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Energy Efficiency Increase by Improved Operation and Control in Wood Stoves

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The purpose and novelty of this work was to evaluate both the total and the transient energy efficiency of three types of modern wood stoves based on experimental results at different loads and elaborate on the level of energy efficiency increase that can be achieved by improved stove operation (user-controlled) and control (by design or automation). The experimental results show that the energy efficiency for modern wood stoves is around 80%, which is much higher than for old wood stoves due to improved stove designs and better combustion process conditions. This gives much reduced emission levels, contributing to a higher combustion efficiency, improved mixing conditions reducing the excess air need and improved heat exchanger designs reducing the chimney inlet temperature, both increasing the thermal efficiency. However, there is a significant improvement potential through further improved combustion control and stove operation, reducing the negative effects on emissions and efficiencies of the crucial period after igniting a new batch and in the final part of the char burnout. Improved heat exchanger designs and increased heat storage capacity will further increase the thermal efficiency. The total (stove) efficiency has the potential to approach the efficiency of pellets stoves.

1. Introduction

Wood stoves are widely used for space heating in cold climates and provides energy security and relieves the pressure on the electricity grid, especially on cold winter days. Biomass, including wood, is defined as CO_2 neutral when it comes to direct CO_2 emissions, as continuous regrowth of the biomass is assumed. Still, efficient use of the biomass is needed for sustainability reasons, including economical. More efficient biomass use will lead to an increased fossil fuels substitution potential, through maximising the utilisation of the energy potential of the biomass, i.e. minimising emissions of unburnt towards 100% combustion efficiency and minimising the excess air ratio and the flue gas temperature into the chimney to maximise the thermal efficiency. Regarding wood stove development history, development of new combustion chamber concepts was addressed in the late 1980s to make wood stoves more environmentally friendly and energy effective. The concept of staged air combustion was implemented, and regulations on particle emissions from wood stoves were introduced in Norway in 1998. Since then continuous optimization has led to significant further reductions of emissions and increased energy efficiency, when testing the stoves according to different type approval standards. However, the individual emission levels typically can vary significantly depending on the type approval standard, due to different testing procedures. Regarding energetic performance history, old wood stoves have in the Norwegian national energy statistics been included with an energy efficiency of 50%, while open fireplaces with 15%. The 50% energy efficiency coincides with the energy efficiency demand in the NS-EN 13240:2001 (EN01) standard. In practise the energy efficiency of old stoves will vary significantly based on the stove operation, and the energy efficiency of an old stove operated at optimum conditions will be much higher than 50%. However, the much improved combustion conditions and thereby reduced emission levels in modern stoves combined with improved stove designs will anyway contribute to significantly higher energy efficiency compared to old stoves. In Skreiberg and Seljeskog (2018) it was shown a clear trend of increasing energy efficiency also within the modern wood stove category, in the time period 1998-2014. This improvement is due to a further improved combustion process and reduced emission levels, and improved stove designs. In comparison, pellet stoves today typically have an energy efficiency of 80-90% according to the new standard NS-EN 16510-1:2022

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(EN22), where the energy efficiency demand for new wood stoves is 75% (NS-EN 16510-2-1:2022), but this can be considered to be a rather conservative demand, as modern wood stoves in general perform significantly better than this.

2. Methods

The focus in this work has been on the modern wood stove category, and the influence of reduced emission levels, reduced excess air ratio, and reduced flue gas temperature into the chimney on the stove efficiency is analysed throughout the transient combustion process based on experimental results. Based on the experiments, also the effect of ignition and refill strategy and automation, all leading to more stable combustion conditions, can be elaborated upon.

