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Performance History and Further Improvement Potential for Wood Stoves

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Low load wood stoves in new highly-insulated buildings demand new technologies and solutions with an increased focus on the combustion process and its control, the combustion quality and optimum design to ensure low emissions and high energy efficiency. The goal is to maintain or even further reduce the particle emission levels achieved for the larger units, while at the same time achieving a high energetic performance.
The objective of this work is to 1) review the environmental and energetic performance history for wood stoves, with special focus on the last two decades, and 2) evaluate the further improvement potential for wood stoves.
The introduction of the Norwegian wood stove testing standard, NS 3058/3059, in 1998 introduced an emission limit for particles of 10 g/kg dry wood for new wood stoves. From this moment in time the staged combustion air units, with both primary and secondary air addition, have completely dominated the wood stove market. These wood stoves also have the potential to perform energetically much better than old types of wood stoves, due to better combustion air control, reducing the overall excess air ratio.
During the last two decades, continuous improvements have resulted in wood stoves with much reduced particle emission levels, down to more than 80% particle reduction compared to the 10 g/kg dry fuel emission limit, in commercial wood stoves. However, there is still a significant further improvement potential.

1. Introduction

Wood combustion for space heating in wood stoves has come far today regarding environmental performance compared to just two decades ago. This is due to standardized test methods enforcing requirements on the environmental performance of the wood stoves. However, several quite different test standards exist in Europe, and there is a need to agree on a common standard which should ensure both good environmental and energetic performance for wood stoves. Current work on achieving a harmonized standard for Europe (CEN TC 295, 2018) has been delayed and the current status is considered as “unknown” as of ultimo 2017.
Additionally, future buildings will increasingly turn towards low energy buildings due to more stringent building regulations, where today’s modern wood stoves would not fit in due to low modularity, they need to become smaller and the heat release profile to the room needs to be flattened out (Georges, 2013). This is a considerable challenge, and needs to happen without degrading the stove performance, environmentally or energetically.
During the years many researchers have assessed the performance of wood stoves, however, none has thoroughly presented the performance history and coupled this to the further improvement potential for wood stoves. Most fail to investigate or analyse in sufficient detail the factors influencing the performance. As a part of the competence building projects StableWood (Skreiberg, 2011) and the successor WoodCFD (Skreiberg, 2015), analyses of the last 20 years wood stove approval tests carried out at the Norwegian Fire Research Laboratory (NBL) and RISE Fire Research Norway have been carried out. The aim was to reveal interesting findings regarding factors influencing the particle emission level from, and the energetic performance of, today’s modern wood stoves. This knowledge would be novel and very useful in the development of the wood stoves of the future.
Also, as of 2018, new Ecodesign (Ecodesign, 2018) emission regulations and knowledge regarding the emissions performance of the state-of-the-art technology have encouraged Norwegian authorities to initiate a

50 % reduction of the current particulate emission limit, from 10 to 5 g/kg. Currently the background basis to initiate this change is being worked out by the Norwegian directorate for building quality, responsible for enforcing the emission regulations through the Norwegian building regulations.

2. Experimental section

Anonymous experimental results were received from NBL and RISE Fire Research Norway covering 20 years of approval testing results according to mainly the Norwegian standard (NS 3058, 1994 and NS3059, 1994), but also the EN 13240 (2001). This amounts to about 300 approval tests, providing a large data set, useful for analysing univariate trends as a function of year or development degree, as well as correlations between the particle emission level and different parameters that may influence this.

