoves.

---

[1] The European study was open to all and advertised online through various channels [36]. The Danish study was invite-only, based on a sample of the population. The response rate among those invited was 30.5%. The total number of respondents for *all types of heating units* was 3396, with approximately 16% owning a wood stove [37]. No details for the German data are given.

With regards to maintenance, the user should be advised to check the stove each year to make sure that seals and packings are still tight. The insulation material can also break over time due to mechanical influences, either from the stove or from loading of the stove with fuel logs. It is important that the end-user is instructed to change the insulation if breakage occurs, since this will affect the combustion properties.

ECONOMIC EVALUATION

New stoves must comply to current emission legislation, but there are often exceptions for existing stoves. For example, the German BImSchV allows stoves built before 2010 to operate until 2024, even if they do not meet current emission standards[2]. There may however be limits on selling and/or re-installing older, non-compliant stoves. There is often little economic incentive to upgrade older stoves if their operation is still permitted. Given the above estimated average lifetime of a stove, the market for retrofit emission control is likely a niche market.

Economics of retrofitted draft controllers were investigated in [27]. Gaseous emissions were found lower, and the efficiency increased. Standing losses (i.e., heat loss between operation periods) were reduced. A price goal of EUR 250 is suggested [27]. Current market prices are around EUR 500–1000, excluding installation (as of 2020). Inlet air control systems (as retrofit) vary between EUR 270 and EUR 1100 [25].

Retail prices for electrostatic precipitators are approximately EUR 2000–3000, those for catalysts are around EUR 300.

For new stoves, emission reduction technology is often only a minor fraction of the production cost. Regarding stricter emission limits in 2020, the U.S. Congressional Research Service estimated the annualized compliance costs to be 2.4 % of the annual sales for wood stoves [38].

Combining the above cost of retrofit (ESP, catalyst, draft controller) solutions with the cost of modern stoves (automatically controlled) the cost of a complete unit would be in the range of EUR 6000-7000 for a regular free-standing wood stove in the range of 5-7 kW.

---

[2] Legal information given for reference purposes only.

Conclusions

This report summarizes the experience from several recent research and development projects for low-emission wood stoves. Emissions considered here are particulate matter (PM), carbon monoxide (CO), organic gaseous carbon (OGC) and nitrogen oxides (NOx). Reducing these emissions from wood stoves requires to optimize the entire system (stove, chimney, and additional equipment) and ensuring that the oven is operated with proper draft and the correct fuel. A general recommendation is to reduce emissions as far as possible with primary measures (i.e., to prevent unwanted emissions). Secondary measures should be implemented only when a further reduction of emissions is required.

The report offers a guide through the development of wood stoves, as a supplement a guideline has been presented as appendix 1 which gives a short overview of the key aspects of improved development of wood stoves. The report furthermore provides the link to literature with a more comprehensive description of the different development steps, where the reader can increase their knowledge on specific areas.

Primary measures reviewed in the report are: construction of the combustion chamber (geometry, insulation, windows), air staging, and draft control. Geometry and insulation of the combustion chamber influence the temperature distribution in the oven. Air staging and draft control the local availability of oxygen. Sufficient oxygen and high temperatures are equally important in achieving a complete burnout (reducing CO and OGC), while excessive oxygen and temperature promote formation of NOx and soot-precursors.

Once formed and beyond the reach of primary measures, unburned materials can be catalytically oxidized downstream of the combustion chamber, while particles can be removed with the help of electrostatic filters in the chimney. There are currently no secondary measures against NOx, as wood stove NOx-emissions are well within legal requirements using primary measures (especially air staging) alone.

Automatic control systems can help to adapt temperature and air flows to the dynamically changing conditions during combustion. As wood stoves are operated in batch-firing mode, there is no single optimal operating point. With sensors, actuators, and electronic control systems becoming cheaper and more reliable, automatic control systems are expected to play an increasing role in wood stoves. The main parameters to control are the amount and distribution of combustion air.

The development of new, modern, and low emissions wood stoves is not only driven by legislation, but also by the request of the end-consumer and funding schemes and market labels such as the Nordic Swan Ecolabel, the French Flamme Verte and the German Blauer Engel. With regards to new legislation, US has in 2020 established new legislation and testing methods and Europe will have a common legislation via Ecodesign from 2022. Real life testing is being introduced with the German Blauer Engel method and will increase the need of focus on the development of improved and robust combustion control within the wood stove.

