Advanced Test Methods for Pellet Stoves

Report on Consequences of Real-Life Operation on Stove Performance

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Report on Real-Life Operation on Stove Performance

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1 Introduction

Pellet stoves refer to direct room heating appliances which can be categorized in several different technologies. However, in contrast to manually fuelled direct room heating appliances (e.g. firewood stoves, insets, biomass cookers or slow heat release appliances), pellet stoves are automatically fuelled. In a previous report the effects of testing procedures and their consequences on real-life performance were discussed for manually fired stoves [1] with a special focus on firewood stoves classified according to the standard EN 13240 [2].

This report focuses on pellet stoves classified according to the European standard EN 14785 - "Residential space heating appliances fired by wood pellets – Requirements and test methods" [3]. In detail, the priority is set on pellet stoves for room heat supply only (warm air). Pellet stoves featured with water jackets for an additional central heat supply (hot water) are not in the focus of this report.

1.1 OBJECTIVES AND APPROACH

The overall objective of this report is the provision of an overview on different test methods for pellet stoves. These are either already implemented as an official test standard, or (up to now) only used in science as testing procedures to evaluate the performance of such technologies. Thereby, the focus is on the comparison of main differences regarding test procedures, fuel requirements, measurement methods and data evaluation procedure, especially in view of real-life relevance.

Furthermore, the report aims at following additional objectives:

- Overview on available data how pellet stoves are typically operated in real-life
- Discussion and evaluation of potential influencing factors on real-life emission and efficiency performance of pellet stoves
- Comparison of "official type test" (ott) results (EN 14785) with measurement results from the field as well as from the lab on test facilities (according to different testing procedures)
- Comparison of emission factors (EFs) assessed by advanced testing protocols in comparison to officially used emission factors for pellet stoves

The above-mentioned topics are addressed by reviewing available official test standards as well as further scientific literature, i.e., technical reports, presentations at conferences and papers in scientific journals.

1.2 TECHNOLOGY OF PELLET STOVES

Typically, the heat output of pellet stoves without water jacket ranges between 2.5 kW and 12 kW. In Austria for example, the average nominal heat output of pellet stoves is in the range of 8.0 kW to 9.0 kW [4].

Pellet stoves are equipped with a fuel supply storage tank that can commonly store a pellet mass of around 15 kg to 20 kg. The pellets are transported automatically to the burning pot of the combustion chamber, for example by using an auger screw (**Figure 1**). The ignition of the pellets at the beginning of heating operation is induced automatically by an electric heating element or hot air fans. The flue gases are conveyed through the heat exchanger system towards the flue gas outlet and the chimney by a ventilator which is located at the flue outlet of the pellet stove. The combustion air is commonly supplied according to an air staging concept via primary, secondary and window purge air (or tertiary air). Heat is released via convection and radiation into the installation room or additionally in further rooms that are connected to the stove by convection pipes. Commonly, pellet stove users can adjust the heat output in several discrete levels by a control panel at the stove. However, the settings of the heat output level can be also regulated by a control system, e.g., according to the room temperature. Moreover, some pellet stoves are equipped with a temperature control in the combustion chamber in order to adjust the heat output to the fuel quality (e.g., caused by various bulk density). The rotation speed of the ventilator is controlled according to the load level as well as the operating phase of the stove (e.g., start-phase, cleaning interval, stop-phase, etc.). Typically, the burner pot of pellet stoves is regularly cleaned during operation, e.g., once an hour. In most cases, this is done by an acceleration of the ventilator speed for a certain time while the fuel supply is stopped. Thereby excessive ash is blown out of the burner pot and falls into the ash collection pan.

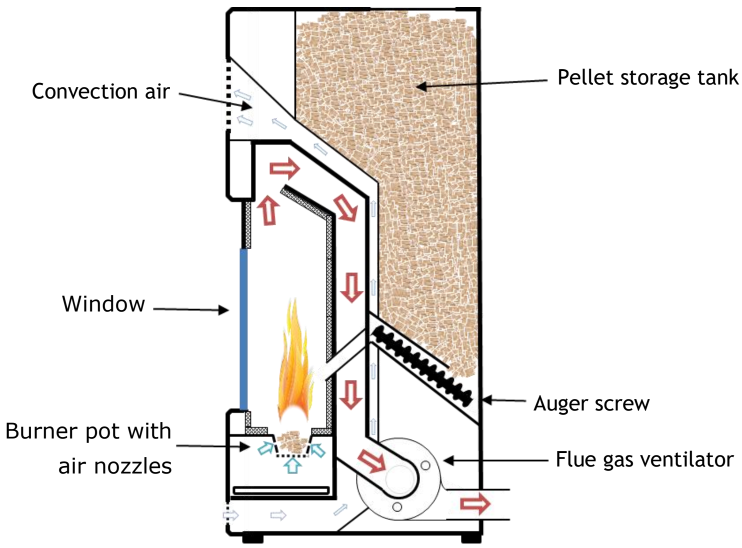


Figure 1: Scheme and main features of a pellet stove
Source: WÖHLER 2017 [5], translated into English

In comparison to manually fired room heating appliances pellet stoves are more sophisticated technologies and reach in principle lower gaseous and particulate emissions as well as higher thermal efficiencies [4] (see also **Figure 12**). But in contrast to firewood stoves an operation without electricity is in principle not possible – only few, historic examples exist. However, there are ongoing R&D efforts to find technical solutions to enable also heating operation without electrical supply for pellet stoves [6].

1.3 STOCK AND MARKET

In 2017 the stock of pellet stoves was quantified at nearly 4 million appliances in Europe (**Figure 2**) [7]. From 2016 to 2017 the stock has increased by around 11%. The annual sales ranged around 10% of the stock in 2016 and 2017. Currently, Italy and France cover around 85% of the total stock of pellet stoves (2017: Italy: 67% / France: 19%).

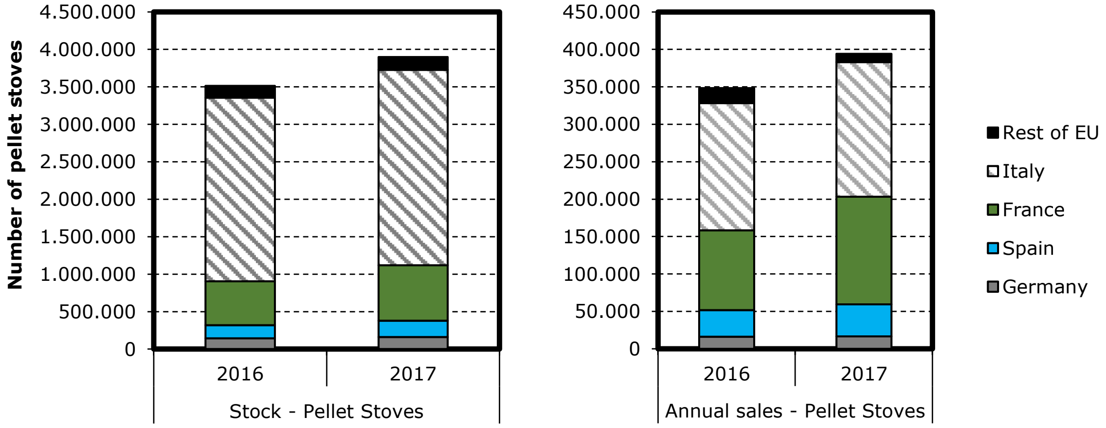


Figure 2: Stock (left) and sales (right) of pellet stoves in Europe as well as its share in most relevant European countries
Source: Own figure, data based on EPC survey 2018, Bioenergy Europe, Statistical report 2018 [7]

Based on the previously described data it could be assumed that pellet stoves and their share among direct room heating appliances will further increase in future. The following list illustrates some benefits and advantages of pellet stoves compared to other room heating technologies which might be relevant for the increasing popularity of pellet stoves in recent years as well as in future:

- High user comfort – long operating times without refilling or maintenance possible
- Quite simple adaption of load settings
- Regulation of heating operation according to room temperature or by clock-timer possible
- Controlling of appliance operation via web-connection possible
- Pellets represent a commercial and highly standardized fuel
- Good availability of pellets and space-saving storage options by bagged cargo
- Cheaper investment costs in comparison to central heating systems
- National funding programs enhancing the installation of pellet stoves
- Higher efficiency and lower emissions than manually operated wood stoves.

1.4 IMPORTANT CRITERIA OF PERFORMANCE TESTING OF TECHNICAL PRODUCTS

The testing of pellet stoves or in general testing of technical appliances is necessary to guarantee the following aspects:

- A minimum product quality,
- Sufficient product safety and
- Certain product reliability.

Typically, new products must be tested prior to market introduction in order to comply with the above-mentioned aspects as well as with potential other legal requirements.

Test protocols should result in repeatable and reproducible test results. Furthermore, they should offer equal opportunities for different manufacturers. Therefore, product testing is carried out according to specific test standards which define basic requirements for the tested product. Additionally, standards define testing conditions, testing procedures, measuring methods, accuracy of measurement devices as well as the data evaluation procedure.

Moreover, testing methods are regarded as a potential instrument which is capable to push technological development. Therefore, an important criterion is that the testing protocol and its testing procedure reflects quite closely real-life use of the respective product. However, in terms of repeatability and reproducibility as well as regarding manifold influencing factors during the real-life application this is often a challenge and only to some extent or even not possible.

Nevertheless, testing methods which evaluate performance parameters, e.g., emissions and thermal efficiency, that could be regarded as "*true*" or better as "*real-life representative*" are important to guarantee good product reliability and to enable the differentiation between excellent and poor products for the customer. This fact can also be seen in the car industry where the development of testing methods is strongly guided in the direction of evaluating "real-life performance with serial products", e.g., Real Driving Emission Test (RDE-Test) since other test methods lost (at least partly) their reliability due to manipulation of tested products and/or due to artificial test procedures that can lead to performance test results that are far away from real-life performance.

In recent years, emissions of small-scale biomass combustion systems (both stoves and boilers) have become more relevant since pollution measurements showed increased emission concentrations in ambient air in Europe, especially in winter times [8] [9] [10] [11]. Therefore, emission limit values have been tightened more and more aiming to improve the situation in real-life [12]. However, since the testing protocols and testing procedures of existing test standards insufficiently reflect the real-life application of those products, the effect of this tightening will be limited [13] [14] [15]. Consequently, comprehensive efforts were put into the development of testing methods for wood and pellet stoves. These test results better reflect real-life use of products and simultaneously having a good repeatability and reproducibility of test results [16] [17] [18] (see also chapter 5).

1.5 FUTURE EMISSION LIMIT VALUES FOR PELLET STOVES

According to national regulations pellet stoves must comply with specific requirements on emissions and thermal efficiency. According to standard EN 14785 [3] only carbon monoxide (CO) emissions and thermal efficiency are mandatory parameters that are evaluated during the performance test, the so called "official type test" (ott), at specific load settings. However, according to national regulations more emission parameters are relevant (e.g., particulate matter (PM), volatile organic compounds (VOC) as well as NO_x) and evaluated during performance testing according to the EN standard (e.g., Austrian 15a B-VG [19], German 1. BImSchV [20]). Therefore, the previously mentioned emission parameters which are not covered by the official standard EN 14785 are evaluated according to the technical specification CEN/TS 15883 [21] or according to the new European test standard EN 16510-1 [22].

In recent years common emission limit values (ELVs) were elaborated during the ecodesign and ecolabelling process [23]. Accordingly, the following ELVs (in mg/m^3, dry, STP: 273.15 K/ 1013.25 hPa, referred to 13 vol.-% O_2), which refer to official type test procedure (ott) at nominal load, has come into force from the 1st February 2022:

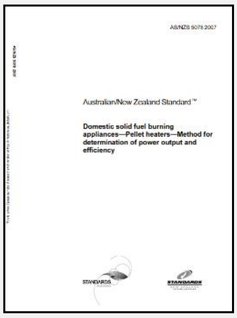
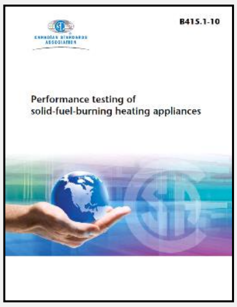
- Carbon monoxide (CO): 300 mg/m^3
- Volatile organic compounds (VOC): 60 mg/m^3, measured as organic gaseous compounds (VOC) using flame ionization detector (FID)
- Nitrogen oxides (NO_x): 200 mg/m^3
- Particulate matter (PM): 20 mg/m^3, referred to the gravimetric measurement in hot and undiluted flue gas

The measuring methods and principles are also described in the ecodesign and ecolabelling document [23].

2 Overview of Existing Test Standards

In the following chapter an overview of existing international and European standards for official type testing of pellet stoves is presented. The findings are based on reviewing the standards itself (**Table 1**).