2.1 Introduction to NS 3058/3059 and EN 13240

The standards NS 3058/3059 and EN 13240 are two approaches to the challenging task of making a wood stove testing standard for approval testing of wood stoves. They are quite different (Seljeskog et al., 2017). While NS 3058/3059 includes testing, with natural draught, also on part load operation EN 13240 only tests, with forced draught (12 Pa), at nominal load operation. NS 3058/3059 focuses on particles sampled at 35°C in a dilution tunnel (emission limit: 10 g/kg dry wood), while EN 13240 focus on CO (emission limit: < 1 vol%) and efficiency (> 50%). Other main differences between NS3058/3059 and EN 13240 are (EN vs. NS): Fuel type: Hardwood (logs) vs. softwood (profiled timber); Fuel loading: According to manufacturer vs. 112±11 kg/m^3 of the firebox volume; Test condition: Nominal heat output vs. 4 burning rate categories. It could be expected that EN 13240 is not as good as NS 3058/3059 if the goal would be to also ensure that the tested wood stoves also are capable of operating at low part loads without excessive emissions of unburnt compounds.

2.2 Data treatment procedure

Two datasets were received from NBL, a set with a limited amount of data from wood stove producers not participating in the StableWood project, and a set with more detailed information included from the four wood stove producers participating in the StableWood project. Additionally, the set with limited data was complemented by including newer tests up to 2017. The data was received from RISE Fire Research Norway within the WoodCFD project. All single datasets were checked for consistency and correctness, and where possible also with regard to calculations carried out according to the standards. The energetic performance of a wood stove can only be calculated correctly in cases where flue gas analysis (CO_2, or O_2) are reported in addition to the chimney inlet flue gas temperature, i.e. the EN tests. In the NS tests, the chimney inlet flue gas temperature together with an estimated CO_2 level (8.5 vol% in dry flue gas) based on the EN tests can give a quite good indication of the stoves efficiency.

3. Results and discussion

3.1 Particle emission levels as a function of year or development degree

As can be seen in Figure 1, the weighted particle emission levels, determined according to NS 3058/3059 are for all tests below the particle emission limit of 10 g/kg dry fuel. As also can be seen, there has been a significant decrease in the particle emission levels since the particle emission limit was introduced in 1998. This can be attributed to a continuous development effort, carried out by the wood stove producers themselves and research institutes, optimising the staged air combustion principle. The best wood stoves have a weighted particle emission level of below 2 g/kg dry fuel, mostly after year 2005.

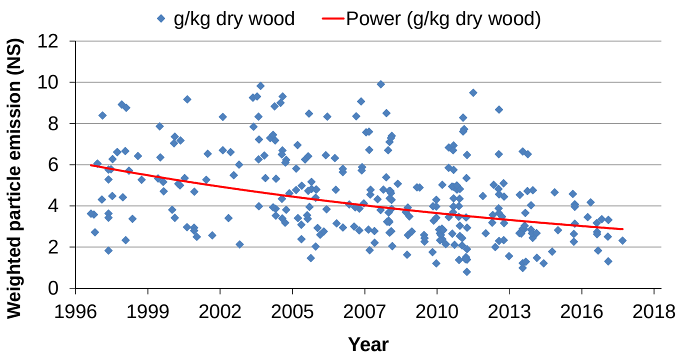
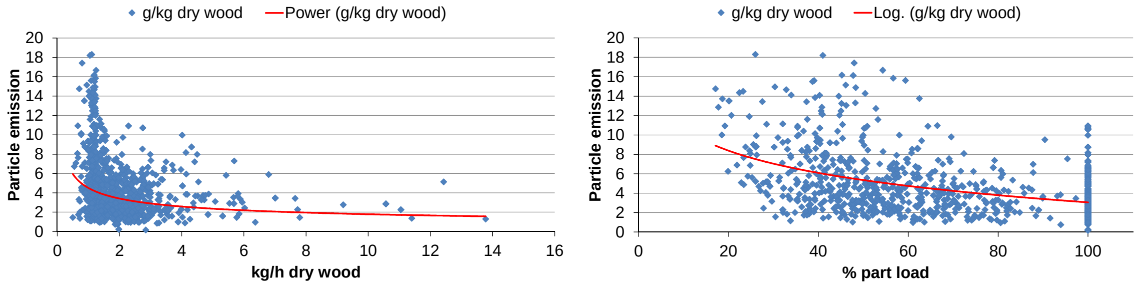


Figure 1: Weighted particle emission levels as a function of year or development degree.

