Final report

Project details

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Project partners	DTU Chemical Engineering HWAM A/S
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Final report

Intelligent Heat System – high energy efficient wood stoves with low emissions

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Preface

This report summarizes the results obtained in project ‘Intelligent Heat System – high energy efficient wood stoves with low emissions’.
The partners in project have been DTU Chemical Engineering and HWAM A/S. The project started in 2010 and has been supported by EUDP (Energy Technology Development and Demonstration Program).

Content

Summary

This development and demonstration project conducted by HWAM A/S and DTU Chemical Engineering has contributed to the development of an automatically controlled wood stove (HWAM IHS), which is on the market today. The new digital control system ensures optimal combustion conditions by keeping optimal temperatures and overall oxygen concentrations in the combustion chamber throughout a complete wood log combustion cycle.

This improved performance has been verified by field tests in private homes where measurements showed significant reduced emissions and higher efficiency for the IHS stoves compared to traditional manually controlled stoves. The tests also showed that in many cases it is impossible to visually tell if non-optimal combustion occurs. Also, in practice it is impossible to manually control the combustion air as fast and optimally as the automatically controlled air inlet valves.

Emission measurements at the research wood stove set-up at DTU Chemical Engineering showed generally low emissions of particles, well below current standards, and high energy efficiency.
The highest emissions of CO, VOC and PM were seen in the ignition phase while only a small particle peak was observed in the flame phase. The CO emission in the char combustion phase increased due to decreasing temperature in freeboard – but almost no particle emissions were seen this combustion phase.

For the further optimization of the state of art technology of the IHS stoves developed in this project, the improvement of the tertiary air injection showed a considerable potential, which may result in an improved combustion and reduced pollutant emissions. Some important areas of future work include further development of control system sensors and measuring methods, and optimisation of the combustion process and chamber.

1. Introduction

In 2010, the CHEC (Combustion and Harmful Emission Control) research centre at DTU Chemical Engineering and the stove manufacturing company HWAM A/S established an EUDP collaboration project which has led to development and marketing of wood stoves equipped with a digital control system that can be used in existing wood stove combustion chamber designs. The goal was to develop a new 'intelligent' wood stove with high energy efficiency, reduced emissions (CO, VOC, PM), and high-level of comfort (well controlled heat release and limited time used for operating) for the wood stove users.

A first version of an automatically controlled wood stove, HWAM IHS (Intelligent Heat System), was launched on the market in 2012. The project was the first Danish development project focusing on optimal combustion conditions by introducing digital control of the combustion air.

Objectives

The aim of this project has been to develop a wood stove with high energy efficiency and low emissions of pollutants by developing a generic control system for wood stoves and an optimized combustion chamber – both usable in various wood stove designs. The generic control system composes of measuring devices for vital parameters of the process and a system of control valves to regulate the individual flow of three air streams to the combustion chamber.

The project plan included the goals:

1. In a reasonably short time-frame, a new digital control system for existing wood stoves will be developed and tested both in the laboratory and in controlled field tests.
2. The system will be made available in the market and mounted on existing stove designs and will provide a decreased particle emission and an improved heat release profile (and thereby a more constant room temperature), and at the same time ensure higher combustion efficiency.
3. The system will improve stove operation irrespective of stove owner's behaviour.

Focus in the first part of the project was on developing a control system that automatically controls the air flows to the combustion chamber for optimization of the combustion conditions. Before introducing this new control system on the market, it was decided to test the prototype of the control system in field tests on a number of wood stoves operated by ordinary wood stove owners and thereby test the influence of private user practices on emissions and energy efficiency. The last part of the project included investigations of particle emissions and optimisation of the control system.

2. Emissions from wood stoves – literature review

2.1 Emissions

The use of wood stoves is potentially an efficient and CO_2-neutral residential heating method. However, use of old wood stove technologies and poor firing habits limit optimal utilization and today combustion of wood in small-scale appliances is a major emission source of particulate matter smaller than 2.5 µm ($PM_{2.5}$), contributing more than 60% of the total estimated Danish $PM_{2.5}$ emissions [1]. The high emission level is due to the challenging conditions: batch firing in small combustion chambers with a wide range of wood types and wood log sizes, and typically manual control of combustion air flows and fuel loads, which makes it difficult to achieve good combustion [2].