Table 1: Overview of reviewed international and European test standards used for official type testing of pellet stoves

Standards	
Australian/New Zealand test protocol - AS/NZS • AS/NZS 5078:2007 – Domestic solid fuel burning appliances – Pellet heaters – Method for determination of power output and efficiency [24] • AS/NZS 4886:2007 – Method for determination of flue gas emission [25] • AS/NZS 4014.6:2007 – Wood Pellets [26]	 AS/NZS 5078:2007 Australian/New Zealand Standard™ Domestic solid fuel burning appliances—Pellet heaters—Method for determination of power output and efficiency
Canadian test protocol - CSA • CSA B415.1-10 (2010) – Performance testing of solid-fuel-burning heating appliances [27]	 B415.1-10 Performance testing of solid-fuel-burning heating appliances
US standards - ASTM • ASTM E2779 – 10 (2017): Standard Test Method for Determining Particulate Matter Emissions from Pellet Heaters [28]	
European test protocol - EN • DIN EN 14785:2006 – Residential space heating appliances fired by wood pellets – Requirements and test methods [3]	 DIN EN 14785 Residential space heating appliances fired by wood pellets – Requirements and test methods English version of DIN EN 14785:2006-09

Following the main characteristics of the standards mentioned in **Table 1** are summarized and presented. The content of the respective reviews is structured regarding the following topics:

- Preconditioning (e.g., operating time before testing)
- Fuel requirements (e.g., chemical, and physical fuel requirements)
- Testing procedure (e.g., number and settings of different burn periods)
- Measurement methods (e.g., PM measurement, thermal efficiency determination)
- Data evaluation and test results.

2.1 AUSTRALIAN/ NEW ZEALAND TEST STANDARD – AS/NZS

The test principle of the Australian/ New Zealand test standard (AS/NZS standards) is that the stove is installed in a calorimeter room and operated in a specific manner at different load settings for a certain period. During the different load settings, the heat output is directly measured via the calorimeter room. Additionally, PM emissions are measured in diluted flue gas using a full flow dilution tunnel. As test result an average particulate emission factor in “g/kg dry fuel” based on the different tested load settings is calculated. Additionally, the thermal efficiency based on two consecutive test burn periods is evaluated.

2.1.1 Preconditioning

Stoves must be operated before testing by two separate burn periods, each of them lasting at least 8 h at the maximum burn rate of which the stove could be operated. A minimum time of 4 h is allowed between the two burn periods. Subsequently to this so called “conditioning burns”, maintenance adjustments as specified by the manufacturer’s manual are permitted.

2.1.2 Fuel requirements

As test fuel wood pellets shall be used without containing any non-woody materials. The chemical and physical properties must be analysed for the test fuel and have to comply with specific requirements.

- Moisture content in the range of 4% - 8% (w/w; percentage referred to wet fuel mass)
- Bulk density ≥ 640 kg/m³ (as received, a.r.)
- Ash ≤ 0.5% (w/w)
- H_s (gross calorific value) in the range of 18 – 21 MJ/kg
- Pellet size should be maximum 10 mm in diameter and ≤ 38 mm in length
- Fines ≤ 1% (fines = particles with a diameter of < 3 mm)

2.1.3 Testing procedure

After starting the combustion according to the manufacturers manual, a pre-test burn-cycle (one or more hours) is carried out until the combustion conditions of the respective burn rate is achieved (within an accuracy of ±10%). A full test consists of at least two burn periods. Each must last at least two hours for the respective burn rate.

In total, the appliance must be tested at three different burn rates.

- High burn rate: Combustion rate control settings adjusted to maximum
- Low burn rate: Combustion rate control settings adjusted to minimum
- Medium burn rate: Combustion rate control settings adjusted to ± 10% of mean burn rate.

Appliances without load control options are only tested at the high burn rate. Potential thermostatic controllers of the test appliance, which regulates heating operation as a function of a specific room temperature, must be disabled. If the tested appliance is featured with a convection fan the fan should be operated at constant settings (either at maximum settings or as specified by the operating instructions of the appliance).

2.1.4 Measurement methods

The heat output as well as the thermal efficiency is measured directly using the calorimeter room. The calorimeter room is an enclosed space of at least 15 m^3 of volume. It allows the evaluation of the released heat to the surrounding calorimeter room by convection and radiation. The walls of the calorimeter room must be insulated (thermal resistance ≥ 2.5 m^2K/W). The length of the flue gas pipe shall be terminated at a height of 4.6 ± 0.1 m above the bottom of the appliance (= platform scale). The insulation of the flue gas pipe of the pellet stove downstream the flue outlet shall start 2.0 ± 0.02 m above platform scale. There are special requirements regarding the range of inlet (10°C – 25°C) and outlet temperatures (sum of inlet and outlet temperature ≤ 80°C) during the tests. Furthermore, surface wall temperatures of the calorimeter room as well as air flow conditions in the calorimeter room are limited (wall temperatures 20°C – 45°C, air flow ≤ 1 m/s). A specific calibration process for the calorimeter room must be carried out in advance of testing.

PM emissions are measured in diluted flue gas. Therefore, the flue gas volume flow is diluted by ambient air using a full flow dilution tunnel which is located downstream the 4.6 m flue gas pipe of the calorimeter room. The volume flow in the dilution tunnel must be adjusted to a flow rate of 6.0 ± 0.5 m^3/minute (NTP: 293.15 K, 1013.25 hPa). Flue gas draft induced into the appliance flue gas pipe (terminated at a height of 4.6 m above platform scale) by the dilution tunnel is monitored and should be < 1 Pa.

The orientation of the PM sampling probe which has an internal diameter of 9.5 mm is vertical to the flue gas flow. The particles are sampled on two plane filters (glass fibre, Ø 50 mm, 99.95% collection efficiency on 0.3 µm dioctyl phthalate smoke particles) which are consecutively arranged. Between both filters the temperature of the flue gas is monitored by a thermocouple. The sampling temperature shall be in the range of 15°C to 32°C. The leakage rate of the sampling train must be evaluated and shall be ≤ 4% of the sampling train flow rate. The flow rate of the PM sampling is adjusted to 0.005 m^3/minute ± 10% (NTP).

PM sampling is conducted during the whole test duration of the respective burn rates. If a change of filters is necessary, the time of measurement interruption shall be less than 30 s. For pre-and postconditioning the filters must be desiccated for at least 24 h under ambient conditions before weighing. Rinsing of the sampling probe is done by using acetone. The temperature for desiccation in the laboratory shall be below 30°C.

Based on all measurements of the different burn rates the PM emission test result is calculated.

2.1.5 Data Evaluation and Test Results

The maximum data recording intervals for measurements that are used for the heat output determination (e.g., temperatures) are 2 minutes. Other measurements (e.g., relative humidity and barometric pressure) shall be determined at least once per burn period.

As the most relevant test result the average particulate emission factor based on each of the tested burn rates is calculated in “g/kg dry fuel”. Therefore, all the performed tests at high, medium and low burn rates are considered. For compliance with the standard the emission factor shall be ≤ 1.0 g/kg.

Thermal efficiency is evaluated based on two consecutive test burn periods which deviates ≤ 5%. The minimum overall average efficiency should not be less than 70% according to the test standard.

2.2 CANADIAN TEST STANDARD - CSA

The Canadian test standard B415.1-10 specifies the requirements for performance testing for manually and automatically fuelled heating appliances, typically below 150 kW heat output. The test principle of the Canadian standard is to operate the appliances at different load settings (burn rates) under stationary conditions. The measurements of the different burn rates are used to calculate specifically-weighted average test results for CO emissions, thermal efficiency, heat output and particulate matter emissions ("g/h" or "g/MJ of heat output"). PM emissions are sampled gravimetrically in diluted flue gas using a full flow dilution tunnel. Thermal efficiency is determined by the evaluation of energy losses (indirect method).

2.2.1 Preconditioning

The test appliances must be operated a certain time duration in advance of testing. Therefore, non-catalytic stoves must be operated for at least 10 h and catalytic stoves for at least 50 h at a medium burn rate before testing. For catalytic stoves the average temperatures at the exit of the catalyst should be > 260°C. The hours of operation must be recorded and reported.

2.2.2 Fuel requirements

For pellet stoves wood pellets of each specified grade by the manufacturer must be used for testing. Moisture content must be ≤ 8% (w/w; wet basis). According to the standard wood pellets for the residential use are characterized by a length typically < 3.8 cm and between 6 to 12 mm in diameter. A sample of the test fuel must be taken and analysed regarding gross calorific value (H_s), ash content, elemental analysis (C, H, O_2) and moisture content.

For automatically fuelled appliances that can be potentially operated with other types of fuel (e.g., wood chips or corn) those fuel types must be tested, too.

2.2.3 Testing procedure

The appliances are tested at the required load settings in hot conditions. This means that the appliances are started by ignition of the fuel according to the manufacturer's manual and are operated until stationary conditions of the respective burn rate are reached (but not less than 1 h). When finishing the heating-up procedure the appliances are tested at different burn rates.

The testing procedure concerning the tested burn rates depends on the control options of the test appliances. Appliances without any possibilities to adapt the load settings must be tested with three test runs at their specific burn rate. Appliances that offer the possibility to adapt the load settings, as it is typical for pellet stoves, should be tested in four different burn rate categories (target output in % of maximum output).

- Category 1: As specified by the manufacturer but not > 30% (actual output < 35%)
- Category 2: 44% (actual output 35% - 53%)
- Category 3: 65% (53% - 76%)
- Category 4: 100%

Each category should be tested at least for 2 h. During testing manual adaptions are not allowed. The ambient temperature of the test room shall be between 18°C and 32°C when the tests are carried out. During all test runs as well as burn rates gaseous emissions are continuously measured as well as particulate emissions are continuously sampled.

For stoves that are automatically controlled by a room thermostat the testing of the four burn rates is carried out by specific manipulation of the control settings. During category 1 – 3 the stove is operated by operation in a defined test use pattern, which means a specific on-off operation. During Category 4 the appliance is operated continuously with control settings at "on" position.

2.2.4 Measurement methods

Carbon monoxide (CO) emissions must be measured using gas analysers with defined requirements regarding calibration and accuracy.

PM emissions are measured during the whole test run in diluted flue gases. The sampling procedure as well as pre- and post-conditioning of the filters is quite similar compared to the procedure described for the AS/NZS standard (see chapter 2.1.4).

Thermal efficiency is calculated indirectly by evaluating the thermal and chemical flue gas losses as well as the losses of unburned residues.

Flue gas temperature is measured 2.44 m ± 0,15 m above the platform scale using a thermocouple type K.

2.2.5 Data Evaluation and Test Results

For evaluation of the test results all data of the single test runs referring to the respective burn rates are considered. They are weighted in a specific way, so that finally one test result for each parameter is determined. Accordingly, average particulate emission rates including the required test runs in "g/h" or "g/MJ of heat output" are evaluated. Furthermore, average thermal efficiency, heat output and average carbon monoxide emissions are evaluated.

2.3 US STANDARD – ASTM

The principle of the US Test standard ASTM E2779 – 10 is the evaluation of pellet heaters using a so-called integrated test run. Accordingly, the pellet heater is heated up and then the integrated test run starts. The integrated test run consists of heating operation of the pellet stove at specifically defined load settings which are subsequently adjusted. The load settings are specified by three burn rates including minimum, medium, and maximum load settings. The tested appliance is operated in the respective burn rate segments in a defined order as well as in defined times per segment. During the whole integrated test run PM emissions must be sampled. Subsequently, PM emissions representing the whole integrated test run are calculated, e.g., in "g/h" or "kg/dry kg of fuel burned".

2.3.1 Preconditioning

After installation of the test appliance on the test bench the stove must be operated at least 48 h at a medium burn rate. The 48 h represent the total duration of preconditioning, meaning that this time duration requirement could be also achieved in several shorter operating intervals.

2.3.2 Fuel requirements

There are no specific requirements regarding physical or chemical properties defined within the test standard. However, the main requirement is that the pellets/fuel can be supplied in the burning pot of the combustion chamber by a feeding mechanism or by an auger screw.

All types of fuel that are permitted by the manufacturer's manual must be tested. In the case that different fuel grades of one fuel type are feasible the lowest grade of this type of fuel must be used for testing.

From all fuels which are used for testing a representative sample must be taken and analysed regarding gross calorific value (H_o) and moisture content.

2.3.3 Testing procedure

The test appliance is placed on a platform scale. The vent height (= flue gas system downstream the flue outlet) is specified in 4.6 m ± 0.3 m from the floor or the platform scale. Subsequently, the flue gas is conveyed by a full flow dilution tunnel which is also used for measuring PM emissions.

The fire in the test appliance is ignited by following the manufacturer's instructions. The controls for load settings are adjusted to achieve the maximum burn rate. The maximum burn rate is defined as the "maximum achievable" burn rate. When the maximum burn rate is achieved the appliance must be operated at the maximum burn rate for at least 1 h before the integrated test run is started. Subsequently, the PM sampling is started, and the appliance is operated for 60 +5/-0 minutes at the maximum burn rate (maximum achievable), followed by the medium burn rate (≤50% of maximum burn rate) for 120 +5/-0 minutes and finally at the minimum burn rate (minimum achievable) for 180 +5/-0 minutes.

For pellet stoves that are automatically controlled, e.g., by a room thermostat, the burn rates are adjusted by artificial manipulation of the controls. Thereby, the high burn-rate means 60 minutes-on, whereas the medium burn rate is represented by two cycles of 30 minutes "On" and 30 minutes "Off". Finally, the low burn rate is emulated by three cycles at 20 minutes "On" and 40 minutes "Off". For stoves that are featured with only two burn rate control settings (high and low) both burn rates are tested (300 +5/-0 minutes at low and 60 +5/-0 minutes at high burn rate). Ventilators for convective heat transfer from the stove to the surroundings are respected by following the manufacturers manual or by adjusting specific settings.