2.1 Experimental

Experiments were carried out according to NS 3058/3059:1994 (NS94) for three types of modern wood stoves, a cast iron stove (Stove 1), a plate steel stove (Stove 2) and a lightweight soapstone stove (Stove 3). This is a wood stove type approval standard that requires testing of the stoves at different loads, ranging from part load operation to above nominal load operation. Weighted results can then be calculated based on a statistical load firing frequency. This is by default done to determine a weighted particle emission level, but can also be done for other emission compounds, and for efficiencies as well, to determine representative mean (weighted) values, i.e. representing conditions closer to real life wood stove operation. NS94 does not include a method for efficiency determination, so the method used in EN22 was applied to have a standardised method to refer to, but in addition an inhouse method (Skreiberg, 2002) was used to account for the transient behaviour through one experiment. In the EN22 method, only arithmetic average values are used for the experimental input values to the efficiency, and emissions, calculations. However, due to the typical transient behaviour of wood stoves, the weighted average values can deviate significantly from the arithmetic average values. In addition to measuring the chimney temperature according to NS94, a thermocouple was placed further up the chimney, measuring the chimney temperature according to EN22. This latter thermocouple was used in the efficiency calculations in this work. In addition to evaluating the total (stove) efficiencies, also transient efficiencies (combustion, thermal and total) throughout one experiment were evaluated as well as weighted average efficiencies for the characteristic combustion cycle periods; during two periods after igniting the wood batch, two periods during the char burnout, and during the longer and more stable period in between. Before type approval according to any standard, preheating of the stove is done, making the type approval test itself a refill operation. Based on this the effect of refilling the stove with a reduced amount of wood, as well as the effect of improving the air supply control, can be elaborated upon regarding further improvement potential with respect to combustion process stability, and resulting effects on efficiencies.

2.2 Theoretical background

Several factors influence the energy efficiency of a wood stove, and the most important factors are the emission levels of unburnt species, the excess air ratio and the stove design through its heat transfer area as well as its heat storage capacity, determining the temperature into the chimney. Once the flue gas has reached the chimney inlet, its heat content is regarded as lost as in principle no heat loss is wanted in the chimney, to uphold a sufficient chimney draft to supply the stove with enough combustion air. The fuel moisture content influences the fuel heating value, but since the efficiency calculation is based on the effective heating value of the fuel, the influence of the fuel moisture content is indirect, through its impact on the combustion process, emissions, the flue gas amount, and the flue gas composition and its corresponding specific heat capacity. For modern wood stoves, the emission levels of unburnt are typically low on average but might be significant during low load operation and during the ignition period, especially at cold start but also to some extent in a period after refilling. Typically, emission levels are also increasing in the last part of the char combustion period. Through the inhouse efficiency calculation method, based on accounting for the transient behavior through one experiment, both the transient combustion efficiency as well as the transient thermal efficiency can be calculated, and then based on these, the transient energy efficiency of the stove. Finally, the inhouse calculation method calculates the corresponding weighted average efficiencies for an experiment.

3. Results

3.1 Experimental

A typical transient behaviour for an experiment (Exp 2 in Table 1), at about nominal load operation for Stove 1, carried out according NS94, is shown in Figure 1. The transient behaviour both with respect to O_2 and CO_2 concentration, CO emission and chimney inlet temperature can clearly be seen. Typically, the O_2 concentration is increasing when opening the stove door to insert a new batch, and then decreasing again when the new batch has ignited. Then a relatively stable combustion period is reached, until the char combustion period starts, where the O_2 concentration increases again, since the combustion activity and the O_2 demand is reduced due to the relatively slow heterogeneous char combustion process, while the air intake valve is not adjusted, and the chimney draft is mostly upheld as the chimney inlet temperature is not much reduced. Reducing and stabilizing the oxygen concentration, without significantly impairing emission levels, and reducing the chimney inlet temperature are the keys to an increased energy efficiency at nominal load operation.

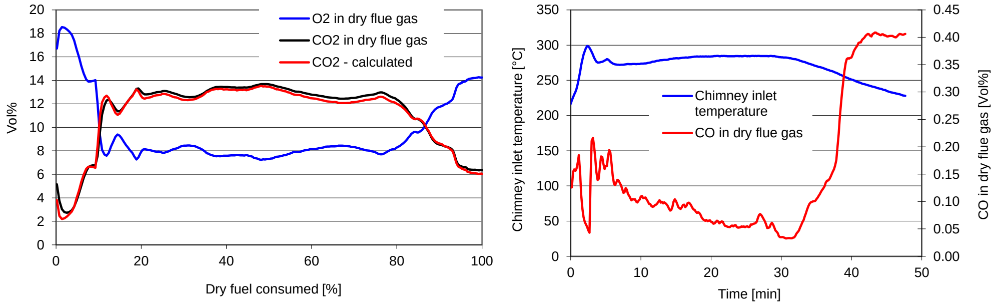

Figure 1: O_2 and CO_2 concentration, CO emission and chimney inlet temperature throughout a combustion cycle (The inhouse calculation method provides a means to also calculate the CO_2, to verify the experiment)

