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Posted Date: 3 March 2026

doi: 10.20944/preprints202603.0033.v1

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Review

# Emission Control Devices for Residential Combustion Sources: A Mini Review

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## Highlights

- Experimentally tested emission control devices for residential combustion sources.
- Explains why emission control devices from small- or large-scale combustion sources are unsuitable for residential combustion sources.
- Notes the lack of measuring instruments for PM removal efficiency across all size ranges.
- Calls for compact, low-cost, integrable emission control devices.
- Integration must meet technical requirements, for example, proper chimney draft.

## Abstract

Flue gases generated by residential solid fuel combustion sources contain both particulate matter and gaseous pollutants. Their concentrations can be effectively reduced using emission control devices, which have traditionally been applied in small- and large-scale combustion sources. However, in residential combustion sources, such emission control devices remain unimplemented, except for electrostatic precipitators. This mini review provides a coherent summary of the current state of knowledge regarding emission control devices experimentally tested on residential combustion sources. It also outlines the technical and measurement challenges that must be addressed to enable effective, standards-compliant integration into residential combustion sources.

**Keywords:** residential combustion sources; particulate matter (PM); flue gas cleaning; emission control devices; measurement instruments

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## 1. Introduction

The number of residential solid-fuel combustion sources in operation in the Czech Republic is in the hundreds of thousands [1], and none of them are currently equipped with additional emission control devices for reducing the pollutant concentrations in the flue gas. According to Commission Regulation (EU) 2015/1189 on ecodesign requirements for solid fuel boilers, the seasonal emissions, particularly particulate matter (PM), shall not exceed 40 mg/m<sup>3</sup> for automatically stoked boilers and 60 mg/m<sup>3</sup> for manually stoked boilers [2]. In Germany, the 1st Federal Immission Control Ordinance (1st BImSchV) set an even stricter national emission limit for PM of 20 mg/m<sup>3</sup> in 2015 [3,4].

It is necessary to focus on reducing emissions from residential combustion sources in order to protect health and the environment. Emission reduction can be achieved by using emission control devices. Small- and large-scale combustion sources are equipped with emission control devices, and given the especially high cost of large-scale combustion sources, the operating costs of these devices are almost negligible. In residential combustion sources, the high operating cost of emission control devices is a problem.

To date, the following review articles have focused on this topic: Ozgen et al. [5] in their review article analyzed the primary and secondary methods of reducing PM emissions from small non-industrial combustion sources, specifically pellet boilers, including their efficiency and operational limitations. Jaworek et al. [6] reviewed electrostatic precipitators (ESPs) for residential combustion sources, and it was found that, in order to meet the Ecodesign emission target (< 20 mg/m<sup>3</sup>), they

must achieve a collection efficiency higher than 95% for PM<sub>2.5</sub>. Singh et al. [7] reviewed various cleaning methods, such as wet (wet electrostatic precipitators (WESPs), mop fans), dry (cyclones, ESPs, fabric filters), and hybrid (electrocyclones, novel swirl cyclones). The authors concluded that none of the reviewed methods are fully suitable for residential biomass combustion sources due to high maintenance requirements and costs.

This mini review aims to fill a gap in existing knowledge by providing an overview of the current state of knowledge on emission control devices that have been experimentally tested on residential combustion sources, and to assess their practical applicability. Furthermore, the article presents, in accordance with European relevant standards, the technical aspects of small-scale combustion sources that form the basis for further research and development in this field. It also evaluates the available measurement instruments for determining removal efficiency. Relevant research articles were searched using combinations of the keywords "small-scale", "combustion", "cleaning", "reduction", "flue gas", "high-temperature", "PM", "particulate", "emissions", "filtration", "boilers", and "combustion sources".

## 2. Experimentally Tested Emission Control Devices

PM contained in flue gas can be captured and thus reduced in concentration by using emission control devices that operate, for example, through physical filtration mechanisms described in a previous study [8]. According to the current state of knowledge from previous studies on ceramic filters [8] and metal filters [9], it has been found that the use of ceramic and metal filters in the form of candles is suitable for small- or large-scale combustion sources. They filter with high efficiency (>90 %) for PM<sub>2.5</sub>, and thanks to pressure pulse cleaning, they maintain a pressure drop below 2000 Pa [8,10]. Metal filters in the form of candles (metal candle filters) have been experimentally tested for residential combustion sources [11,12]; however, such external filters in the form of metal candle filters may be unsuitable for residential combustion sources due to large dimensions, high pressure drop, and high energy consumption of pressure pulse cleaning. Aflaha et al. [13] summarized in their review article nanofiber membranes made of materials such as OPAN/PVP/SnO<sub>2</sub>, PI, PTFE, or SiO<sub>2</sub> for high-temperature filtration of PM. Although they also achieve high filtration efficiency (often >99 %), due to high pressure drop and more costly cleaning, they are also not suitable for residential combustion sources. Lu et al. [14] experimentally tested a nanofibrous membrane made of PI/SiO<sub>2</sub>, also not suitable for residential combustion sources.