2.3.4 Measurement methods

Flue gas temperature is measured in the centre of the flue gas pipe 2.6 m ± 0.15 m above the floor or platform scale (thermocouple type K). The used platform scale should have an accuracy of ± 0.05 kg. It must weigh the test appliance, the fuel of the test run and the venting system downstream the flue outlet (until the decoupling due to the dilution air). Both measuring devices must be specifically calibrated.

PM sampling is conducted in the diluted flue gas according to the gravimetric measurement principle. The emission sampling is carried out over the whole length of the integrated test run, meaning that also load changes between the different burn rates are included in the measuring interval.

2.3.5 Data Evaluation and Test Results

Average particulate emission rates over the whole integrated test run in "g/h", "kg/dry kg of fuel burned" or "g/MJ of heat output" are calculated (if the optional heat output is measured).

If more than one integrated test run is conducted at least two thirds of the test runs must be considered for calculating the average test results. Additionally, the measurement data and results of all tests must be documented in the test report.

2.4 EUROPEAN TEST STANDARD - EN

The European test standard EN 14785 applies to pellet room-heaters with and without water jacket up to a heat output of 50 kW. The following description focuses on pellet room-heaters without water jacket.

The standard specifies requirements regarding construction, production, design, safety aspects as well as performance criteria (thermal efficiency, emissions). Furthermore, the standard specifies the test procedures to evaluate the above-mentioned aspects. The testing procedure to evaluate the emission and thermal efficiency performance is called "official type test" (ott).

2.4.1 Preconditioning

No special requirements regarding preconditioning are specified. The tested appliance must be a serial product which is representative for the whole production (if production has already started) or a "final prototype", meaning that significant changes are not permitted after testing.

2.4.2 Fuel requirements

For testing commercial wood pellets must be used. The wood pellets consist of untreated wood with or without bark as well as also in some cases additives (e.g., supplied during pelletizing as binding agent, like molasses). The test fuel must meet certain requirements regarding physical and chemical properties. The most relevant parameters are moisture content ≤ 12% (w/w), ash content ≤ 0.7% (w/w), net calorific value (H_i): 16.9 – 19.5 MJ/kg, Pellet size: Ø 4 mm – 10 mm and length ≤ 50 mm.

2.4.3 Testing procedure

The test procedure of pellet room-heaters consist of two testing sections:

- Ignition and one or several pre-tests
- Test period.

The first section (ignition and pretesting) aims to achieve or adjust stationary conditions at the respective load setting. Stationary conditions are defined by a maximum range of the flue gas temperature of ± 5K for at least 30 minutes (test at nominal load) or at least 60 minutes (partial load).

The test period for nominal load is at least 3 hours and for partial load at least 6 hours. Each load must be tested for at least two times in separate burn periods. For each test stationary conditions must be adjusted by using a pre-test period. In principle, it is possible to conduct partial load testing subsequently to nominal load testing when stationary conditions are achieved.

The load settings must be defined by the manufacturer. Partial load is defined as the lowest load which is possible for a continuous operation. Typical values are 100% thermal output for nominal load and 30% thermal output for partial load.

Controlling devices which automatically adjust the load settings of appliances, e.g., a room thermostat control, must be switched off during testing.

2.4.4 Measurement methods

Gaseous flue gas composition regarding CO and CO_2 or O_2 is measured continuously during the tests with a measuring interval of maximum 1 minute. Therefore, appropriate flue gas analysers are used which must be calibrated as well as meet certain requirements regarding measurement precision and accuracy.

The flue gas temperature as well as room temperature must be measured continuously by using appropriate thermocouples with a measuring interval of maximum 1 minute.

The average flue gas temperature which is also used for calculation of the thermal flue gas losses is determined by using a so-called suction pyrometer. The suction pyrometer is a small pipe (Ø 5 mm ± 1 mm) which has three holes that are specifically positioned over the cross-sectional area of the flue gas pipe against flow direction of the flue gas flow. The flue gas is sucked through those holes and its temperature is measured by a thermocouple which is placed within the suction pipe. An important requirement is that the velocity of the flue gases within the suction pyrometer is between 20 m/s and 25 m/s. This is to guarantee an equal sampling via all three holes of the suction pyrometer to measure the “representative” temperature over the whole cross-sectional area of the flue gas pipe.

Thermal efficiency is measured indirectly, meaning that thermal and chemical flue gas losses are calculated based on measured flue gas temperature and CO emission concentrations, respectively. Additionally, losses of unburnt residues are considered which are estimated at a fixed value of 0.2% of thermal efficiency.

For PM emission measurements no specific measurement procedure is specified in the standard. Also, no minimum requirements regarding PM emissions are defined by the EN 14785. However, meeting specific requirements regarding PM emissions is typically relevant in European countries. Therefore, PM emissions are measured according to national standards or guidelines, e.g., by gravimetric PM measurements in hot and undiluted flue gases according to CEN/TS 15883 [21].

2.4.5 Data Evaluation and Test Results

For calculation of test results the average CO emissions (mg/m^3, STP, dry, 13 vol.-% O_2) and thermal efficiency must be calculated mandatorily. Thereby the average of at least two test intervals, e.g., 2 x 30 minutes, for nominal and partial load, must be used respectively.

The minimum requirements of the standard regarding CO emissions are 500 mg/m^3 (nominal load) and 750 mg/m^3 (part load). The minimum requirements of the standard regarding thermal efficiency are 75% for nominal load and 70% for partial load. However, as already mentioned national requirements in European countries are frequently more stringent and consider also VOC emissions as well as PM emissions, e.g., [19] and [20].

2.5 SUMMARY AND DISCUSSION OF MAIN DIFFERENCES OF REVIEWED TEST STANDARDS

All reviewed standards define the requirements for measuring the performance of the appliance regarding emissions (gaseous and/or particulate emissions) and to some extend thermal efficiency.

The most relevant differences were observed regarding…

- … the number of tested load settings,
- … repetitions of measurements or number of measuring intervals which must be used for final test result evaluations,
- … the type of respected emissions,
- … the PM emission measurement procedure
- … as well as the evaluation procedure for thermal efficiency (direct by using a calorimeter room or indirect by considering relevant energy losses).

In **Table 2** the most relevant differences of the reviewed test standards are summarized.

Table 2: Overview of main characteristics of International and European test standards

Test standard	Preconditioning	Fuel requirements	Load settings & number of measurements	Performance measurements	Data evaluation & test results
Australian/ New Zealand Test Standard - AS/NZS • AS/NZS 5078:2007 • AS/NZS 4886:2007 • AS/NZS 4014.6:2007	Tested stoves must be operated before testing by two separate burn periods, each of them lasting at least 8h at the maximum burn rate (time in between at least 4h)	Wood pellets, moisture content in a range of 4% to 8% (w/w), bulk density (≥640 kg/m³), ash ≤0.5% (w/w), H_o: 18 - 21MJ/kg, pellet size: Ø max. 10mm and length ≤38 mm, fines ≤1% (fines = particles <3 mm)	Test of three burn rates ("high" = maximum, "low" = minimum, "medium" = ± 10% of mean of high and low), Two test runs for each burn rate mandatory, at least 2 h per burn rate	Heat output and thermal efficiency using a calorimeter room, PM sampling during the whole test run (in diluted flue gas using a full flow dilution tunnel)	Average particulate emission factor based on each of the tested burn rates in "g/kg dry fuel" Thermal efficiency based on two consecutive test burn periods which deviates ≤5%
Canadian Test Standard - CSA • CSA B415.1-10 (2010)	Tested non-catalytic stoves must be operated before testing for 10h, catalytic stoves at least 50h at a medium burn rate	Wood pellets of each specified grade by the manufacturer must be tested, moisture content ≤8% Potential types of other allowed fuels (e.g., wood chips, corn) have to be tested, too	Test of 4 burn rates (≤30%, 44%, 65%, 100%) One test for each burn rate mandatory, at least 2h test duration per burn rate) Room thermostat-controlled stoves: artificial manipulation of the controls (on-off operation)	Heat output and thermal efficiency (indirect), CO emissions, PM sampling during the whole test run in diluted flue gas using a full flow dilution tunnel	Average particulate emission rates, thermal efficiency and CO emissions including the required test runs are calculated (special procedure, weighted by burn-rates of all test runs)

Test standard	Preconditioning	Fuel requirements	Load settings & number of measurements	Performance measurements	Data evaluation & test results
US Standard - ASTM • ASTM E2779 - 10 (2017)	Tested stoves must be operated before testing for 48h at a medium burn rate	All types of allowed fuel must be tested; in case of different fuel grades the lowest grade must be used	Integrated test run (= test cycle with different loads): In general, test at maximum (60 min, maximum achievable), medium (120 min, ≤50% of maximum) and minimum (180min, minimum achievable) burn rate At least one integrated test run mandatory	PM sampling during the whole integrated test run (in diluted flue gas) → load changes included in PM sampling	Average particulate emission rates over the whole test run in “g/h”, “kg/dry kg of fuel burned” or “g/MJ of heat output” (if the optional heat output is measured)
European Test Standard - EN • DIN EN 14785:2006	No special requirements	Commercial wood pellets with defined parameters: e.g., moisture content ≤12% (w/w), ash ≤0.7% (w/w), H_u:16.9MJ/kg - 19.5MJ/kg, Pellet size: Ø 4 mm - 10mm and length ≤50mm	Start of test run when stationary conditions are achieved (constant flue gas temperature ± 5K) Test at nominal load (defined by manufacturer) and partial load (minimum load) At least one test at nominal (≥3h) and partial load (≥6h)	CO emissions, thermal efficiency, → no uniform procedure for PM (however, up to now PM is measured most frequently acc. to CEN/TS 15883: Gravimetric measurement in hot and undiluted flue gas	Average CO emissions (mg/m^3, STP, dry, 13 vol.-% O_2) and thermal efficiency mandatory (average of two test intervals, e.g., 2x30 minutes, for nominal and partial load, respectively)

3 Real-life Operation of Pellet Stoves

As mentioned in chapter 1 testing protocols should evaluate performance parameters that reflect the “*true*” or “*real-life situation*” as good as possible. Therefore, the initial questions are “*How are pellet stoves operated in real-life?*” and “*What are impact factors that influence stove performance regarding emissions and thermal efficiency?*”. Finally, the concluding question is “*What are important characteristics that should be included in a real-life oriented test method?*”.

In general, the parameters that mainly influence the emission and efficiency performance of pellet stoves could be categorized in “technology”, “operating conditions” and “fuel specifics” (**Figure 3**).

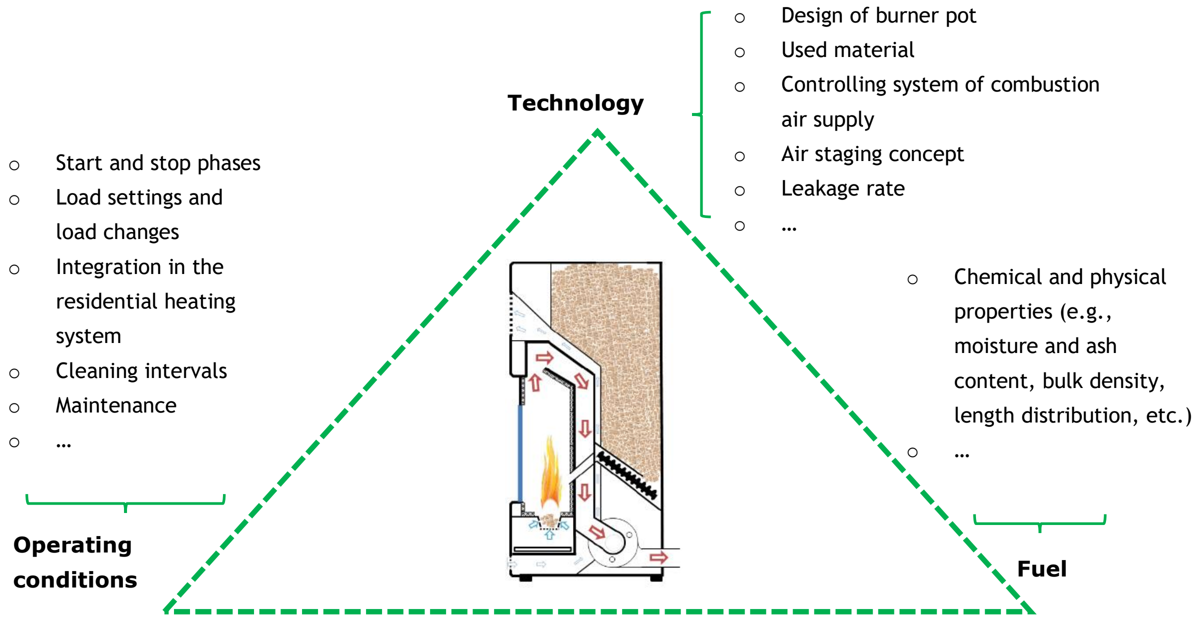


Figure 3: Main aspects that could influence the real-life performance of pellet stoves regarding emissions and thermal efficiency
Source: Own illustration, Figure from WÖHLER M. (2017) [5]

In order to receive more general data about the real-life use of pellet stoves a user survey as well as long term field measurements were conducted within the European R&D project “*beReal - Advanced testing methods for better real-life performance of biomass heating appliances*” [29].

In the following the most relevant aspects are summarized.