In 2015, about 40% of the woody biomass used for energy and heat in Denmark was combusted in small-scale residential appliances (mainly wood stoves). There is thus a huge potential in improving the energy efficiency and reducing the emissions from the more than 700,000 Danish appliances, and there is an obvious need to provide technical measures that can reduce stove emissions [3].

The emission of PM is regulated by various national executive orders and European directives among others the EU National Emission Ceiling (NEC) directive. In 2020 this directive is going to include national emission ceilings for PM2.5. In 2007 the 'Statutory Order regulating air pollution from wood burners and boilers and certain other fixed energy-producing installations' – also called the 'Order for 'woodstoves' – came into force. In the newest Order (BEK no. 46 of 22/01/15) maximum emissions standards are given for stoves and small-scale boilers - for stoves the maximum emission standard is 5 g PM/kg. The standards correspond to the emission levels of modern wood stoves and boilers having a more efficient combustion technology by for instance using tertiary air. Since 2004 it has been possible for Danish wood stoves to obtain the Nordic certification mark the 'Swan'. The emission limit value for these stoves is 3 g PM/kg dry wood and the efficiency shall be above 76%. The certification may have enhanced the development of more energy efficient and low emission stoves.

2.2 Formation of pollutants

The combustion in a wood stove can be seen as a two-step process. The first step takes place within or near the wood logs and includes simultaneous heating, drying, pyrolysis, char oxidation and partial volatiles oxidation. Some volatiles are released from the primary log combustion zone and move further though the stove, and under ideal conditions those volatiles are oxidized to form CO_2 and water in the second step. Generally high CO concentration, volatile organic compounds (VOC) and PM emissions are observed when the volatiles in the second step are not completely converted. To ensure adequate oxidation of the volatiles, high temperatures, good mixing with sufficient amounts of air, and a reasonable residence time is needed in the second combustion step. Poor fuel conversion is indicated by high CO emissions and it has been shown that CO in some cases can be used as an indicator for high emissions of VOC and PM [4].

2 .3 Measurements of particles

Measured emission data can be quite uncertain since the particles emitted from a wood stove to a large extent are formed by condensation of hydrocarbons. Local conditions at which the particles are collected and measured may therefore have a large influence on the measuring results. A further cooling of the flue gas can increase the total mass of particles collected, while a dilution step will greatly influence the particle numbers. Removal of larger particle fractions may increase the number density of

smaller particles in the flue gas by homogeneous nucleation, due to removal of condensation nucleates [5].
Even though emission measurements from different studies are difficult to compare because of different firing procedures and measuring methods [6], the large spread in data indicate that the combustion conditions have a large influence on the emission formation process.

2.4 Wood stove technologies

The increased attention on pollutant emissions has influenced the design of wood stoves since the 1980s. Modern Nordic stoves are designed to minimize harmful emissions. The design features often include a three-step air injection (air staging) which ensures sufficient oxygen in the second step of the combustion process [7]. The three combustion air flows are called primary, secondary and tertiary air: 1) Primary combustion air is led directly through the ash grate in the bottom of the combustion chamber into the layer of gloving charcoal and burning wood logs; 2) Secondary combustion air is led through channels to the top of the stove and is entering into the combustion chamber through an opening at the top of the window; 3) Tertiary combustion air is entering the combustion chamber through an opening or through a row of separate holes in the back wall some distance above the grate. Other design features include air channels for air preheating, mounting of internal insulation boards that ensure fast heating of the stove, and plates (baffles) that facilitate sufficient mixing and residence time in the second-step combustion zone.

Advice on how to design low-emission stoves has been given by, among others [8], and compared to older wood stoves modern stoves are designed to minimize carbonaceous particulate emissions. Still, the improvement of stove designs to minimize particulate emissions has mainly been done on an empirical basis by stove manufactures. Even well-designed and well-constructed stoves cause occasionally high emissions of unburned matter and particulates due to improper firing habits [9].
Most modern stoves are designed without automatic control of the combustion process and therefore have potentially high emissions.

3. HWAM wood stoves – development of the prototype

This chapter describes the work in the first part of the project including evaluation of measurements carried out at HWAM before the start of this project.