3.2 Calculated transient and total efficiencies

Calculated transient combustion and thermal efficiencies, and the corresponding transient total efficiencies, are shown in Figure 2, for the same experiment as in Figure 1, and in addition for a low load experiment in the same stove. Except for the initial experimental period and the final part of the char combustion period, the combustion efficiency is high, and the efficiency improvement potential at nominal load mainly lies in reducing the oxygen concentration and reducing the chimney inlet temperature, i.e. improving the thermal efficiency. By improved operation and stove design, significantly improved thermal efficiency is achievable without impairing the chimney draft to the extent that the (natural draft) air supply to the stove is penalised. However, a reduced oxygen concentration means a reduced air supply need, and the possible influence of the reduced air supply on air velocity and mixing conditions in the combustion chamber becomes a more important issue in practise, i.e. the stove design with respect to the air supply system must be dimensioned to work effectively also at reduced air supply conditions. For the low load experiment, the combustion conditions are significantly worsened in a period after igniting the batch, due to throttling down of the air supply to achieve the low load, resulting in reduced combustion efficiency. Thereafter the combustion efficiency is relatively high in the stable combustion period and the thermal efficiency is higher than at nominal load, due to a lower chimney inlet temperature due to the reduced load. Then in the char combustion period, the combustion efficiency again is reduced, while the thermal efficiency is increasing due to a reducing chimney inlet temperature.

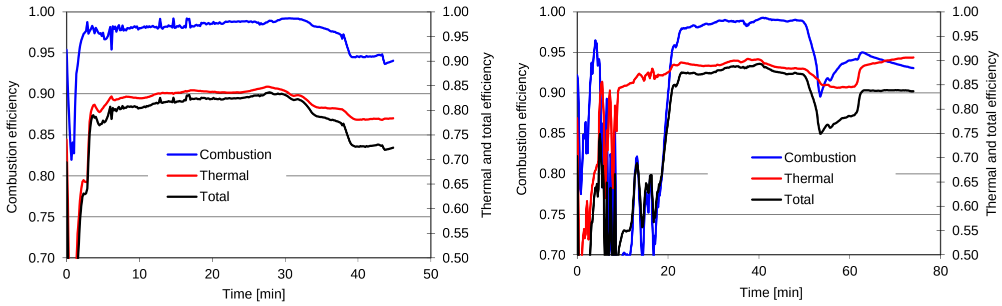

Figure 2: Transient combustion and thermal efficiencies, for the same experiment as in Figure 1 (left) and a low load experiment (Exp 4 in Table 1) in the same stove (right)

The accumulated combustion and thermal loss, as shown in Figure 3, showcases the effect of stabilising the combustion conditions towards a more continuous combustion process by improved combustion and air supply control in a period after the ignition of the wood batch and in the last part of the char burnout phase. Typically these periods contribute to the largest part of the combustion efficiency loss, and also to a higher than average thermal loss due to a higher O_2 concentration. However, it is important to note that a stable oxygen concentration or a stable chimney inlet temperature does not mean that the combustion process is stable, as the individual wood logs will go through a transient decomposition process, from moist wood to charcoal. I.e., the properties of the fuel burning will change continuously throughout the combustion cycle. The only way to somewhat abate this transient behaviour is to reduce the wood batch size and refill the stove more often and with a smaller amount of wood. A pellet stove can be considered close to a continuous combustion process as the pellets are small, and even though the individual pellets will go through the same transient decomposition process, the frequent loading of a new pellet will in sum disclose the transient behaviour, and the overall combustion process can be considered as stable. The effect of an improved combustion and air supply control would be that the combustion process stabilises faster after ignition of the wood batch and that the negative effect of a distinct char burnout phase is reduced, resulting in reduced oxygen concentration, increased combustion temperature, increased residence time and lower chimney inlet temperature. This has the potential to also reduce emissions.