3.1 RESULTS OF A EUROPEAN USER SURVEY

A comprehensive user survey was conducted evaluating the user behaviour as well as identifying typical real-life operating characteristics [17] [30] [31]. The main focus was on the user behaviour of manually fired room heating appliances, but also several questions regarding user behaviour and operating characteristics of pellet stoves were asked. In total, results of more than 2,000 respondents were collected from which 183 respondents of mainly four different countries (Italy-72%, Germany-19%, Austria-3%, Sweden-3%, others-3%) refer to users of pellet stoves.

The most relevant findings were:

- Most pellet stoves are used as secondary heating system
- Heating operation of pellet stoves is either controlled by a room thermostat (36%), directly by the user on the stove control panel (35%) or by a clock timer (25%)
- Heat output is typically adjusted by the user during heating operation
- Maximum load is only marginally used (~10%). Predominantly the stoves are operated at a reduced power level or in a mixed operation of different power levels (90%) (**Figure 4**, right)
- Regarding fuel supply 61% of the respondents declared to buy their pellets from a specialized fuel dealer, 37% from a do-it-yourself store or a normal retailer and 15% are using other supply options. Only 2% of respondents declared to buy their pellets via an internet shop
- Around 80% of respondents use EN_{plus} certified pellets (**Figure 4**, left)
- Regular cleaning as a maintenance of the appliance, e.g., cleaning of heat exchanger, is predominantly conducted. Around 60% of the respondents declared to do this by themselves and around 20% by using the service of a technician.

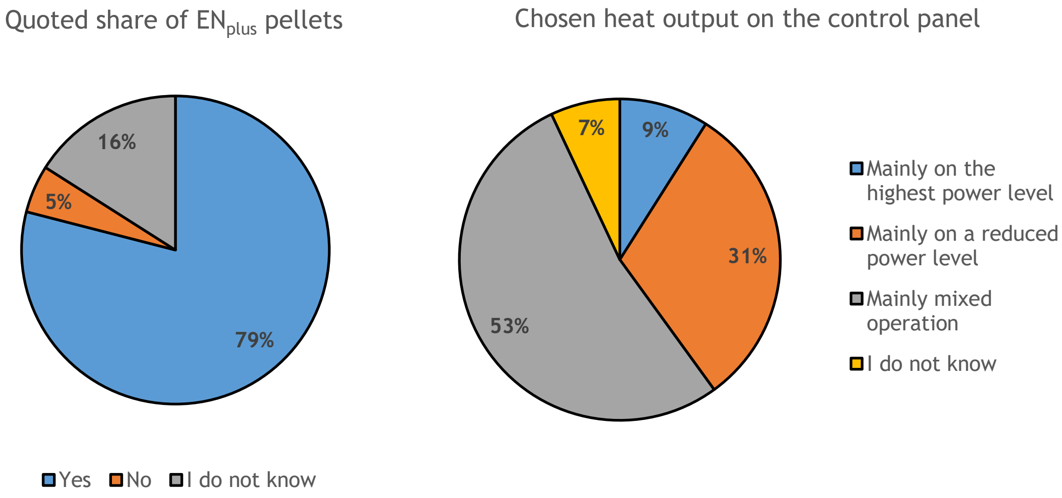


***Figure 4**: Results of the user survey regarding the use of EN_{plus} certified pellets (left) and typical adjustments of load settings for heat output on the control panel (right)*
<u>Source:</u> Own illustration based on data of WÖHLER et al. 2017, WSEDnext [31]

3.2 RESULTS OF LONG-TERM FIELD MONITORING

In addition to the user survey also long-term field monitoring was conducted at 9 different serial-production pellet stoves (5 stoves without and 4 stoves with water jacket) in order to assess real-life operational patterns and (if possible) to validate the findings of the survey with real measurement data [17]. The long-term field monitoring was conducted in parallel to the user survey. For long-term field monitoring the temperature of the flue outlet pipe was measured continuously using a surface thermocouple for around three months. According to the temperature curves important parameters were evaluated, e.g., time of operation, number of cold and warm starts as well as stand-by phases between two starts, load settings and load changes.

The findings of this long-term measurements showed that heating at nominal load settings account only for about 10% of the total operation time while partial load is the preferred heat output during operation of pellet stoves (51% of total operation time at low partial load in the range of 30% to 65% load and 39% of total operation time at high partial load in the range of 65% to 90% load). Furthermore, significant amounts of starting periods per day (cold and warm starts with stand-by phases in between) were observed for several stoves.

Consequently, the survey as well as the long-term field measurements confirmed that testing procedures which focus on real-life evaluation of the emission and thermal efficiency performance should include different load settings, load changes as well as cold and warm starts.

More details about the user survey as well as long-term field measurements are available in [17] [30] [31].

Consequences of user survey and long-term field monitoring on requirements regarding test methods focussing on real-life evaluation

- Variable load settings with a high share of partial load as well as frequent starts and stops are characterizing the typical use of pellet stoves in real-life operation.

➢ Real-life test methods should respect the findings of the survey and long-term field monitoring and consequently should include different load settings, load changes as well as cold and warm starts within their testing procedure.

➢ In comparison of the reviewed test standards the new US test method, ASTM E2779 – 10 (2017), meets the previously listed requirements best. However, no cold start is included within its test procedure.

4 Effects of Selected Parameters on Emission and Thermal Efficiency Performance

Based on the previous chapter some important findings of selected parameters that influence emissions and thermal efficiency performance of pellet stoves are summarized and discussed in the following chapter. Some experiments were conducted in the frame of the "*beReal*" project, some were additionally conducted.

4.1 FUEL

The results of the survey indicate that EN_{plus} pellets are typically used within pellet stoves (**Figure 4**, left). A screening of the pellet quality of 42 samples (27 labelled according to EN_{plus}, 22 according to DIN_{plus}, 8 without label) showed quite positive results regarding chemical and physical quality properties of pellets [32] [33]. For example, the ash content of only one pellet sample exceeded 0.5% (w/w) significantly. Also, the moisture content of 10% (w/w) was exceeded only by one sample. Regarding the share of fines only two samples did not meet the EN_{plus} A1 quality requirements (<1%; w/w). More details are available in [34].

However, tests showed that there could be large emission variations when a pellet stove is operated with different pellets, even when only EN_{plus} certified pellets are used.

This was observed by experimental combustion tests in one pellet stove when 12 different EN_{plus} certified pellet samples were consecutively fueled [32] [33]. However, as shown in **Figure 5** the emissions did not correlate with the potassium content, the ash content or the bulk density. Therefore, it seems that there are still unknown parameters or factors which influence the combustion quality of pellets within pellet stoves at nominal load.

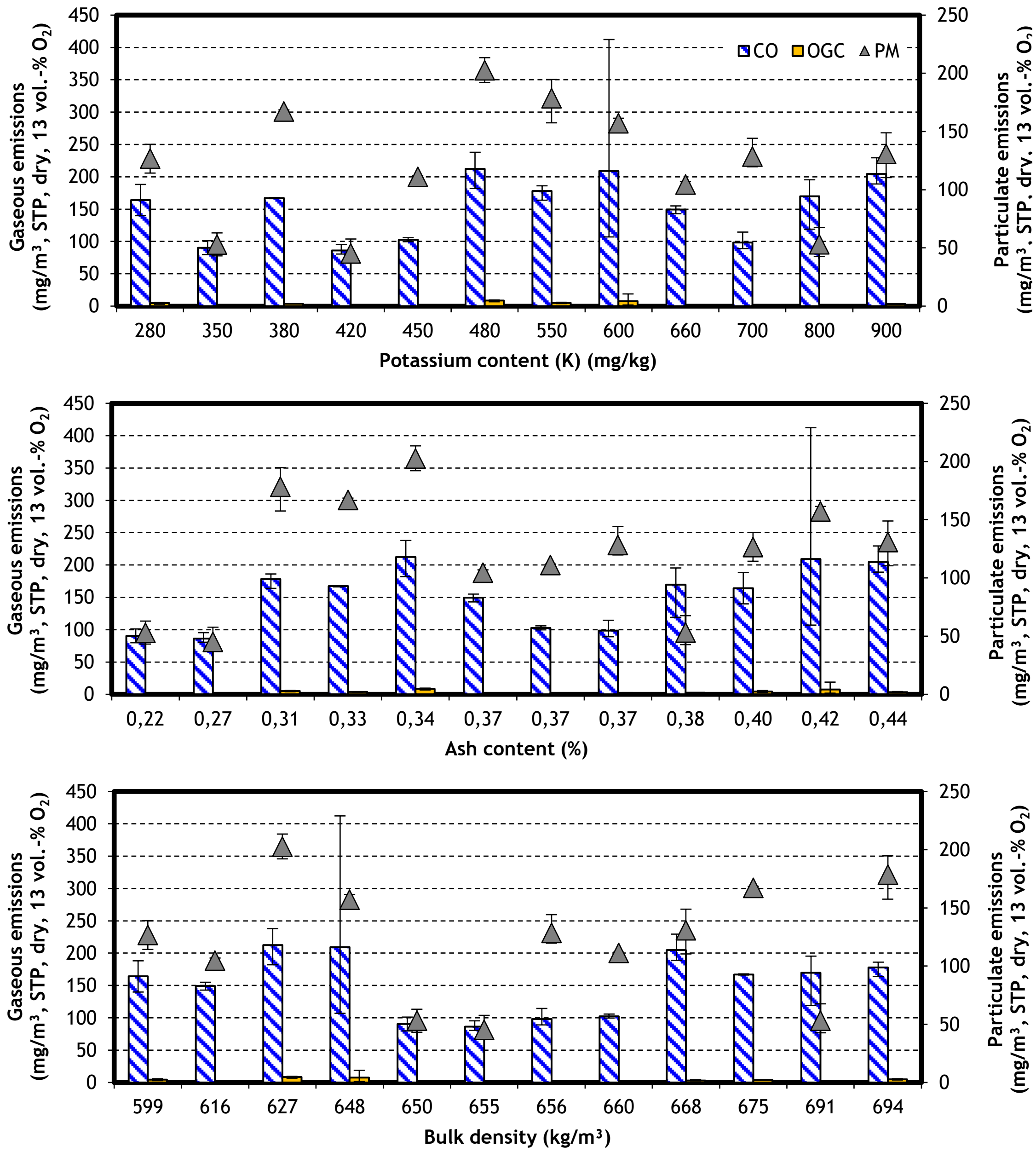


Figure 5: Emission concentrations of 12 different EN_{plus} certified pellet samples in relation to potassium content (top), ash content (middle) and bulk density (bottom) used in the same pellet stove in consecutive tests
Source: REICHERT et al. 2017 [32]

4.1.1 Pellet Length

Based on the previously presented findings further experimental combustion tests were conducted to evaluate if the combustion quality, i.e., the concentrations of CO and PM, correlate with the length distribution of pellets having a diameter of 6 mm. Therefore, pellets from one charge of sawdust and shavings (spruce, *Picea abies*) with three different length distributions (short, middle, long) were combusted using two different types of serial-production pellet stoves (EN 14785 without water jacket) [35].

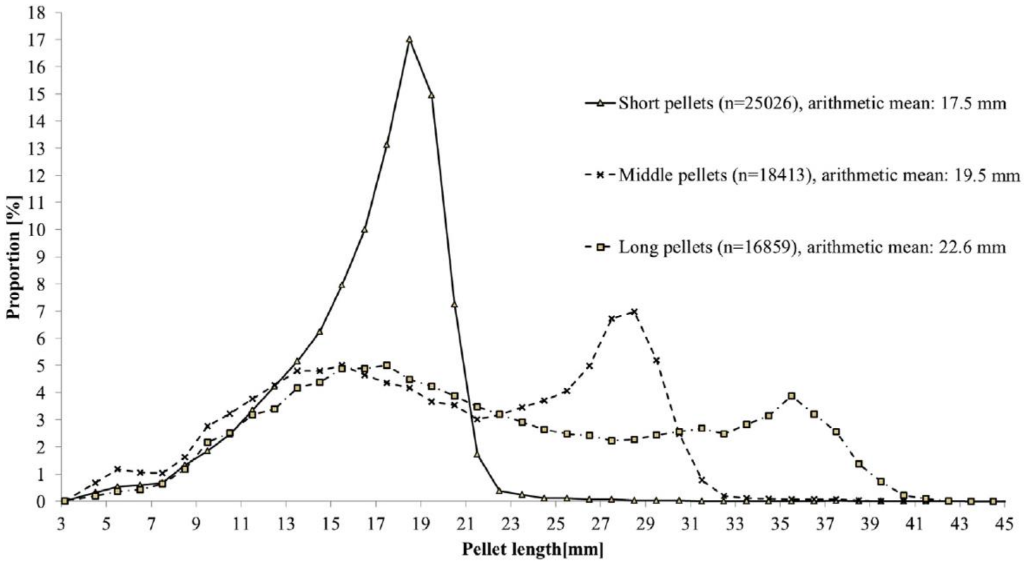


Figure 6: Results of pellet length measurement
Source: WÖHLER et al. 2017 [35]

The measurements revealed a reduced fuel mass flow (up to 36%) into the combustion chamber for long pellets (Ø length: 22.6 mm) compared to short pellets (Ø length: 17.5 mm). For one stove the CO and PM emissions increased for long pellets compared to short pellets from 185 mg/m^3 to 882 mg/m^3 (STP: 0°C, 1013.25 hPa, dry, 13 vol.-% O_2), and from 27 mg/m^3 to 37 mg/m^3 at nominal load operation, respectively.