References

[1] R. Mack, H. Hartmann, C. Mandl, I. Obernberger, I. Schüßler, J. Furborg and F. Volz, "Guidelines for Low Emission and High Efficiency Stove Concepts," ERA-NET Bioenergy, 2017.

[2] C. Mandl, I. Obernberger, R. Mack, H. Hartmann, I. Schüßler, J. Furborg, J. Illerup and F. Volz, "Guidelines for automated control systems for stoves," ERA-NET Bioenergy, 2017.

[3] J. Warnatz, U. Maas and R. W. Dibble, Combustion. Physical and Chemical Fundamentals, Modeling and Simulation, Experiments, Pollutant Formation, Springer Berlin Heidelberg, 2006.

[4] P. Glarborg, A. D. Jensen and J. E. Johnsson, "Fuel nitrogen conversion in solid fuel fired systems," *Progress in Energy and Combustion Science,* vol. 29, p. 89–113, 2003.

[5] G. Reichert and C. Schmidl, "Advanced Test Methods for Firewood Stoves – Report on consequences of real-life operation on stove performance," IEA Bioenergy , 2018.

[6] F. Fachinger, F. Drewnick, R. Gieré and S. Borrmann, "How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions," *Atmospheric Environment,* vol. 158, p. 216–226, 6 2017.

[7] F. Klauser, E. Carlon, M. Kistler, C. Schmidl, M. Schwabl, R. Sturmlechner, W. Haslinger and A. Kasper-Giebl, "Emission characterization of modern wood stoves under real-life oriented operating conditions," *Atmospheric Environment,* vol. 192, p. 257–266, 11 2018.

[8] S. Ozgen, S. Caserini, S. Galante, M. Giugliano, E. Angelino, A. Marongiu, F. Hugony, G. Migliavacca and C. Morreale, "Emission factors from small scale appliances burning wood and pellets," *Atmospheric Environment,* vol. 94, p. 144–153, 9 2014.

[9] I. E. Nielsen, A. C. Eriksson, R. Lindgren, J. Martinsson, R. Nyström, E. Z. Nordin, I. Sadiktsis, C. Boman, J. K. Nøjgaard and J. Pagels, "Time-resolved analysis of particle emissions from residential biomass combustion – Emissions of refractory black carbon, PAHs and organic tracers," *Atmospheric Environment,* vol. 165, p. 179–190, 9 2017.

[10] D. Bhattu, P. Zotter, J. Zhou, G. Stefenelli, F. Klein, A. Bertrand, B. Temime-Roussel, N. Marchand, J. G. Slowik, U. Baltensperger, A. S. H. Prévôt, T. Nussbaumer, I. E. Haddad and J. Dommen, "Effect of Stove Technology and Combustion Conditions on Gas and Particulate Emissions from Residential Biomass Combustion," *Environmental Science & Technology,* vol. 53, p. 2209–2219, 1 2019.

[11] M. Kortelainen, J. Jokiniemi, P. Tiitta, J. Tissari, H. Lamberg, J. Leskinen, J. G.-L. Rodriguez, H. Koponen, S. Antikainen, I. Nuutinen, R. Zimmermann and O. Sippula, "Time-resolved chemical composition of small-scale batch combustion emissions from various wood species," *Fuel,* vol. 233, p. 224-236, 12 2018.

[12] E. D. Vicente, M. A. Duarte, A. I. Calvo, T. F. Nunes, L. Tarelho and C. A. Alves, "Emission of carbon monoxide, total hydrocarbons and particulate matter during wood combustion

in a stove operating under distinct conditions," *Fuel Processing Technology,* vol. 131, p. 182–192, 3 2015.

[13] G. Reichert, H. Hartmann, W. Haslinger, H. Oehler, R. Mack, C. Schmidl, C. Schön, M. Schwabl, H. Stressler, R. Sturmlechner and C. Hochenauer, "Effect of draught conditions and ignition technique on combustion performance of firewood roomheaters," *Renewable Energy,* vol. 105, p. 547–560, 5 2017.