3.2 Particle emission levels as a function of load

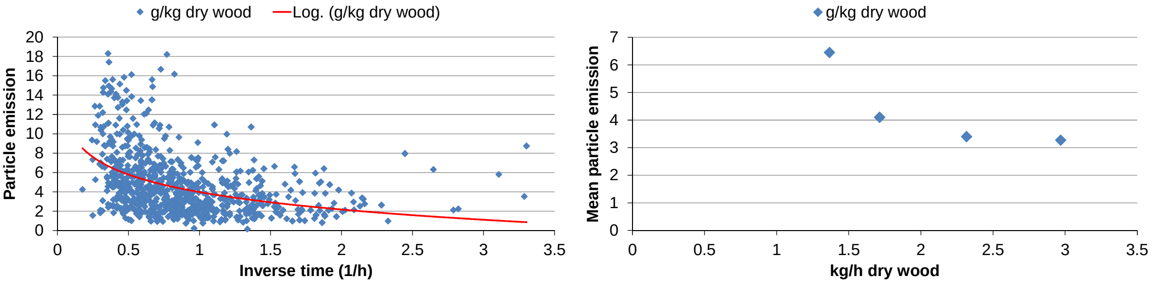
Considering the individual tests at different loads that contribute to the weighted particle emission level, Figure 2a shows the particle emission levels in g/kg as a function of the dry wood consumption in kg/h, Figure 2b shows the particle emission levels in g/kg as a function of % part load, Figure 3a shows the particle emission levels in g/kg as a function of inverse time, and finally Figure 3b shows the average particle emission level for each of the four load categories according to NS 3058/3059. Clearly, firing at part load, i.e. at a low wood consumption rate, results in significantly higher particle emission levels, almost double that of the weighted particle emission limit, than at nominal load. Test standards that only test the unit at nominal load therefore are not suitable if the unit is intended for part load operation also. A particle emission level of 10 g/kg at nominal load could mean that the unit will emit five times that at the lowest part load. Part loads down to about 20% of nominal load have been tested, as shown in Figure 2b. Clearly, the particle emission level increases at low part load.

To check the influence of test duration the particle emission levels were also plotted as a function of the inverse test duration (1/h), as shown in Figure 3a. Clearly, the long duration experiments give the highest particle emission levels, typically corresponding to part load operation, where the inlet air amount is reduced to increase the test duration and, hence, part load operation is achieved, without reducing the amount of fuel loaded into the stove before the test start.



(a) (b)

Figure 2: Particle emission levels as a function of a) load and b) % part load.

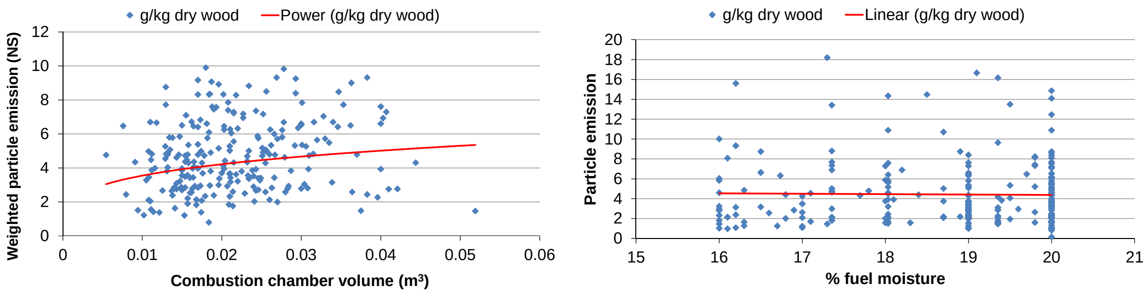


(a) (b)

Figure 3: a) Particle emission levels as a function of inverse time and b) Mean particle emission levels as a function of load.