Finally, the findings indicate that the length distribution of pellets might have a significant effect on the emission concentrations of pellet stoves. However, there are further tests necessary to clarify those results and to identify or evaluate potential correlations of fuel and/or appliance specifics.

More details about those experiments as well as results are available in [35].

4.2 LOAD SETTINGS

As mentioned above the results of the survey and long-term field measurements indicate that pellet stoves are typically operated with different load settings [17] [31]. According to evaluations of the long-term field measurements partial load operation covers about 90% of the total operating time. Around half of operating time the stoves were operated at load settings between 30% to 65% (see also chapter 3).

As illustrated in **Figure 7** exemplary measurements at an 8 kW pellet stove indicate that partial load emissions, especially in high partial load (65% load), are not generally higher compared to nominal load (100% load) [17]. Gaseous emissions were highest at low partial load (30% load) whereas the PM emissions were interestingly even highest for nominal load.

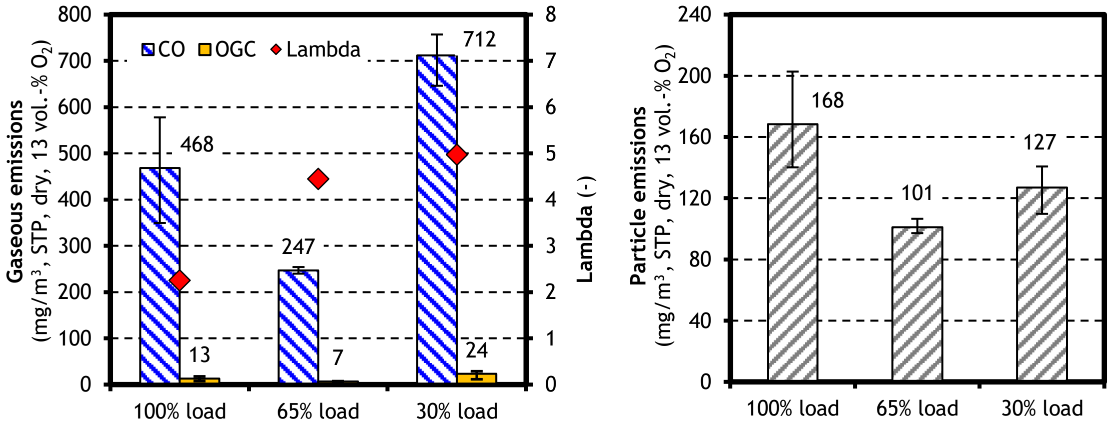


Figure 7: Influence of load settings on gaseous and PM emissions (n=3, error bars represent the minimum and maximum measurements)
Source: OEHLER et al 2016 [17]

In addition, other studies confirmed that different load levels during operation of pellet stoves result in different emission levels [36] [37]. Furthermore, the studies showed that during start-up phases gaseous as well as particulate emissions are significantly increased compared to steady-state operation.

4.3 DRAFT CONDITIONS

Draft conditions have a major effect on emissions and thermal efficiency of manually operated firewood stoves. This was shown by experimental combustion tests when varying the draft conditions in the range of 12 Pa to 48 Pa [38]. Regarding emissions the effect of higher draft conditions was found as highly appliance specific whereas for all tested appliances the thermal efficiency at higher draft levels decreased significantly.

The same approach as applied for firewood stoves was also applied for pellet stoves [39]. Combustion tests at nominal load for three selected pellet stoves were carried out in order to evaluate potential effects of the draft level on emissions and/or thermal efficiency. For each combustion test the draft level was constantly controlled on a fixed value – 12 Pa, 24 Pa or 48 Pa (**Figure 8**).

The results showed quite similar results regarding emissions and efficiency when comparing the results referring to 12 Pa as well as 24 Pa (except PM emissions of stove 3). However, comparing the results of 12 Pa with the results of a draft level of 48 Pa there might be an impact, but depending also on appliance specifics, e.g. gaseous emissions of stove 2, thermal efficiency of stove 1.

However, the results for pellet stoves [39] indicated that there is not such a clear draft interdependency, e.g. for thermal efficiency, as observed for firewood stoves [38].

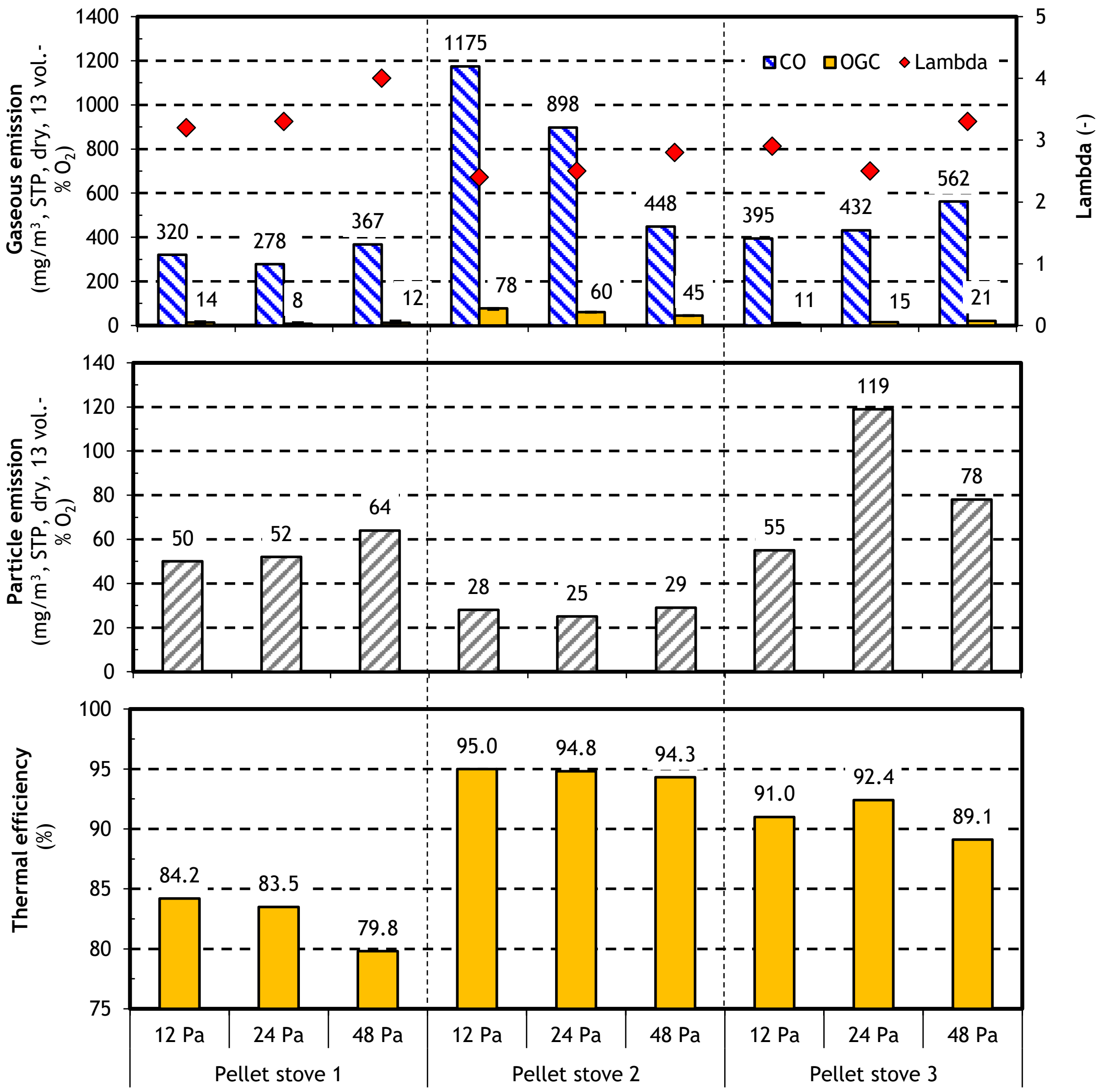


Figure 8: Results of experimental evaluation regarding the impact of draft conditions on emission and efficiency performance of pellet stoves
Source: Own illustration based on data of RÖNNBÄCK et al. 2016 [39]

4.4 CLEANING INTERVAL

Typically, burner pots of pellet stoves are regularly cleaned during operation (e.g. once per hour) in order to avoid an excessive increase of the fire bed height. Therefore, fuel supply is stopped and the ventilator speeds up in order to increase the volume flow of air to entrain ash particles out of the burner pot. In total the cleaning interval lasts about two minutes (e.g. as mentioned in [35]).

The effect of the cleaning interval on emissions as well as on thermal efficiency was evaluated by combustion experiments using a pellet stove with a nominal heat output of 8 kW [32]. Thereby, three different pellet samples were used and 30 minutes intervals (after ignition and preheating of the appliance under stationary conditions) were analysed with and without the cleaning interval included (**Figure 9**).

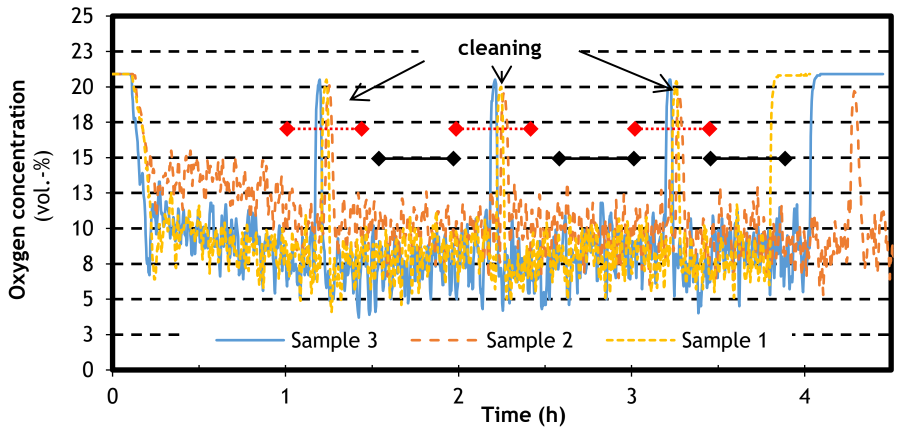


Figure 9: Approach for experimental evaluation regarding the impact of the cleaning interval on emission and efficiency performance of pellet stoves (red: average oxygen content during 30 minutes interval with cleaning and black: average oxygen content during 30 minutes interval without cleaning)
Source: REICHERT et al. 2017 [32]

As illustrated in **Figure 10** the gaseous as well as particulate emissions are clearly higher when the cleaning interval is considered. Compared to the periods including the cleaning interval CO emissions of the interval without the cleaning are only in a range of 50% to 69% and VOC emissions in the range of 59% to 65%. For PM emissions the differences between periods with and without cleaning process were lower in a range of 5% to 13%. Thermal efficiency was slightly decreased when considering the cleaning process.

Consequently, the experiments showed that the automatic cleaning of the grate increases gaseous and particulate emissions and reduces thermal efficiency.

Additionally, those results further revealed the impact of different fuels on emission levels since they resulted in different emission levels when fueled to the same stove under equal operating conditions (see also chapter 4.1).

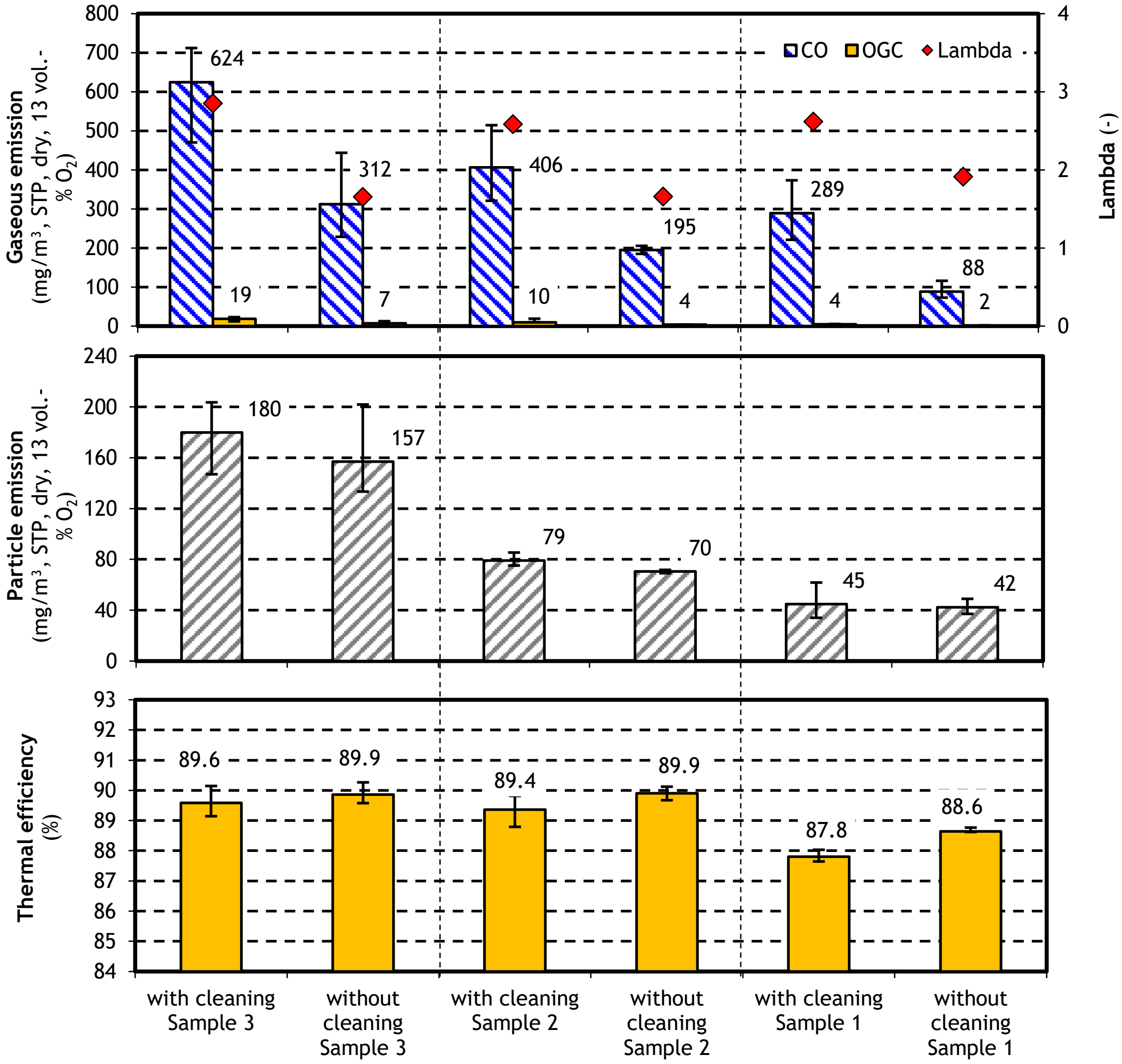


Figure 10: Results of experimental evaluation regarding the impact of the cleaning interval on emission and efficiency performance of pellet stoves
Source: REICHERT et al 2017 [32]