[14] G. Reichert, C. Schmidl, W. Haslinger, M. Schwabl, W. Moser, S. Aigenbauer, M. Wöhler and C. Hochenauer, "Investigation of user behavior and assessment of typical operation mode for different types of firewood room heating appliances in Austria," *Renewable Energy,* vol. 93, p. 245–254, 8 2016.

[15] B. Brandelet, C. Rose, C. Rogaume and Y. Rogaume, "Impact of ignition technique on total emissions of a firewood stove," *Biomass and Bioenergy,* vol. 108, p. 15–24, 1 2018.

[16] R. Mack, C. Schön, D. Kuptz and H. Hartmann, "Nutzereinflüsse auf das Emissionsverhalten von Kaminöfen. Anzünden, Lufteinstellungen, Brennstoff. Berichte aus dem TFZ 61," (in German). TFZ, 2019.

[17] H. Hartmann and P. Turowski, "Fuel moisture influences in log wood combustion," in *Proceedings of the 18th European Biomass Conference and Exhibition*, 2010.

[18] C. Schön, H. Hartmann and P. Turowski, "User and fuel impacts flue gas emissions of a chimney stove," in *Proceedings of the 19th European Biomass Conference and Exhibition*, 2011.

[19] J. P. Carroll, J. M. Finnan, F. Biedermann, T. Brunner and I. Obernberger, "Air staging to reduce emissions from energy crop combustion in small scale applications," *Fuel,* vol. 155, p. 37–43, 9 2015.

[20] H. Khodaei, F. Guzzomi, D. Patiño, B. Rashidian and G. H. Yeoh, "Air staging strategies in biomass combustion-gaseous and particulate emission reduction potentials," *Fuel Processing Technology,* vol. 157, p. 29–41, 3 2017.

[21] M. Bugge, Ø. Skreiberg, N. E. L. Haugen, P. Carlsson and M. Seljeskog, "Predicting NOx Emissions from Wood Stoves using Detailed Chemistry and Computational Fluid Dynamics," *Energy Procedia,* vol. 75, p. 1740–1745, 8 2015.

[22] K. Nuutinen, J. Jokiniemi, O. Sippula, H. Lamberg, J. Sutinen, P. Horttanainen and J. Tissari, "Effect of air staging on fine particle, dust and gaseous emissions from masonry heaters," *Biomass and Bioenergy,* vol. 67, p. 167–178, 8 2014.

[23] R. L. Hvidberg, J. S. Andersen, K. Vang, P. K. Sørensen, B. Eskerod, O. Hansen and S. N. Bertel, "LowCarbon Brændkammer - MUDP 1946," (in Danish). Miljøstyrelsen, 2017.

[24] A. Virén, H. Lamberg, J. Tissari, O. Sippula, J. Jokiniemi, I. Obernberger, F. Biedermann, T. Brunner, H. Hartmann, C. Schön and P. Turowski, "Guidelines for Low Emission Chimney Stove Design. Report within the scope of the ERA-NET Bioenergy Project "FutureBio Tech"," 2012.

[25] R. Mack, D. Kuptz, C. Schön and H. Hartmann, “Optimierungspotenziale bei Kaminöfen. Emissionen, Wirkungsgrad und Wärmeverluste. Berichte aus dem TFZ 57,” (in German). TFZ, 2018.

[26] A. M. Frey, “Luftoptimeret Brændeovn – MUDP 2081,” (in Danish). Miljøstyrelsen, 2019.

[27] R. Mack, H. Hartmann, C. Mandl, I. Obernberger, I. Schüßler, F. Volz, J. Furborg and J. Illerup, "Wood Stoves 2020 – Development of Next Generation and Clean Wood Stoves," 2017.

[28] R. Mack and H. Hartmann, "Standing losses via chimney when using log wood stoves," in *24th European Biomass Conference and Exhibition*, 2016.

[29] R. Mack, H. Hartmann and C. Schön, "Influence of User Behaviour on Emissions from Firewood Stoves," in *Proceedings of the 27th European Biomass Conference and Exhibition*, 2019.

[30] T. Kaivosoja, A. Virén, J. Tissari, J. Ruuskanen, J. Tarhanen, O. Sippula and J. Jokiniemi, “Effects of a catalytic converter on PCDD/F, chlorophenol and PAH emissions in residential wood combustion,” *Chemosphere,* vol. 88, p. 278–285, 7 2012.