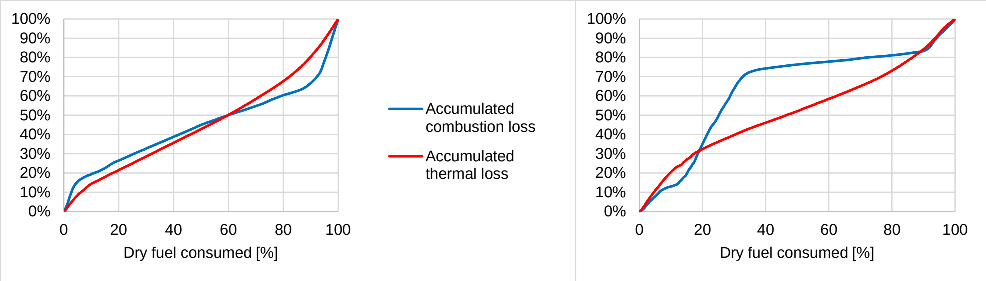

Figure 3: Accumulated combustion and thermal loss, for the same experiments as in Figure 2, at nominal load (left) and at low load (right)

Table 1 shows an overview of the weighted average efficiencies reached in the single experiments with the three different stoves, as well as calculated efficiencies for each stove taking into account the NS94 statistical load firing frequency. Based on these, average efficiencies for all three modern stoves are calculated. Low load (in kg/h of dry wood) experiments yield lower combustion efficiency than at nominal load, but to which degree depends also on the stove design. The thermal efficiency depends both on the chimney inlet temperature and the O_2 concentration, which both depends on the stove design, and the regulation of the air intake valve. The highest thermal efficiency is achieved at reduced load, due to a significantly reduced chimney inlet temperature, which outweighs a somewhat increased O_2 concentration. The resulting total efficiency is around 80% for all three stoves, and the highest efficiency was achieved for the stove with the highest heat storage capacity, Stove 3. It operates with the lowest chimney inlet temperature and the lowest O_2 concentration as well. Typically a heat storing stove can be fired more intensively without resulting in thermal discomfort. **Based on these experiments it can be concluded that the total efficiency of modern wood stoves today is about 80%**.
Figure 4 shows the weighted average efficiencies in five different parts of the combustion cycle, showcasing the transient behaviour of the combustion process in a wood stove. Typically, the combustion efficiency is lower in the first period (accounting for the first 10% of the total dry mass loss, and in the last period (accounting for the last 10% of the total dry mass loss). In the middle period (20-80% dry mass loss) the combustion process conditions are typically relatively stable, the combustion efficiency is high, and the thermal efficiency is at its highest. For a specific stove, this is the period that can be considered a benchmark for the performance potential of the overall combustion cycle. Improvement possibilities are related to proper loading and ignition of the wood batch, ensuring fast ignition but preventing a long period with excessive air supply resulting in a high excess air ratio, and reducing the excess air in the char combustion period. Reducing the batch size and more frequent batch loading will further contribute to faster reaching stable combustion conditions. Improving the efficiencies in the stable combustion period is possible, through optimising the combustion chamber design as well as the stove heat transfer section. The former will allow operation with a reduced excess air ratio while the latter will reduce the chimney inlet temperature. A reduced excess air ratio will contribute to increased combustion temperature and residence time. The wood stoves are typically operating at their best at nominal effect, and hence operation at the declared nominal effect is recommended, giving also the lowest emissions of unburnt per unit heat output. Finally, Figure 4 shows the corresponding weighted average heat outputs (kW) from the five periods. The heat output is based on the weighted average effective heating value of the period, providing the generated heat, and the weighted total efficiency in the period. Typically, the heat output is lowest in the first period, due to both higher excess air ratio and the high drying and heat of evaporation demand. The heat output in the last period is typically also low, due to a high excess air ratio and a much reduced combustion rate, where the high heating value of the char is not able to compensate for the reduced combustion rate with respect to heat generation. When calculating the stove efficiency using the EN22 calculation method with its arithmetic average input values, a significant deviation is found (see Table 1) compared to the more correct approach taking into account the transient behaviour of the combustion process, especially at conditions with relatively low combustion efficiency.