In 2009 HWAM started a project with the aim of developing an advanced digital controlled wood stove. HWAM had for some years worked on the idea to optimize the combustion process in a woodstove by means of a digital control system where the process parameters are measured oxygen concentration and temperature in the flue gas.

The development work has included combustion experiments in different types of stove equipped with measuring facilities to measure relevant parameters during the combustions. The results of the experiments showed how different controlling modes of the combustion air inlets influenced the combustion process and thereby the combustion temperature, emissions, and efficiency. From this knowledge fundamental algorithms to control the combustion air supply were developed.

Figure 3.1. Example of a test wood-stove at HWAM

The test set-up included a wood stove placed on a scale for measuring the weight change during wood log conversion, an analyzer for measuring the concentrations of O_2, CO, and CO_2, and facilities for measuring temperatures and flows. As part of the process regulation a λ-probe for measuring O_2, and a thermocouple (T10, Figure 4.1) for measuring the temperature in the flue gas were placed just above the stove in the chimney. A prototype of an airbox for controlling the three combustion air flows was placed below the combustion chamber.

Furthermore, thermocouples were placed in the combustion chamber to follow the temperatures in various combustion zones. All signals were logged on a PC. Standard procedures for the test combustions were developed to achieve the same conditions from time to time.

Control of the air supply

The three air inlets were controlled by a software program based on the definition of five combustion phases and the process parameters: measured temperature (T10) and O_2 in the flue gas. Definition of the combustion phases for a combustion cycle (a charge) is: 0. Start-up of a cold chamber, 1. Ignition of the wood log, 2. Combustion of volatiles, 3. Combustion of char, and 4. Burn out and cooling of the chamber.

Results

Before start of this project development activities had already taken place and were used for the iterative process of developing the algorithms and the air inlet valves. One of the observations from the experiments carried out at HWAM was that the CO concentration increased at the end of a combustion cycle where the char burns out and the temperature starts to decrease. The experimental data was analyzed to improve the knowledge about the relation between the temperatures in the chamber and in the chimney and it was considered how to decrease the emissions by changing the temperature-process-parameter and temperature set-point.

The control system was initially developed to regulate the combustion air based on T10 (placed in the first part of the chimney) but it was considered if a better regulation could be achieved by using the temperature measurement in the top at the combustion chamber (T8) as the process parameter.

The CO concentration was plotted as function of T8 and T10 and the relation between the CO concentration and the temperature was mapped for phase 2 and 3 for charge 1, 2, and 3. Also theoretical calculations were conducted to estimate the influence of temperature, residence time and H_2O connections on the CO concentration (Internal document 1).