[31] G. Reichert, C. Schmidl, W. Haslinger, H. Stressler, R. Sturmlechner, M. Schwabl, N. Kienzl and C. Hochenauer, “Long term durability and safety aspects of oxidizing honeycomb catalysts integrated in firewood stoves,” *Biomass and Bioenergy,* vol. 105, p. 428–442, 10 2017.

[32] C. Mandl, T. Brunner, I. Obernberer, R. Mack, H. Hartmann and I. Schüssler, "Report on catalysts and foam ceramics — ERA-NET "Wood Stove 2020"," 2017. [Online]. Available: https://www.tfz.bayern.de/mam/cms08/en/dateien/stoves2020-report_temperature_catalysts.pdf.

[33] L. Bäfver, J. Yngvesson and F. Niklasson, “Residential Electrostatic Precipitator - Performance at efficient and poor combustionconditions. SP Rapport :2012:42,” 2012.

[34] T. Brunner, G. Wuercher and I. Obernberger, “2-Year field operation monitoring of electrostatic precipitators for residential wood heating systems,” *Biomass and Bioenergy,* vol. 111, p. 278–287, 4 2018.

[35] J. Carroll and J. Finnan, “Use of electrostatic precipitators in small-scale biomass furnaces to reduce particulate emissions from a range of feedstocks,” *Biosystems Engineering,* vol. 163, p. 94–102, 11 2017.

[36] M. Wöhler, J. S. Andersen, G. Becker, H. Persson, G. Reichert, C. Schön, C. Schmidl, D. Jaeger and S. K. Pelz, “Investigation of real life operation of biomass room heating appliances – Results of a European survey,” *Applied Energy,* vol. 169, p. 240–249, 5 2016.

[37] Energistyrelsen, *Hvordan er landets boliger opvarmet og hvor ofte skiftes opvarmningsform?- Resultater fra en spørgeskemaundersøgelse. https://ens.dk/sites/ens.dk/files/Statistik/opvarmningsundersoegelsen.pdf (in Danish),* 2017.

[38] J. E. McCarthy and K. C. Shouse, “EPA’s Wood Stove / Wood Heater Regulations: Frequently Asked Questions. CRS Report 43489,” Congressional Reserach Service, 2018.

[39] H. Czech, T. Miersch, J. Orasche, G. Abbaszade, O. Sippula, J. Tissari, B. Michalke, J. Schnelle-Kreis, T. Streibel, J. Jokiniemi and R. Zimmermann, “Chemical composition and speciation of particulate organic matter from modern residential small-scale wood combustion appliances,” *Science of The Total Environment,* vol. 612, p. 636–648, 1 2018.