3.3 Particle emission levels as a function of combustion chamber volume

One factor that could influence the particle emission level is the combustion chamber volume. According to NS 3058/3059 the combustion chamber should be filled with wood so that the loading density is 112±11 kg/m^3. Large combustion chambers indicate larger and heavier stoves with larger glass surfaces, and firing these at low part loads may lead to lower combustion chamber temperatures due to their high heat storage capacity compared to the heat production and relatively speaking higher heat loss from the combustion chamber through the glass. A lower combustion chamber temperature will increase the particle emission level. Figure 4a shows the weighted particle emission levels as a function of the combustion chamber volume, and a trend of increasing particle emission levels with increasing combustion chamber volume can be seen.



(a) *(b)*

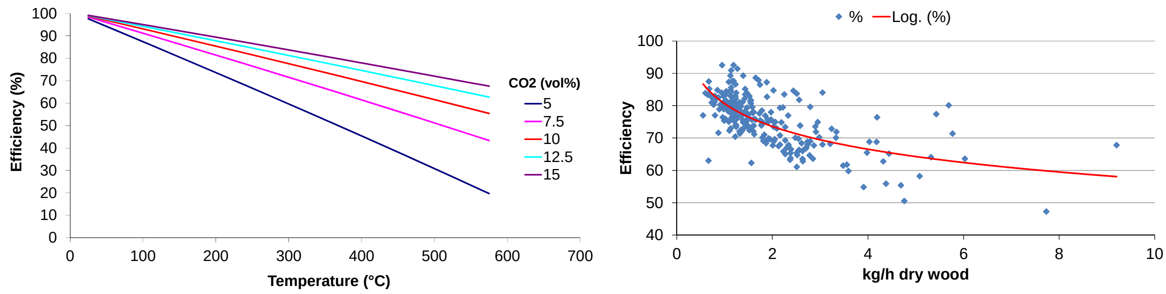
Figure 4: Particle emission levels as a function of a) combustion chamber volume and b) fuel moisture content.

3.4 Particle emission levels as a function of fuel moisture content

The fuel moisture content was only available in the data set from wood stove producers participating in the StableWood project. According to NS 3058/3059 the fuel moisture content should be in the range 16-20% on wet basis. Figure 4b shows the particle emission levels as a function of the reported fuel moisture content. The trend line in Figure 4b shows a slightly decreasing particle emission level with increasing fuel moisture content, which would be unphysical, however, no conclusions can be drawn from this other than that it seems like the fuel moisture content is not an important influencing factor on the particle emission level in the tested fuel moisture content range.