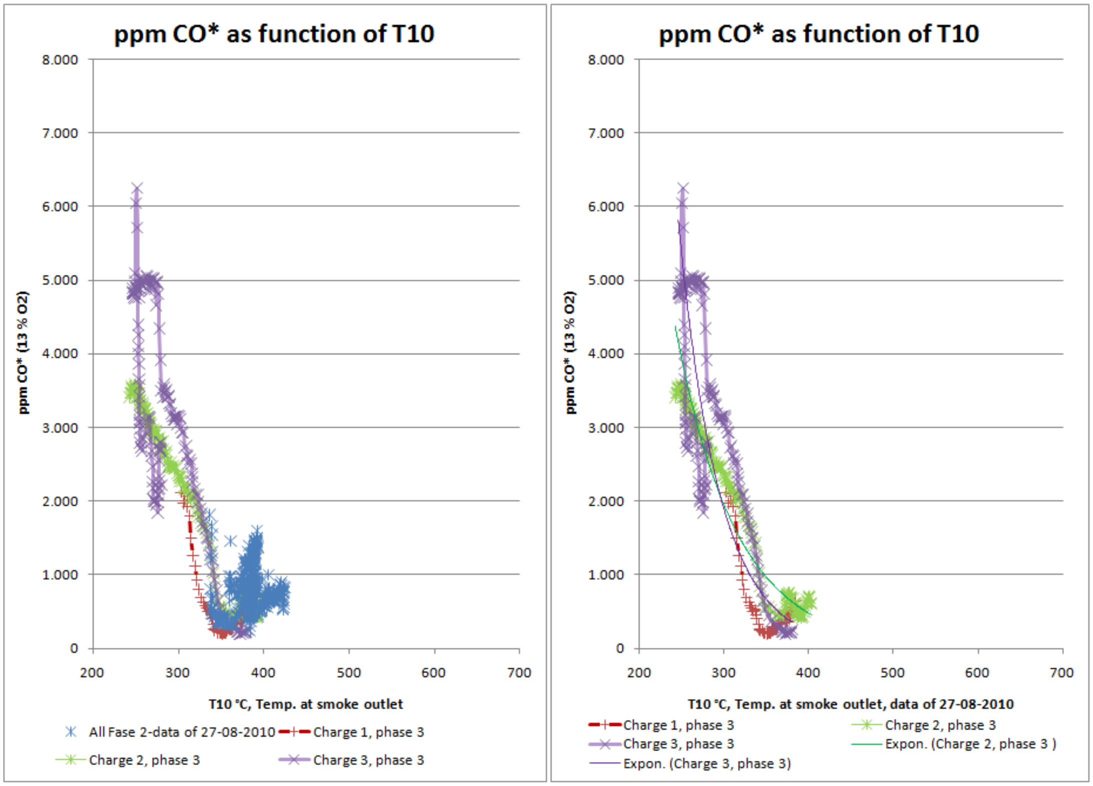


Figure 3.2. CO concentration as a function of the temperature in the chimney (T10)

Figure 3.2 shows the graphs for T10 and it is seen that very low CO concentration are obtained if T10 is above 350 ^{0}C. Furthermore it is seen that the CO concentrations increases with increasing number of charges. It is explained by an increasing temperature in the fireplace and thereby a lager formation of CO which a not able to be oxidized in the freeboard at the given temperatures and residence times.

The evaluation of the measurements at HWAM and the model calculations showed that an effective and complete reaction between the oxygen in the tertiary air and the fuel in the gases above the wood logs depends on the temperature in this part of the burning chamber. If the temperature is too low it will prevent ignition and/or complete combustion of the fuel/air-mixture resulting in emission and unburned gasses and particles. As the tertiary air is not preheated significantly before entering the burning chamber it can actually cool the flames and fuel gasses to a mixture temperature which is too low to ensure complete combustion.

From these analyses it was concluded that to obtain a complete combustion in the wood stove and high efficiency there are two essential conditions in the combustion chamber that have to be met:

1. The amount of combustion air has to be in the right level. Experiments show that the excess air number (λ) should be of around 1.8 – 2.2.
2. The temperature in the combustion chamber has to be above a certain level. The experience showed that this level should be around 450 °C in the top of the burning chamber (T8) and about 350 °C in chimney (T10).

4. The wood stove experimental set-up at DTU KT – Phase one

An experimental set-up was built at DTU Chemical Engineering to investigate combustion processes and emission formation in a wood stove and to support the development of the automatically controlled stove. In this chapter the first version of the set-up is described together with the results obtained.

4.1 Wood stove used for the tests

Test stove

The research wood stove set-up consisted of a modern wood stove with process control and analyzers to measure the process parameter, and relevant gas and particle concentrations in the flue gas. It was decided to use a modern Swan-marked (approved) wood stove for the test setup and a Hwam 3640 model was selected. The stove has a nominal heat output of 6 kW (Internal document 2).

The test stove was a special built version with automatic controlled supply of the three combustion air flows. Furthermore, the stove was modified by incorporating a number of temperature measuring points (thermo-couples) in the burning chamber placed as indicated on figure 4.1.