Effects of selected parameters on emission and thermal efficiency performance

Experimental combustion tests showed that following parameters could affect the emission and thermal efficiency performance of pellet stoves during real-life operation:

- Type of pellets – even if high quality pellets (e.g. EN_{plus} or DIN_{plus}) are used the emissions and thermal efficiency for pellet stoves can be influenced by the pellet properties. The length distribution might be an important parameter regarding emissions, too
- Different load settings as well as transient phases, e.g. start-up phases, influence the emission as well as thermal efficiency. Nominal load did not show generally the best performance
- Regular cleaning intervals increase emissions and result in lower thermal efficiencies
- Draft conditions might influence emission and thermal efficiency performance depending on appliance specifics. However, the observed effect was not as high as for manually operated firewood stoves.

Consequences of experimental evaluations on requirements regarding testing methods focussing on real-life evaluation

- ➢ Test fuel should be provided by the testing body and not by manufacturers in order to avoid "fuel optimization".

- ➢ Regular cleaning intervals should be included in the testing procedure and respected for data evaluation.

- ➢ The relevance to implement different load levels in the testing procedure and data evaluation is obvious. Additionally, start-up and stop phases as well as load changes should be respected for real-life evaluation.

5 "beReal" – A Novel Test Concept for Pellet Stoves reflecting Real-Life operation

In the European R&D project "*beReal*" [29] a test concept for pellet stoves without water jacket which focuses on the real-life evaluation of emissions and thermal efficiency was developed. The most relevant aspects which were the basis for definition of the testing procedure were presented in the previous chapters (chapter 3 and 0).

Below, the most relevant characteristics of the final "*beReal*" test concept for pellet stoves is summarized and presented. Specific details regarding framework conditions, measuring methods as well as data evaluation are published [17] [18] and are also available online [40].

5.1.1 Preconditioning

The "*beReal*" test method applies only to pellet stoves without water jacket. The tested stoves have to be end user market products meaning that they have to be functionally and technical identical with serial products. Before testing the stoves have to be operated for at least 6 hours.

5.1.2 Fuel requirements

As test fuel only end customer marked pellets which are certified according EN_{plus} are permitted. The test fuel has to be supplied by the testing body.

5.1.3 Testing procedure

Figure 11 presents the "*beReal*" testing procedure for pellet stoves. Accordingly, pellet stoves are tested at three load settings – nominal load (100%), low partial load (30%) and high partial load or also called medium load (65%).

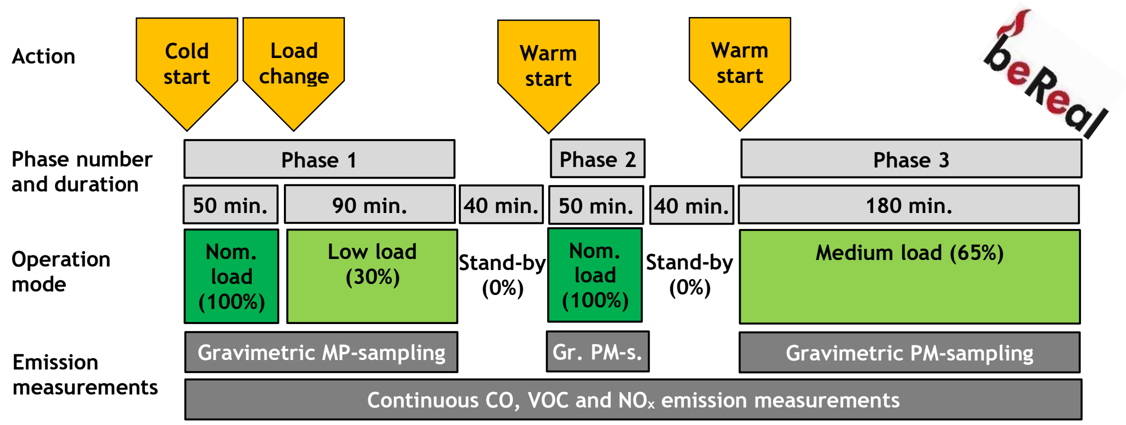


Figure 11: Scheme of "beReal" test concept for pellet stoves (without water jacket)
Source: KLAUSER et al. 2018 [41], adapted

Load settings as well as proportions of the test durations were derived from the long-term field measurements (chapter 3.2). In the case of automatic controlled stoves, e.g., by room thermostats, those levels have to be tested too, for example by switching-off the automatic control modes. One cold- and two warm-starts as well as one load change (phase 1: 100% → 30%) are included within the testing cycle. Respecting also the two stand-by phases the testing cycle lasts around 7.5 hours. Potential cleaning intervals are included in the testing cycle and are not turned off. The draft conditions for the whole "*beReal*" test are permanently controlled at constant settings of 12±2 Pa.

5.1.4 Measurement methods

As illustrated in **Figure 11** gaseous (CO, VOC, NO_x) and particulate matter (PM) are evaluated for "*beReal*" testing. The thermal efficiency is measured indirectly by considering thermal and chemical flue gas losses as well as the losses due to combustibles in the residues. Therefore, CO emissions as well as flue gas temperature measurements are considered.

CO, VOC and NO_x emissions are measured continuously with a measuring interval of ≤ 10s whereas PM emissions are measured discontinuously by gravimetric measurements in all three phases. The gravimetric measurements are conducted in hot and undiluted flue gas by isokinetic PM sampling over the whole three test phases. The filter material can be changed during stand-by phases.

The flue gas velocity is measured continuously over the whole testing cycle using a measuring instrument with an uncertainty of <10%, e.g., by using a vane wheel anemometer in combination with a specific calibration procedure as presented in [42].

For all tested appliances leakage checks before and after "*beReal*" testing at 5 Pa, 10 Pa and 15 Pa (overpressure) are required. Accordingly, the leakage rates are evaluated while the respective static differential pressures are maintained at constant settings.

5.1.5 Data Evaluation and Test Results

As test results, emission concentrations (STP, dry, referred to 13 vol.-% O_2) for gaseous (CO, VOC, NO_x) and particulate emissions (PM) as well as thermal efficiency are calculated which represent the whole "*beReal*" test cycle. The different load settings and consequently also different flue gas mass flows of the respective phases are respected by a so called "volume-weighted" data evaluation based on flue gas velocity measurements. In order to avoid big uncertainties, the total emitted flue gas volumes (at STP conditions, wet) of all different phases are cross-checked by combustion calculations considering the mass and the composition of combusted fuel as well as the flue gas analysis measurements (O_2/CO_2).

The specifics about the calculation modes for volume-weighted emission evaluation as well as efficiency determination are described in detail in [40].

5.1.6 Repeatability and Reproducibility

Several measurements evaluating the repeatability as well as reproducibility of the "*beReal*" test method by analysing the coefficients of variation were conducted [17] [18] [41] [43]. The average coefficients of variations of emissions and thermal efficiency were below 15% for repeatability tests (comparison of measurements of one testing institute for one appliance and fuel) as well as around 30% for reproducibility (comparison of measurements of several testing institutes using the same appliance and fuel). The worst repeatability as well as reproducibility was observed for the VOC measurement results (based on FIDs), the best for the indirect thermal efficiency determination.

According to the knowledge of the authors the "*beReal-Pellet*" test method is currently the only test method where the test procedure aims to evaluate the real-life performance of pellet stoves based on scientifically evaluated long-term field measurements and a user survey. Furthermore, the "*beReal*" test concept is currently the only test method (beside official test standards) which was evaluated regarding repeatability and reproducibility. So far, most of scientific papers evaluated pellet stoves separately based on either nominal or partial load or transient phase (e.g. start-up phase) measurements [43] [44] [45] [46] [47].

6 Real-Life Relevance of EN 14785 and "*beReal*" Test Results

This chapter aims at an evaluation of the real-life relevance of the official type test (ott) method according to the existing standard EN 14785 compared to the new "*beReal*" test approach. Thereby, data of selected lab and field tests are presented and compared with ott results of the used pellet stoves.

In order to have comparable data, emission factors (EF in mg/MJ) are presented. For test results available as emission concentrations the emission factors (EFs) were calculated based on a typical elemental composition of wood pellets [48] (**Equation 1**).

Equation 1: Calculation of emission factors (EF)

$$EF = \frac{E_{mg/m^3\,(STP,\,dry,\,13\,vol.-\%\,O2)} \times V_{min,\,STP,\,dry} \times 2.625}{H_{i,\,f}} \quad (1)$$

$$V_{min,\,STP,\,dry} = 1.87\,c + 0.7\,s + 0.79 \times L_{min} \quad (1a)$$

$$L_{min} = \frac{1.87\,c + 5.6\,h + 0.7\,s - 0.7\,o}{0.21} \quad (1b)$$

EF	...Emission factor based on the net calorific value of fuel; in mg/MJ (as fired basis, f)
$E_{mg/m^3\,(STP,\,dry,\,13\,vol.-\%\,O2)}$	...Emission concentration (mg/m³) in dry flue gas based on standard temperature and pressure conditions (STP: 273.15 K, 101325 Pa) and referred to 13 vol.-% O_2
$V_{min,\,STP,\,dry}$	...Dry flue gas volume of stoichiometric combustion at STP conditions; in m^3/kg_{fuel}
L_{min}	...Stoichiometric minimum combustion air demand at STP conditions; in m^3/kg_{fuel}
c, h, s, o	...Elemental content of carbon, hydrogen, sulphur and oxygen (c=0.461, h=0.056, s=0.000045, o=0.399) of test fuel (as fired basis); in in kg/kg_{fuel}
$H_{i,\,f}$	...Net calorific value (17,13 MJ/kg) of the test fuel (as fired basis, f); in MJ/kg

The approach (**Equation 1**) was also applied to transfer the ELVs of the new ecodesign requirements [23] to mg/MJ.

- CO: 300 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 210 mg/MJ
- VOC: 60 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 42 mg/MJ
- NO_x: 200 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 140 mg/MJ
- PM: 20 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 14 mg/MJ

NO_x emissions of biomass combustion are predominantly fuel dependent [50] and frequently not limited for pellet stoves in most European countries (except Austria – 15a B-VG). Therefore, NO_x emissions were not included in this study.

In some studies, EFs for non-methane volatile organic compounds (NMVOC) are given. The corresponding EF on VOC were determined according to **Equation 2** based on the share of methane of total VOC emissions as suggested by NUSSBAUMER et al. [49].

Equation 2: Calculation of VOC EFs based on EFs proposed for NMVOC

$$\mathrm{EF_{VOC}} = \frac{\mathrm{EF_{NMVOC}}}{0.6} \quad (2)$$

EF_{VOC} …EF for VOC emissions based on EF proposed for NMVOC emissions; in mg/MJ

6.1 EN 14785: OVERVIEW OF OFFICIAL TYPE TEST RESULTS

In the study of SCHIEDER et al. 2013 [4] comprehensive results of official type tests (ott) of manually fired room heating appliances but also for pellet stoves are summarized.

The test results based on a dataset which covers 76 manufacturers from 13 European countries. Data for CO emissions derived from 941, for VOC from 219, for PM emissions from 996 and for the thermal efficiency from 1577 appliances. Therefore, the data can be seen as typical for the European stove market.

In **Figure 12** the technology specific average values of ott results are presented. The difference between conventional (a) as well as modern (b) technologies refers mainly to thermal efficiency differences since the difference between emissions are quite low.

Comparing the ott results of pellet stoves with manual operated firewood stoves it can be observed that pellet stoves perform clearly better in terms of emissions as well as thermal efficiency. The ott CO emissions for pellet stoves are around 100 mg/MJ to 130 mg/MJ, the VOC around 6 mg/MJ and the PM around 15 mg/MJ to 20 mg/MJ. Comparing those figures with the future ecodesign requirements it becomes obvious that it might be challenging to meet the PM emission requirements of 20 mg/m^3 (STP. dry, 13 vol.-% O_2) which corresponds to 14 mg/MJ. In contrast, meeting the future ecodesign ELVs for CO (210 mg/MJ) and VOC (42 mg/MJ) will be a minor challenge since the average ott results are already clearly below these values.