Table 1: Stove efficiencies, and corresponding O_2 concentration and chimney inlet temperature

	Stove 1				Stove 2			Stove 3			Stove 1	Stove 2	Stove 3	Stove 1-3
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Exp 10	Weighted	Weighted	Weighted	Mean
Load (kg/h)	1.98	1.79	1.27	1.25	1.20	2.17	1.70	2.55	0.95	1.31	1.59	1.65	1.73	1.66
O2 (vol% dry)	10.60	10.93	12.10	12.35	11.23	9.73	9.57	8.68	10.56	10.31	11.40	10.18	9.73	10.44
T_Chimney (°C)	281	269	215	190	230	320	276	262	207	232	244	272	240	252
Combustion eff	98.4 %	97.5 %	92.3 %	93.0 %	97.3 %	99.0 %	97.8 %	99.0 %	97.6 %	98.5 %	95.7 %	97.9 %	98.5 %	97.4 %
Thermal eff	79.8 %	80.3 %	83.7 %	85.4 %	83.1 %	78.2 %	81.9 %	83.8 %	85.8 %	84.2 %	82.0 %	81.4 %	84.3 %	82.5 %
Total eff	78.2 %	77.8 %	75.9 %	78.4 %	80.4 %	77.1 %	79.7 %	82.7 %	83.4 %	82.6 %	77.6 %	79.3 %	82.8 %	79.9 %
EN-weighted	79.5 %	79.6 %	80.7 %	82.6 %	81.6 %	77.9 %	80.7 %	83.5 %	84.7 %	83.3 %				
EN-arithmetic	80.3 %	80.7 %	82.0 %	84.5 %	82.5 %	78.0 %	81.6 %	83.9 %	84.3 %	83.9 %				

In general the efficiencies are higher using EN22. When using weighted average input values (derived in the inhouse method) in the EN22 calculation method, the efficiencies are somewhat closer to the inhouse calculation method. The remaining deviation is mainly due to not accounting for other unburnt gas species than CO in EN22. In the inhouse method such species are accounted for using FID analyser measurements. Still there are remaining differences, which is due to different thermodynamic data used for the flue gas heat capacity and the chemical loss due to unburnt CO. In EN22 an empirical expression is used to calculate the specific heat capacity for the dry flue gas and in addition one for that of water vapour, while in the inhouse method detailed expressions for each single gas species in the flue gas is used, and the calculation of chemical losses are also based on detailed thermodynamic data.

Figure 4: Weighted average combustion, thermal and total efficiency, and kW net heat output, for all experiments divided into five phases (accounting for respectively 10, 10, 60, 10 and 10% of the dry mass loss). The experiments are here sorted according to load for each stove

The main drawbacks of the EN22 method are not accounting for other unburnt gas species than CO, and not accounting for the transient behaviour of the wood log combustion process. The latter requires a more extensive calculation approach as in the inhouse method, but the former is easy to implement, as OGC measurements (using FID) are anyway required when carrying out type approval testing according to EN22. What has not been included as losses neither in the inhouse calculation method nor in the EN22 method, is the chemical loss connected to the particle emission level. In the EN22 method there is an option (not used for wood logs) to include the effect of carbon loss due to the presence of a grate and charcoal pieces falling through it, and this could also be used to account for carbon loss in particle emissions. However, particle emissions consist of more than carbon, and the FID analyser account for most of the heavy gas species that condense and is counted as particle emissions in NS94. In addition there will be non-condensable contributions to the total particle emission level, especially elemental/black carbon. This part of the particle emission level could be accounted for through the grate option. As the amount of carbon lost through the grate or remaining in the residue for a single experiment carried out in a wood stove according to a type approval standard is not feasible to measure, EN22 accounts for this through a correction approach. In this work, such a correction is omitted, and is not needed either to compare the inhouse method against EN22. The EN22 correction approach does not account for differences between individual stoves or stove technologies, operating conditions, or wood species, and is only subtracting a given fixed percentage point from the calculated stove efficiency and accounting for the carbon content in the residue based on an empirical expression solely involving the lower heating value of the fuel.