In residential combustion sources, in addition to metal candle filters, catalysts were tested that capture not only PM but also gaseous emissions such as carbon monoxide (CO) and organic gaseous compounds (OGC) [15–17]. Catalyst, for example, TiO<sub>2</sub> – WO<sub>3</sub> – V<sub>2</sub>O<sub>5</sub> for capture PM, CO, and total organic carbon (TOC), is not suitable for residential combustion sources due to the risk of clogging by PM, as they do not (yet) include a particle separation system [18]. Hukkanen et al. [19] integrated in the flue gas path a catalytic combustor with a flue gas temperature >500 °C. The surface of the metal grid had a catalytic layer consisting of platinum and palladium. These catalysts require high operating temperatures (>400–500 °C) to achieve efficient oxidation and are prone to clogging and deactivation by PM and ash under real flue gas conditions.

For reducing emissions, ceramic foams were also tested in residential combustion sources, which were placed above the flame [5,20–22]. As described in a previous study on ceramic filters [8], ceramic foams interact with the flame and cause porous combustion [21]. However, material degradation caused by thermal stress and ash deposition limits the practical use of such flue gas cleaning methods. Well-known emission control devices used in small- or large-scale combustion sources include, for example, mechanical PM separators and wet scrubbers [8]. Among mechanical PM separators are cyclones, which operate on the principle of centrifugal and gravitational force. Furthermore, gravitational separators (sedimentation chambers) are used, which can serve for the separation of dust, PM, and droplets from flue gas [23].

Furthermore, for residential combustion sources, wet flue gas cleaning through wet spraying (scrubbers) and condensing heat exchangers is being investigated [24–26]. Darbandi et al. [27,28] in

their two studies used a packed-bed scrubber with a hygroscopic solution, where PM are captured by a combination of condensation, diffusion, and temperature gradients. Removal efficiency can be increased by optimizing operating parameters (concentration and solution temperature, packed-bed height), while the energy losses can be partially compensated by heat recovery in the condenser. However, the disadvantages of wet flue gas cleaning include the need for an induced-draft fan to overcome pressure drop, the handling of contaminated condensate, and, most importantly, the need for chimney relining for wet operation, as residential solid fuel combustion sources are typically designed for non-condensing (dry) operation, which makes their application in residential combustion sources more challenging.

Electrostatic precipitators are already integrated into residential solid fuel combustion sources in some European countries (e.g., Germany), but such emission control devices are expensive [29–33]. An electrostatic precipitator can be integrated, for example, into a chimney [29], an upper cleaning door [34], or a connecting flue pipe [35]. For the removal of PM in the flue gas for residential combustion sources, according to current information, electrostatic precipitators are currently the most widely available, but these require an electrical connection and depending on the design and installation, may require a flue gas fan. There are studies that deal with increasing the removal efficiency of electrostatic precipitators [36,37].