Appendices

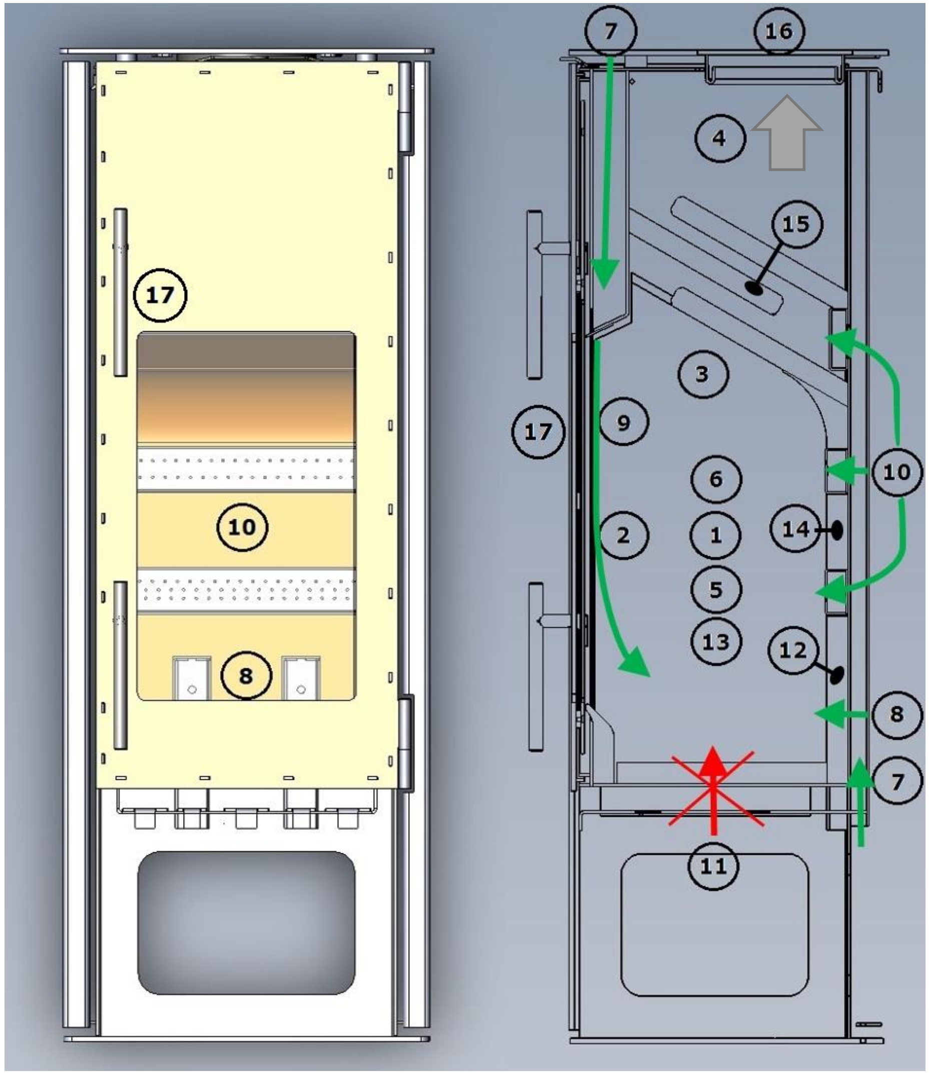
Guidelines for low Black Carbon emissions – example

The following guidelines were developed in a research project to reduce black carbon (BC) emissions [23]. Guidelines such as this can be used as a checklist in designing new stoves.

Guidelines for wood stove designs for reduced black carbon (BC) emissions

The following guidelines and measures help reduce black carbon (BC) emissions. The guidelines only address BC emissions and require adaption to achieve an overall high quality of combustion.

1. Size and dimensions of the combustion chamber matches the desired heat output
2. Simple combustion chamber design
   - No side windows
   - Front window without large curvature or angle
3. Large combustion chamber height for sufficient residence time and flame development
   - Flame formation should not be obstructed by a low flue gas baffle
4. Large head space above flue gas baffle for long residence time and stable flue gas temperature
5. High and steady temperature in the combustion chamber
   - Temperatures should be at least 450–500 °C to avoid emissions
   - Temperature fluctuations should be avoided
   - During rapid heating, emissions may increase even if oxygen is available and temperatures are otherwise sufficiently high.
6. Proper mixing via distributed air streams
   - Reducing excess air quickly reduces emissions. Emissions increase, if excess air ratios exceed 3 during the combustion cycle. Emissions are lowest at low excess air ratios and stable temperatures.
7. Minimal flow resistance in the air inlet
   - Draft regulation only works if the air channel dimensioning does not cause too much resistance. Channel reductions and bends increase resistance and reduce the air flow
8. Pilot air from lower rear wall
   - Several levels (e.g., 2), preferably immediately above embers
9. Window purge air: velocity should not be too high
   - Even and distributed over the window
   - Should not be directed at the embers, as this may increase primary air (adverse effects on emissions, see 11)
   - Avoid long duct systems
10. Secondary air in several levels (e.g., 3)
11. Primary air through embers significantly increases BC emissions and should be avoided!
12. Combustion chamber insulation
    - Maintain a high combustion temperature
13. Increased turbulence by distributed air flows and surfaces in the combustion chamber
    - Fluctuating flames do not necessarily imply poor combustion.
14. Grooved surface patterns
    - Local turbulence and reduces elemental carbon (EC) emissions via longer residence time.
15. Several flue gas baffles of vermiculite (e.g., 3)
    - Distance between baffles not too small. Too large resistance may cause flue gas to escape to the surroundings.
16. Filter color can give a qualitative indication of black carbon/elemental carbon.
17. Air-tight door
    - Prevents leak air from disturbing combustion.



IEA Bioenergy

Technology Collaboration Programme