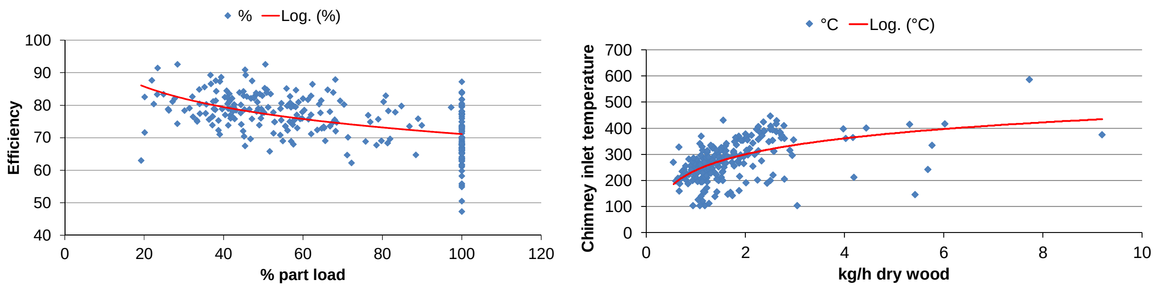
3.5 Energetic performance

For some tests also test results according to the EN standard 13240 standard were available. Figure 5a shows the stove efficiency as a function of chimney inlet temperature and vol% CO_2 in the dry flue gas, calculated according to EN 13240. Figure 5b shows the stove efficiency as a function of load and Figure 6a shows the stove efficiency as a function of % part load. The corresponding chimney inlet temperatures are shown in Figure 6b as a function of load and in Figure 7a as a function of % part load.
The chimney inlet temperature is the most influential factor on the energetic performance, as shown in Figure 5a. For low CO_2 levels, i.e. high excess air ratios, the CO_2 level becomes increasingly important. It is therefore reasonable to use an estimated value for the CO_2 level, chosen as the average value from the EN tests, to be able to estimate the stove efficiencies in the NS tests.



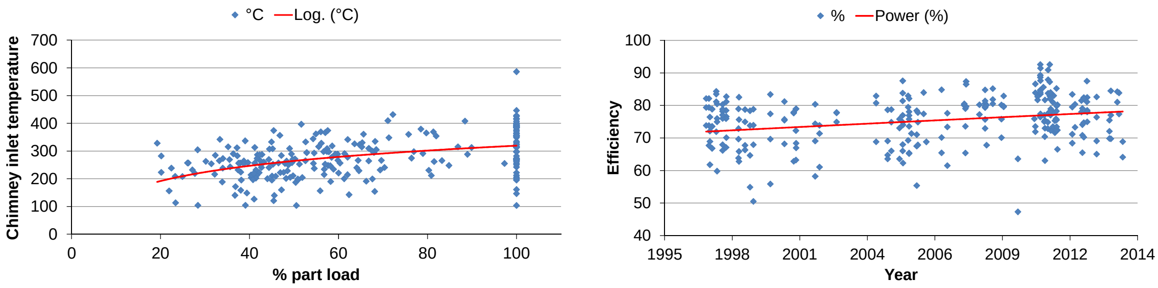
(a) *(b)*

Figure 5: a) Stove efficiency as a function of chimney inlet temperature and vol% CO_2 in dry flue gas, calculated according to EN 13240 and b) Stove efficiency as a function of load.



(a) *(b)*

Figure 6: a) Stove efficiency as a function of % part load and b) Chimney inlet temperature as a function of load.



(a) *(b)*

Figure 7: a) Chimney inlet temperature as a function of % part load and b) Stove efficiency as a function of year or development degree.

As can be seen in Figure 5b and 6a, the stove efficiencies can vary in a wide range, but they clearly increase with decreasing load and % part load. This is mainly an effect of a decreasing chimney inlet temperature with decreasing load and % part load, as can be seen in Figure 6b and 7a. Hence, low load operation gives the highest stove efficiencies, but unfortunately also the highest particle emission levels.

4. Discussions

Below, a general discussion is given based on the results presented in this work.

4.1 Particle emissions

The most obvious influencing factor on the particle emission level is the stove load, i.e. the fuel consumption in kg dry fuel per hour. This is also related to % part load, inverse time, and of course also the stove heat output (effect, kW). Clearly, part load operation increases the particle emission levels, which is the very reason for testing the stoves also at part load operation in the Norwegian standard, where the testing is carried out at four loads, and a weighted particle emission level is calculated based on the particle emission from all four loads. Testing a stove only at its nominal effect is no good, and may result in the approval of a stove which when operated at part load may have a very high particle emission level.

According to the received data, during the last 20 years the particle emission levels have been significantly reduced, even though the particle emission requirements in Norway has not changed. Hence, there is clearly an ongoing continuous development, resulting in decreased particle emission levels down to below 20% of the current particle emission limit for the best stoves.