Instead of the thermal efficiency the new ecodesign requirements defined the so called “seasonal space heating energy efficiency” (SSHEE) which aims at representing a more “real-life” thermal efficiency. The minimum requirement of the SSHEE for closed fronted local space heaters fuelled with pellets is 79.0%.

The SSHEE is calculated based on specific features of the appliance and the thermal efficiency results evaluated by the official type test [23]. In a first approach the SSHEE is calculated using the thermal efficiency of the ott at nominal load minus 10%. Then, different factors are calculated which contribute either positively (e.g., plus some percentage points for the option of manual adjustment options for different load settings or an electronic room temperature control) or negatively (e.g., auxiliary electric demand and energy consumption for a pilot flame). For modern pellet room heating appliances the SSHEE should be quite easily achievable.

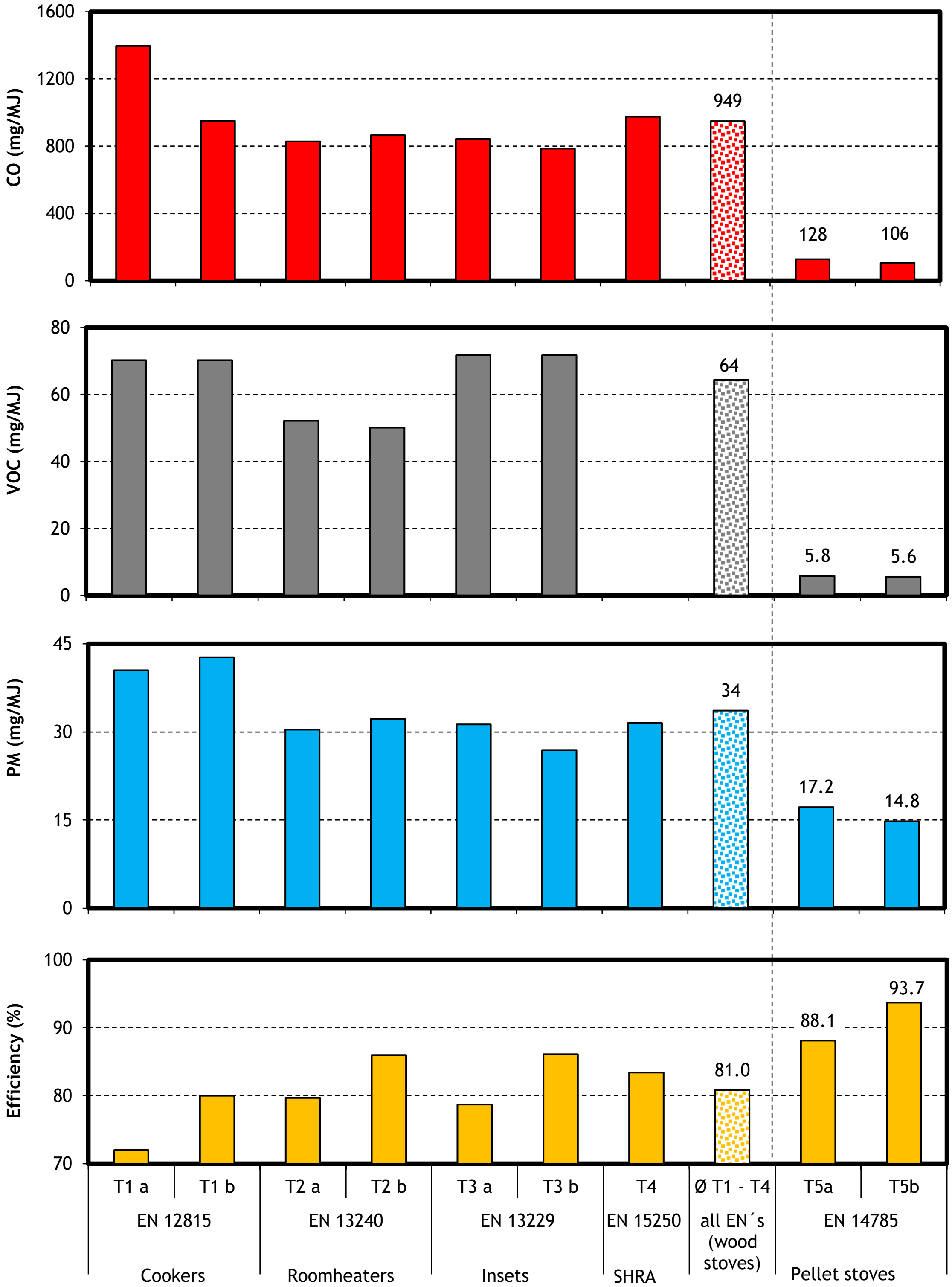


Figure 12: Overview of official type test (ott) results for different types of firewood as well as pellet stoves (conventional technologies…a / modern technologies…b).
Source: SCHIEDER et al. 2013 [4]

6.2 EN 14785 & "*beReal*": LAB VERSUS FIELD – EVALUATION OF REAL-LIFE PERFORMANCE

For evaluation of the real-life relevance of lab test results, they have to be compared with real-life performance tests in the field. In the best case such measurements even refer to the same appliances as well as to the same fuel. This was carried out within the "*beReal*" project [29].

In the following section an evaluation of measurement data provided in RÖNNBÄCK et al. 2016 is presented. The evaluation based on the figures that are given in the appendix of the respective report [39]. In this study comprehensive tests in the lab and in the field were carried out with the same appliances as well as with the same or different pellet charges. Thus, a direct comparison from field to lab performances is possible. Moreover, the fuel impact in the field was observable. The used pellet stoves were 4 serial-production appliances, all of them classified according to the EN 14785 standard. The following tests were conducted:

- Retesting of EN 14785 official type test at nominal load in the lab
    - RTD Type Test, Nominal load (EN 14785)
- "*beReal*" test in the lab
    - "beReal" – Lab (RTD Fuel)
- "*beReal*" test in the field
    - "beReal" – Field (RTD Fuel)
- Test day when the stove was operated according to the user's own habit
    - User (own fuel)
- Test day when the stove was operated according to the user's own habit, but using the RTD fuel
    - User (RTD fuel).

The retests of the EN 14785 type tests and the "*beReal*" tests in the lab were carried out before the pellet stoves were installed in the field. The tests, which were performed by several RTD (Research Technology & Development) partners of the "*beReal*" project consortium, were compared with the ott results – "Official Type Test (EN 14785)" – of the respective stove models (but not the same appliances), the average ott results according to SCHIEDER et al. 2013 (conventional and advanced technologies) [4] and the future ecodesign emission limit values [23].

In **Figure 13** the average results of the different tests are presented.

As illustrated in **Figure 13** the ott results of the used 4 pellet stoves were quite similar for PM emissions as well as for thermal efficiency compared to the average ott results of SCHIEDER et al. 2013 [4]. For CO and VOC emissions the appliances performed better during their ott.

Comparing the ott results with the repeated type tests of the RTD performers (at nominal load) it is obvious that for CO and PM emissions the results were clearly higher and for thermal efficiency clearly lower (ott: CO=74 mg/MJ, VOC=2 mg/MJ, PM=14 mg/MJ, η=91.1% versus RTD type test CO=105 mg/MJ, VOC=2 mg/MJ, PM=28 mg/MJ, η=86.1%). Only for VOC emissions the results of the repeated type tests were on an equal level. Consequently, it was not possible to reproduce the ott results, especially regarding PM emissions as well as thermal efficiency. Moreover, the results confirmed what was already mentioned in the previous section (chapter 6.1) that meeting the future PM ecodesign ELV might be challenging.

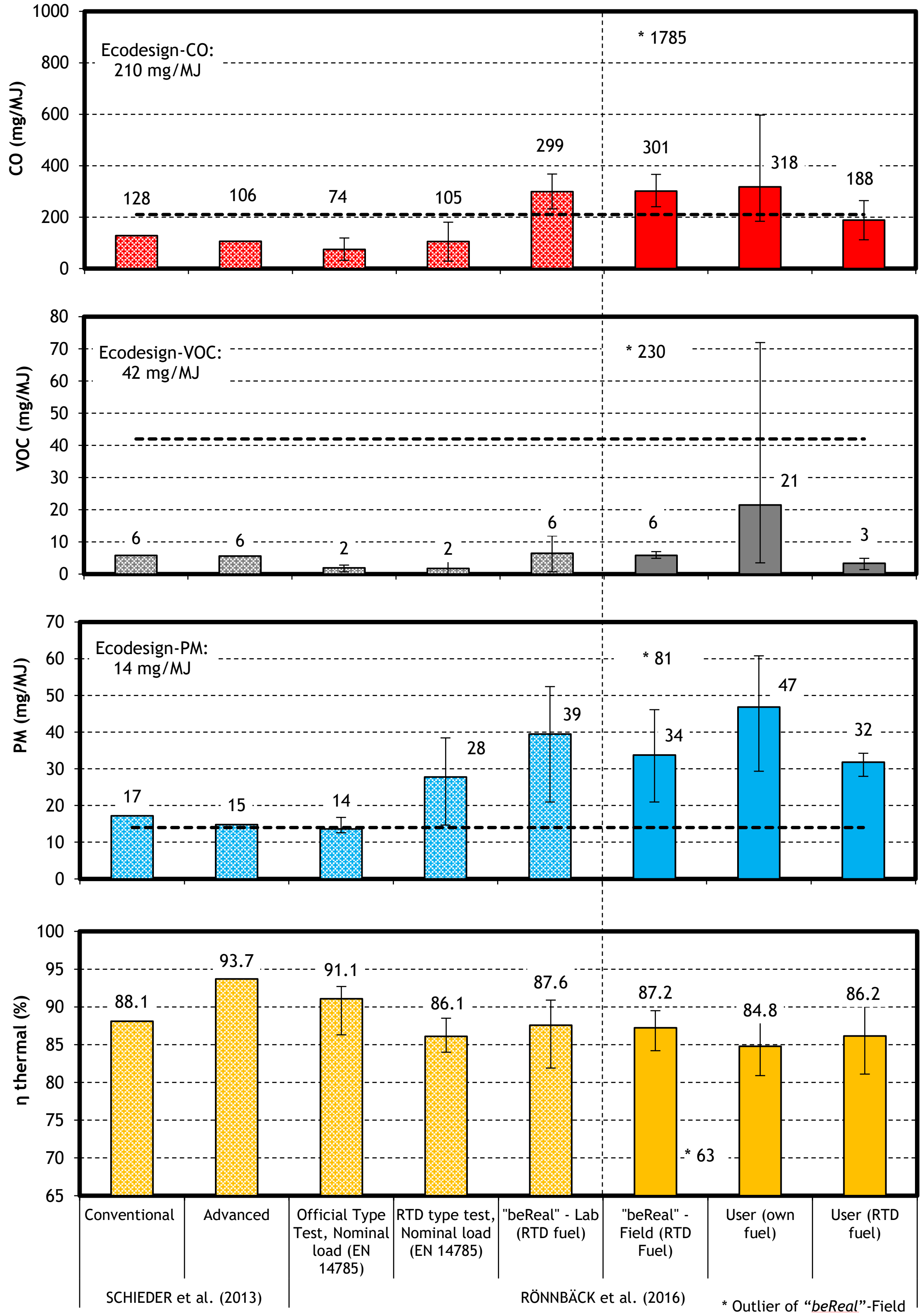


Figure 13: Comparison of official type test (ott) results with lab and field test results. Error bars represent the minimum and maximum values determined. The dashed black lines represent the ELVs of future ecodesign requirements for pellet stoves [23].

Source: Own illustration based on data of SCHIEDER et al. 2013 [4] and RÖNNBÄCK et al. 2016 [39]

In comparison with the "*beReal*" test results in the lab the ott results of used stove models are significantly different. Average CO emissions of "*beReal*" were higher by a factor of about 4, VOC emissions by a factor of about 3 and PM emissions by a factor of about 2.8. The average thermal efficiency was 3.5% (absolute) lower for "*beReal*" test results compared to ott results. Concluding, the "*beReal*" test results which reflect real-life operating conditions result in significantly higher emissions as well as lower thermal efficiency compared to the nominal load ott results.

Analysing the field performance of the respective appliances, it is obvious that also in the field emissions were typically significantly higher (CO: up to a factor of 3, VOC: up to a factor of 10, PM: up to a factor of 3.3) and thermal efficiency lower (about 5% lower at around 85%) compared to nominal load ott results. Comparing "*beReal*" test results from field with lab there is a good agreement for gaseous and particulate emissions as well as thermal efficiency. Compared with "*beReal*" test results (lab and field) as well as with field measurements the future ecodesign requirements are clearly exceeded for CO as well as PM emissions but at the same time clearly below the limits for VOC emissions. Consequently, it seems that in view of a critical evaluation VOC emission limits are not stringent enough and do not consistently fit to CO and PM emission limit values.

The average thermal efficiency of field measurements was about 85% which is clearly higher as the minimum required SSHEE of the ecodesign requirements of 79%. However, it must be considered that the thermal efficiency does not respect the auxiliary energy demand of the stove, e.g., electrical energy for starting, operation or stand-by phases.