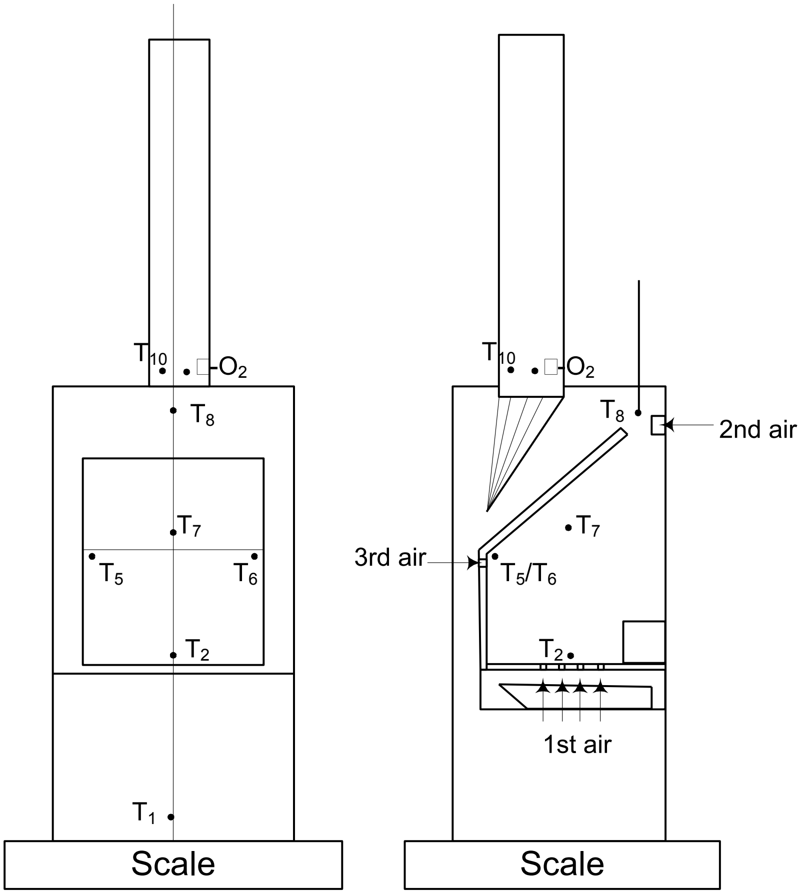


Figure 4.1: Illustration of a test stove with indication of the positions of thermo-couples and lambda probe for measurements of process parameters and temperatures in the combustion chamber.

The burning chamber

The 3640 model is a modern wood stove where combustion air is introduced into the burning chamber through 3 separate channels as illustrated in Figure 2.2:

The three combustion air flows are called primary, secondary and tertiary air:
Primary combustion air is led directly through the ash grate in the bottom of the combustion chamber into the layer of gloving charcoal and / or burning wood logs. The degree of preheating of the primary air is very low before entering the burning chamber.
The primary combustion air is especially effective for heating of new wood to catch fire and to establish a good burning at high temperatures when you put new wood into the stove on a good layer of glowing charcoal.

Secondary combustion air is led through channels to the top of the stove and is entering into the combustion chamber through a wide narrow opening at the top of window in order to have clean air sweeping the glass to keep it clean. The secondary air will be indirectly preheated on its way in channels to the top of the stove. The degree of preheating may be an important parameter for correct functioning of the stove.
The secondary air enters the burning zone partly in the lower zone with glowing charcoal and burning wood logs and partly in the upper zone with burning flames just above the wood logs.

Tertiary combustion air is entering into the combustion chamber through a wide narrow opening or through a row of separate holes in the back wall some distance (around 20 cm) from the bottom. The purpose of the tertiary air is to supply oxygen to the flames above the wood logs to ensure a complete combustion of the volatiles from the wood logs before the flue gasses leaves the combustion chamber. Thereby the tertiary air will not enhance the combustion of glowing charcoal – only combustion of volatiles. The software part consists of the Burn Control Algorithms which is based on the definition of five combustion phases as described in chapter 3.

Digital control system

The tested stoves were equipped with a prototype of the digital control system developed by Hwam. The system regulates the three combustion air flows to the stove combustion chamber. The signals that are used for regulation are: Oxygen in the flue gas (measured by a lambda probe), the temperature in the exit of the flue gas (measured by a thermocouple, T10), and the room temperature. These signals are called the process parameters in the following sections.

The system consists of an air box, a lambda sensor, thermocouples, and a control box containing the software part. The air box is placed below the combustion chamber and regulates the three air flows to the chamber by means of three motor controlled valves. The lamda sensor and T10 measure the oxygen content and temperature in the flue gas. For the tests in DTU pilot hall the room temperature was not used as a process parameter.

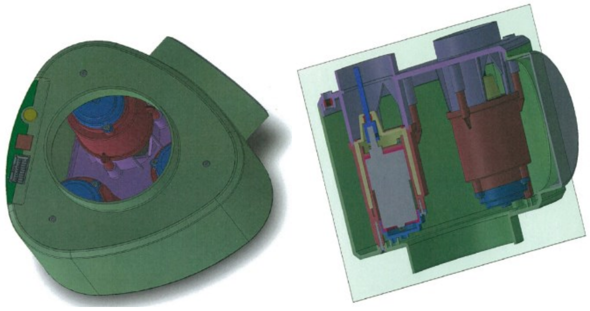


Figure 4.2. Illustration of the air box.