Regarding the fuel moisture content, this is a factor which should be increasingly important at high or very low moisture contents, i.e. outside the fuel moisture content range defined in the Norwegian standard. High moisture contents, above the fibre saturation point, would be expected to increase the particle emission levels, while a very low moisture content can result in a too high load (high reactivity), leading to a too low excess air ratio in the volatiles combustion phase of the batch combustion cycle, resulting in high particle emissions due to a lack of locally available oxygen.

4.2 Energetic performance

A wide range of stove efficiencies can be achieved, depending on mainly the load, which will influence both the chimney inlet temperature and potentially the CO_2 level in the flue gas. It is logical that part load operation, or part effect operation, releases less energy in the combustion process per time unit, and therefore a larger fraction of the released energy will be transferred through the stove walls and the glass to heat the room. Hence the chimney inlet temperature will decrease and the stove thermal efficiency will increase. The combustion efficiency will decrease somewhat at part load operation, due to increasing emissions of unburnt, including particles. However, this influences the overall efficiency, the stove efficiency, much less. Hence, the stove efficiency will increase at part load operation. A decreasing CO_2 level with decreasing load would decrease the stove thermal efficiency for a fixed chimney inlet temperature, however, for a properly designed stove, the CO_2 level should be little influenced by the load, and an influence might go in any direction depending on the specific stove. Stove tightness and air regulation principle are influencing factors.

To influence or control the stove efficiency, the effort must be directed towards avoiding too high chimney inlet temperatures at nominal effect, while at the same time avoiding too low chimney inlet temperatures at low part loads. The latter will cause draught problems in stoves without a fan (i.e. natural draught stoves) to control the amount of inlet air, and potentially also higher particle emission levels. Designing such an optimum stove with respect to both emissions and energetic performance is indeed a challenge.

4.3 Identification of the most influential parameter on the particle emission level

The most influencing parameter is the load, if the fuel moisture content is within certain limits. Of course there are other parameters that also influence the particle emission level, in fact they are the ones controlling it, but they are to a large extent controlled by the load setting. E.g. the amount of inlet air is throttled down to achieve part load operation. The combustion temperature is very important for the particle emission level. A too low combustion (chamber) temperature leads to poor burnout and high particle emission levels. A sufficient residence time is also needed in the hot zone to allow for a good burnout. Finally, the excess air ratio is very important, influencing the availability of oxygen negatively when it becomes too low and influencing the temperature and the residence time negatively when it becomes too high. Improving the mixing conditions in the stove is one way of operating at lower excess air ratios without increasing the particle emission levels. In fact, the particle emission levels should decrease due to increased temperature in the hot zone and also increased residence time. At the same time an increased thermal efficiency can be achieved due to an increased CO_2 content and a reduced flue gas flow rate.

5. Improvement potential for wood stoves

As can be seen from the data presented in this work, particle emission levels below 2 g/kg dry fuel is possible in today's best wood stoves approved for sale in Norway. The goal for the future should be to achieve emissions below 1 g/kg, i.e. getting close to the performance of pellet stoves. For this to happen it is necessary to further control the combustion process. This will create more stable combustion conditions, approaching the potential of a continuous combustion process. The energetic performance of today's wood stoves can be quite high (about 90%), but mainly at low load operation. There is a need to achieve a high energetic efficiency in the whole stove operating range, without increasing the particle emission level. For low energy houses also the heat release profile needs to be flattened out, with additional measures such as using phase change materials in the stoves and applying passive or active control measures.

6. Conclusions

In this work the performance improvement of wood stoves through the last two decades has been analysed. A continues reduction of particle emissions has occurred resulting in decreased particle emission levels down to below 20% of the current particle emission limit for the best stoves, as well as an increase in energetic performance. The most obvious influencing factor on the particle emission level is the stove load. Research and development has led to these improvements, continuously improving upon the staged air combustion principle. However, there is a significant improvement potential, and the goal for the future should be to achieve emissions below 1 g/kg, i.e. getting close to the performance of pellet stoves. As a result of the continuous improvement, stricter emission limits could be enforced.

Acknowledgments

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