The already identified fuel impact, even when using certified wood pellets (according to EN_{plus}), was also observed during the field test campaign. Comparing both user days, operating conditions were quite similar, but the fuel was different. As it is illustrated in **Figure 13** emission levels of the user days when the users operated their stoves with their own pellets were clearly higher compared to the user days with pellets of the RTD performers. This shows once again (see chapter 4.1) that there might be relevant fuel parameters (maybe even in correlation with the stove technology) which are not yet identified but relevant for the real-life performance of pellet stoves regarding.

6.3 "*beReal*" LAB AND FIELD TEST RESULTS COMPARED TO PROPOSED EMISSION FACTORS

As shown in the previous section "*beReal*" test results in the lab correspond quite well with field test results of typical end-user heating operation, especially when the same fuel was used. Moreover, the test results of field and lab for equal appliances are compared with proposed national (Austria's Informative Inventory Report (IIR) 2018, [51]) and international (EMEP/EEA air pollutant emission inventory guidebook 2019, [52]) emission factors (EF) for CO, VOC and PM emissions (**Figure 14**).

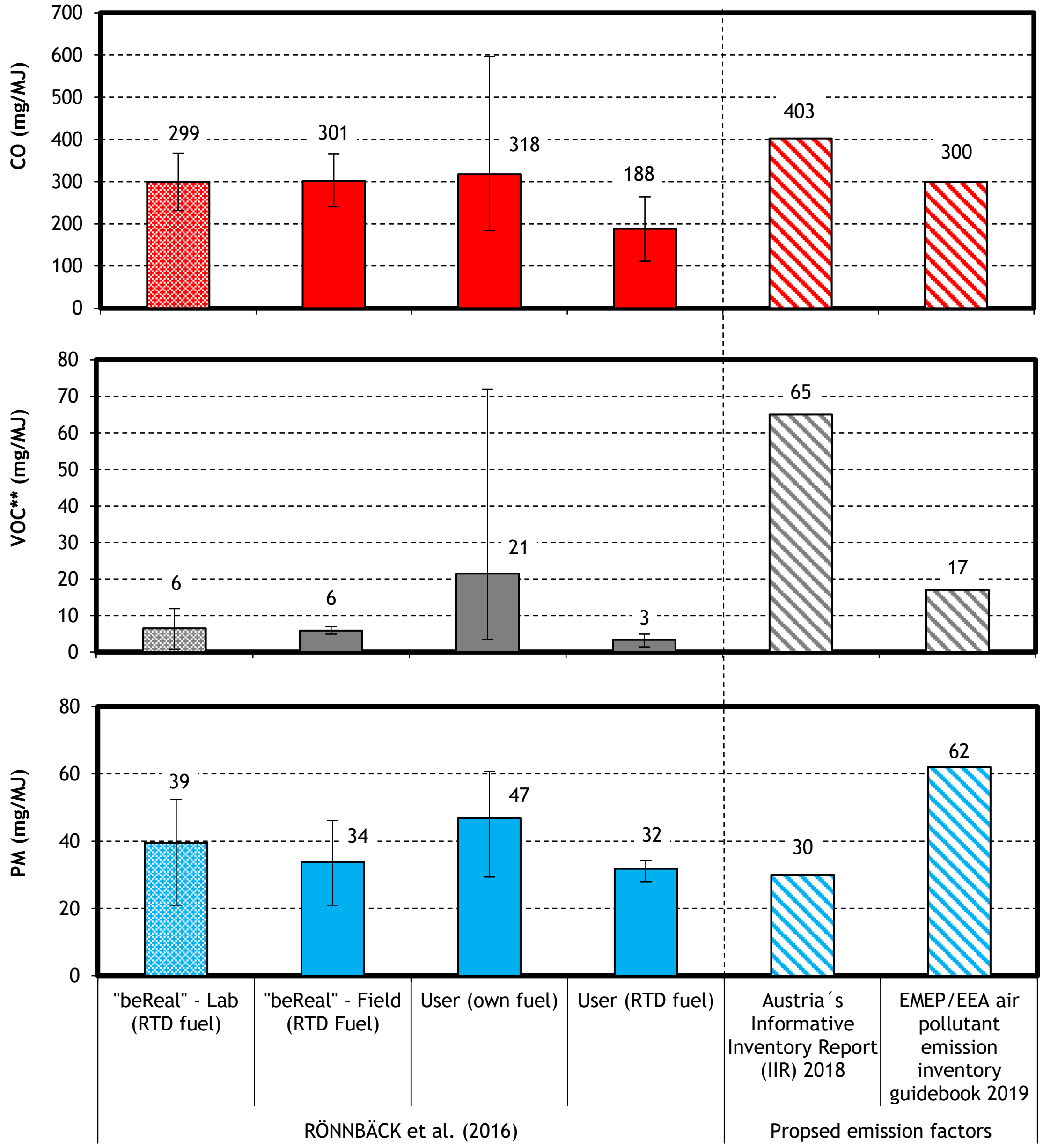


Figure 14: Comparison of lab and field test results of beReal project (same EN 14785 pellet stoves) with proposed emission factors (EFs). Error bars represent the minimum and maximum values determined. ** VOC emission factors based on proposed NMVOC-EF, assuming 40% methane of total VOC emissions (see Equation 2)

Source: Own illustration based on data of RÖNNBÄCK et al. 2016 [39] as well as [51] and [52]

Both proposed emission factors are quite different. Whereas the Austrian EF are higher for CO and VOC emissions they are lower for PM emissions compared to the EMEP/EEA (EMEP ... European Monitoring and Evaluation Programme/ EEA … European Environment Agency) EFs.

Comparing CO emission results of "*beReal*" lab and field tests with the proposed EFs it is evident that the EMEP/EEA EFs are close to the measured results in the field and also for "*beReal*" lab tests. However, for PM and for VOC emissions (except for user (own fuel)) the EFs of EMEP/EEA are higher compared to the average field test results. Interestingly, the

EMEP/EEA EF for VOC emissions (17 mg/MJ) is clearly lower compared to the future ecodesign requirements (42 mg/MJ). Regarding PM emissions it is important to mention that the PM EF for pellet stoves was increased from 31 mg/MJ (2016, [53]) to 62 mg/MJ (2019, [52]). However, the field test results indicate that 31 mg/MJ would be more representative for field performance of pellet stoves than the 62 mg/MJ.

From the proposed Austrian EFs only the PM EF (30 mg/MJ) fits quite well to the average field test results whereas the proposed EF for CO is slightly and the EF for VOC emissions is extremely high compared to the field test results and would not force the manufacturer for further pellet stove improvements.

The EFs proposed by NUSSBAUMER 2010 [49] for 2035 are 200 mg/MJ for CO, 25 mg/MJ for VOC and 30 mg/MJ for PM emissions. The observed field performances of the evaluated pellet stoves were already quite close to those proposed EFs, especially for CO and PM emissions.

For general conclusions about EFs it has to be considered that only four pellet stoves were tested (year of production between 2013 and 2015 [39]).But based on these measurements which enable a direct comparison of lab and field performance for the same appliances it seems that the "*beReal*" test method could be applied for an evaluation of emission factors on the test bench. Since it seems that there is generally a conformity between "*beReal*" test results in the lab compared to typical field performance of pellet stoves "*beReal*" measurements might be useful for a regular update of air pollution inventories as well as to update and evaluate the progress of technological development.

Real-life relevance of EN 14785 and "*beReal*" test results

Analysis of official type test results of pellet stoves as well as an experimental test series using four serial production appliances in the lab and in the field revealed:

- Official type tests (ott) for pellet stoves result in CO emissions of < 100mg/MJ, VOC emission of ≤ 6mg/MJ and PM emissions < 20 mg/MJ as well as in a thermal efficiency of about 90% (all at nominal load).
- It was not possible to reproduce the ott results by testing the four serial production appliances according to EN 14785 at nominal load, especially regarding PM emissions as well as thermal efficiency. In average the differences were 100% for PM and 5% (absolute) for thermal efficiency.
- "*beReal*" test results in the lab using four serial-production pellet stoves result in CO emissions of about 300 mg/MJ, VOC emissions of about 6 mg/MJ and PM emissions of about 35 mg/MJ as well as in a thermal efficiency of about 85%. Other experiments confirmed these results for "*beReal*" testing with different pellet stoves [41].
- The "*beReal*" test results were close to the emission results measured in the field when operated by typical end-users.
- A fuel impact was identified comparing the field test results where two pellet charges (but all high-quality pellets) were used for each appliance.
- According to "*beReal*" test results measured in the lab as well as in the field and according to typical end-user operation in the field emissions of CO and PM were clearly higher than the respective emission limit values of future ecodesign requirements.
- Ecodesign requirements for VOC emissions seem to be not as stringent as ELVs of the ecodesign requirements for CO and PM emissions.

Consequences/key findings of tests regarding evaluation of real-life relevance of "*beReal*" test concept compared to the official type test method (EN 14785) as well as compared to proposed emission factors (EFs) for pellet stoves:

➢ The "*beReal*" test concept for pellet stoves seems feasible to evaluate the appliance performance regarding emissions and thermal efficiency in the lab close to real-life which is not the case for ott results according to EN 14785.

➢ An application of the "*beReal*" test concept appears as a feasible approach to evaluate emission factors on the test bench which could be subsequently used for a regular update of air pollution inventories as well as to update and evaluate the progress of technological development.

7 Summary and Conclusions

As illustrated by the development of stock numbers and market volumes, pellet stoves become more and more popular as renewable and sustainable heating technology in Europe. Compared to manually operated firewood room heating appliances pellet stoves are featured with an automatic fuel supply into the combustion chamber and offer various options for an automatic as well as low-maintenance operation. In future, pellet stoves might also be implemented in smart home systems and can be combined with other residential (heating) systems. Furthermore, emissions and thermal efficiency are typically advantageous compared to manual operated firewood stoves.

This study provides an overview of most relevant test standards for performance evaluation of pellet stoves regarding emissions and thermal efficiency. In detail most relevant characteristics as well as differences of the testing methods regarding preconditioning of the appliance in advance of testing, fuel requirements, testing procedure, measurement methods, data evaluation and testing results were reviewed.

The number of tested load settings, repetitions of measurements, respected emissions and PM measurement procedures were identified as most relevant differences between the reviewed testing methods. All reviewed test standards evaluate the appliance performance under heated-up conditions. Load changes are only considered by the latest official test standard, the US Standard – ASTM E2779 – 10 (2017). Concluding the review of existing official test standards indicates that international standardization (ISO) in principle seems feasible. This would enable better international market opportunities for manufacturers and therefore support the industry to increase their market shares and market volumes, especially for high quality pellet stoves.

The "*beReal*" test concept as an example for an advanced testing method for real-life performance evaluation of pellet stoves was presented. The "*beReal*" method evaluates the appliance performance regarding emissions and thermal efficiency considering cold and warm starts as well as different load settings, load changes and further transient phases, like cleaning intervals or cool down phases. Furthermore, the scientific background behind the "*beReal*" test method, e.g. user survey, long-term field measurements and experimental development and demonstration tests, but also its limitations, for example the evaluation of a potential fuel impact (even for certified high-quality pellets), were mentioned. Concluding, potential parameters of pellets or/and technology restrictions which influence the emission and efficiency performance of pellet stoves need further investigations.

Comparative tests in the lab as well as in the field according to the existing test standard (EN 14785) and "*beReal*" revealed that the "*beReal*" method is in principle capable to reflect real-life performance and might also be a potential approach to assess emission factors of pellet stoves in the lab. This might be useful for a regular update of air pollution inventories and to update and evaluate the progress of technological development. However, for such an approach further investigations are necessary.

Comparing the field test results with proposed Austrian and European (EMEP/EEA) emission factors it seems that the EF for VOC (EMEP/EEA & Austrian EF) as well as PM emissions (only for EMEP/EEA EF) might be too high to reflect real-life performance. However, as already mentioned the number of tested pellet stoves was only four and also only modern products were evaluated.

Moreover, the field test results compared to official type test (ott) results confirmed that EN test results (at least at nominal load) do not reflect real-life performance of pellet stoves. EN test results underestimate the real-life emissions up to more than 100%. Moreover, the comparison of ott results with repeated type test results using serial-production appliances revealed that it is not possible to reproduce ott results, especially for PM emissions as well as thermal efficiency. Therefore, the implementation of a market surveillance concept, as it is introduced by the new ecodesign directive, might represent an effective measure to guarantee a constant product quality of sold appliances.

The new ecodesign requirements will set an equal benchmark of performance criteria for new stove technologies in Europe. However, analysing the future ecodesign requirements for pellet stoves regarding emissions it seems that it will be no challenge for most manufacturers to comply with CO and VOC emission requirements as they are met already. Only the compliance with PM emission requirements might be a challenge for some manufacturers.

Moreover, it is important that the future ecodesign ELVs are only valid for testing the appliances according to the existing EN standard at nominal load under stationary conditions which, however, was identified as no typical real-life operation mode. Therefore, the effect of improving real-life situation as well as of pushing technological development towards optimized real-life operation is limited. Furthermore, a differentiation between good and poor or good and very good products for the end customers will not be possible according to the future ecodesign ELVs. Consequently, the implementation of a real-life oriented test concept (e.g. the "*beReal*" method) which would be capable to better reflect the real-life performance of the appliances compared to existing EN standard is preferable. In a first step the implementation of such a test concept as a quality label could represent an appropriate option.

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