### *2.1. Removal Efficiency Evaluation Using Measuring Instruments*

The common method of evaluating the amount of PM in the flue gas is through a manual gravimetric method according to the European standard ČSN EN 13284-1, which is used to determine dust concentrations up to 50 mg/m<sup>3</sup> [38]. For high-temperature flue gas sampling, an isokinetic probe is used, and as filter material, PTFE (<230 °C), fiberglass (<200 °C), or quartz fiber (<700 °C) is used [38]. Ryšavý et al. [15] measured the concentration of PM using a gravimetric method. A disadvantage of this method is that only the total mass (of all sizes) is evaluated, and therefore, the particle size distribution is unknown. Ciria et al. [21] measured PM in flue gas using an OPS 3330 optical particle analyzer, TSI, and gaseous emissions using a Testo 350. OPS 3330 measures the number of PM in the size range from 0.3 to 10 µm and PM concentrations up to 3000 particles/cm<sup>3</sup>. Another disadvantage of this measuring instrument is that it requires low temperatures for operation; therefore, the flue gas has to be cooled and diluted [9]. Rico et al. [22], Hukkanen et al. [19], and Meloni et al. [20] measured PM emissions using Dekati® Low Pressure Impactor (DLPI), and Cornette et al. [24] measured using Dekati Electrical Low Pressure Impactor (ELPI+). Best et al. [25] measured using Nine-stage Berner-type low-pressure impactors (BLPIs). The disadvantage of the impactor is its gravimetric evaluation by weighing, and the measurable range of PM mass concentration only includes particles up to 10 µm in size. Schott et al. [11] measured PM emissions using a light scattering instrument (SICK Dusthunter SP30), which is up to +220 °C [39]. The instrument measures dust mass concentrations up to 3000 mg/m<sup>3</sup>, so it is suitable for monitoring filters in industry [39]. Dusthunter SP30 with a thread size of approximately 33–34 mm is designed for connecting flue pipe diameters >150 mm, and could therefore be suitable for testing emission control devices in residential combustion sources [40]. The disadvantage of this instrument is that it does not provide information about the particle size distribution, but only about the total concentration calibrated for a specific type of dust [40].

The concentration of PM in flue gases is variable. Measurement of PM in flue gas is performed only at nominal boiler output, for a time period lasting several minutes. The ideal device should automatically evaluate the particle mass concentration for all particle size fractions, ideally even for particle sizes above 10 µm. At the same time, a single instrument should be able to measure, in addition to the mass concentration of PM, also other important quantities, such as O<sub>2</sub>, CO concentration, in order to limit the number of measuring openings for the probes. Such measuring instruments are not yet commercially available, which limits more accurate and user-friendly testing of the emission control device for the evaluation of the size of PM not removed by the emission control device.

For the evaluation of the removal efficiency of emission control devices, the gravimetric method is the preferred method among the approaches described above. It requires particulate matter sampling upstream and downstream of the separation device, together with the determination of the flue gas volumetric flow rate. Measurements shall be carried out in straight duct sections at distances specified by relevant standards.

### 3. Technical Aspects for the Integration of Emission Control Devices into Residential Combustion Sources

The current European standard ČSN EN 15287-2 mentions filters or separators of PM and states that when dimensioning the flue gas path, it is necessary to take into account the pressure drop of the emission control device for the operating condition [41]. The current Czech national standard for chimneys and connecting flue pipes, ČSN 73 4201, also mentions fly ash separators or dust removal devices [42]. It is stated that the equipment must have a supporting construction according to the manufacturer [42]. Updated standards, therefore, take into account the existence of an emission control device. European standard ČSN EN 15287-1 states that a filter or particle separator must not cause, for example, during self-cleaning of dust separators, excessive noise [43]. In the case that the average flue gas flow velocity is lower than 0.5 m/s at the nominal output of the combustion device, a CO detector must be installed [42]. At velocities lower than 0.3 m/s, the installation of a flue gas fan is recommended [42].

The boiler manufacturer specifies in the combustion device's operating instructions the minimum chimney draft (or the permissible range of chimney draft values) at the flue gas throat; or, if not provided, it can be determined according to the European standard ČSN EN 13384-1+A1 [44]. The chimney draft can be changed using a draft regulator with an adjustable damper [41]. For ensuring safety, the chimney draft specified by the manufacturer must be maintained when installing the emission control device. Any intervention in the flue gas path shall be performed only by authorized personnel.

### 4. Conclusions

Several authors have tried to test emission control devices on residential combustion sources, but this issue has not been technically resolved; therefore, emission control devices are not yet commonly used in practice in most countries, and this remains a knowledge gap. The reason for this is also that they have not been required by legislation or supported by grants. Here are the future challenges:

- Further research should focus on enhancing the removal efficiency of existing emission control devices.
- Emission control devices should be affordable, and chimney draft should not be affected beyond the prescribed range specified by the manufacturer.
- PM concentration is variable, so the measurement of removal efficiency must be carried out at the same boiler output and over a longer period.
- The measurement instruments of PM should allow the measurement of all size fractions, including particle sizes
- above 10  $\mu\text{m}$ , and other essential parameters, such as, for example, CO concentration.

**CRedit authorship contribution statement:** Eva Gregorovičová: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration.

**Declaration of Competing Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgements:** This research was funded by projects of the Brno University of Technology: FSI-S-23-8223 Optimization of processes and fuels for lower emissions.

**Data Availability Statement:** Data is not contained within the article.

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