3.3 Efficiency influence on other performance parameters

Measures to increase the energy efficiency can both positively and negatively influence on other performance parameters, primarily emission levels. A reduced oxygen concentration increases the combustion temperature, increases the residence time and reduce emissions of unburnt. However, at a certain point, depending on mixing conditions, the oxygen concentration becomes too low, and the emissions increase again due to local oxygen deficiency. In a wood stove, due to the transient combustion process, this point depends on where you are in the combustion cycle. A reduced chimney inlet temperature will influence the chimney draft, and if the draft from the beginning is relatively poor, this may lead to poorer combustion conditions, because of a reduced air supply or too low air velocities to achieve sufficient mixing conditions. When the chimney inlet temperature reaches a certain level, the draft is usually high enough, and then it becomes a matter of reducing the air supply by throttling down the air intake valve. If the chimney itself cannot provide a sufficient draft, due to several possible technical reasons, then refurbishing the chimney is the solution to enable achieving a higher energy efficiency. Using a chimney fan to generate a forced and adjustable draft would give better opportunities to ensure sufficient draft to supply the air needed for the combustion process, throughout the combustion process. However, it is only by automating the air supply to the stove and its division in the stove that real control with the air supply can be achieved. In such an approach, feedback to the air supply system from combustion performance measurements are needed, to ensure a good combustion performance, i.e. yielding low emissions of unburnt.

4. Conclusions

In this work, three types of modern wood stoves have been tested according to the type approval standard NS94. Extensive emission and energetic performance mapping were carried out. Based on the experimental results and an inhouse calculation method taking into account the transient behaviour of the combustion process, combustion, thermal and total (stove) efficiencies could be calculated throughout the combustion process, as well as corresponding weighted average values. Stove efficiencies of around 80% was achieved for all three stoves, with the highest efficiency achieved for the stove with the highest heat storage capacity. When carrying out the stove efficiency calculation according to EN22, higher efficiencies resulted, mainly due to EN22 not accounting for other unburnt gas species than CO, but also because the arithmetic average input values used in EN22, does not reflect the transient combustion process in a wood stove. The potential for further efficiency increases in wood stoves is significant, as during the combustion process the total efficiency in these modern wood stoves can approach 90%. It is mainly the first period after igniting the wood batch or refilling the stove and the last part of the char burnout phase that contributes to reduce the stove efficiency. Improved stove operation and ultimately automatic air supply control together with a stove design that ensures good mixing conditions, can abate the challenges connected to both these periods, approaching the stove efficiencies of pellet stoves. However, as the chimney inlet temperature is a decisive factor influencing the stove thermal efficiency, the design of the stove heat exchanger section becomes crucial. Increasing the stove heat storage capacity is one measure that both will increase the stove efficiency and the thermal comfort for the user as well. To further increase the energy output from the wood logs and increase the thermal output of the stove, additional drying of the fuel is the key.

Acknowledgments

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References

NS EN13240:2001, Roomheaters fired by solid fuel, Requirements and test methods.

NS-EN16510-1:2022, CSN EN 16510-1 - Residential solid fuel burning appliances - Part 1: General requirements and test methods, and Part 2-1: Roomheaters (NS-EN16510-2-1:2022).

NS 3058:1994, Enclosed wood heaters, Smoke emission; NS 3059:1994, Smoke emission - Requirements.

Skreiberg Ø., 2002, Fuelsim-Transient: A Mass, Volume and Energy Balance Spreadsheet for Batch Combustion Applications, Trondheim: NTNU.

Skreiberg Ø., Seljeskog M., 2018, Performance history and further improvement potential for wood stoves, Chemical Engineering Transactions, 65, 199–204.