The software part consists of the Burn Control Algorithms which is based on the definition of five combustion phases as described in Chapter 3.

The aim of the first tests at the new wood stove set-up at DTU was to develop procedures for firing and measurements, and to determine the reproducibility of the measured gas concentrations and other measured parameters. Also the performance of the control system was to be tested for a new type of wood stove and the choice between a T8 or T10 based control system was evaluated to supplement the HWAM analysis.

4.2 Preliminary experiments and results

The test procedures concerning pressure drop, wood log sizes and water content, and reloading of wood logs were defined. The stove was reloaded three times as day in order to compare combustions cycles conducted the same day. The experimental conditions were close to what is used at test institutes where wood stoves are approved.

About 50 combustion experiments were performed. A detailed description of the measurements and the results are given in Internal document 2. In the first test period, a number of mechanical and software problems were observed related to the control system.

These first tests at DTU of the automatically controlled stove showed overall a god control of the three combustion air flows resulting in constant concentrations of CO and temperature in the flue gas. Also, the process parameters, O_2 (lambda) and T10 were close to the set-points and in a constant level throughout most of phase two and first part of phase three. The lower temperature and higher O_2 concentration in the last part of phase three are due to the low fuel load in the combustion chamber during char combustion burn out.

A typical combustion cycle is illustrated in figure 4.3.

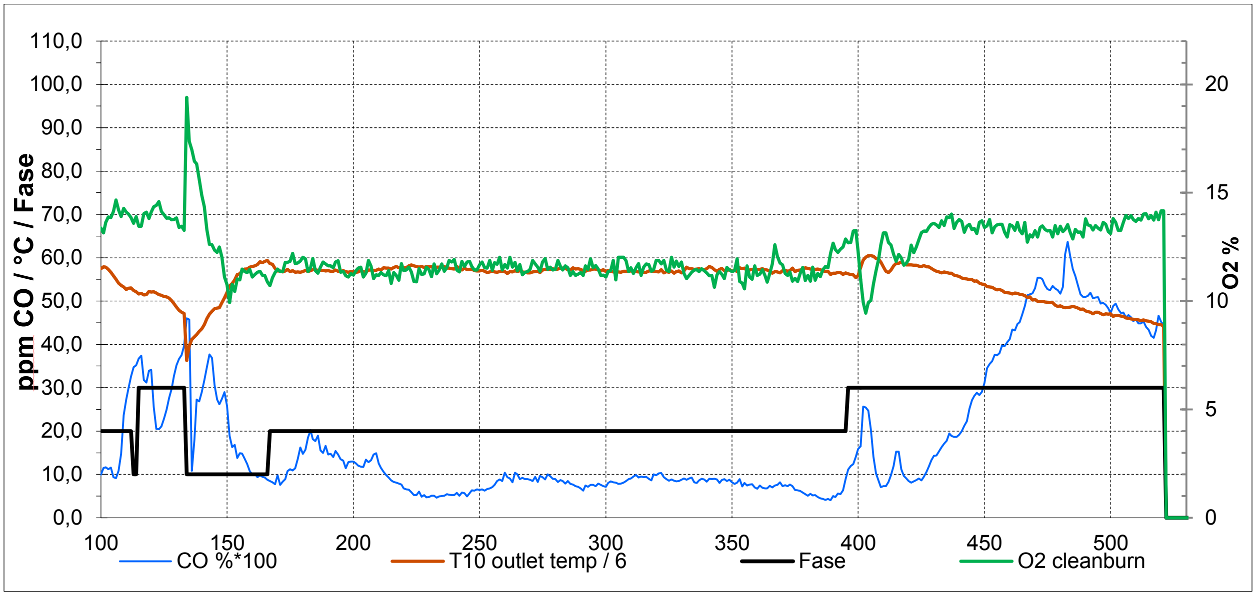


Figure 4.3. An example of a combustion cycle for a prototype of the automatically controlled stove.

After a short ignition period the temperature and the O_2 concentration stabilize to the constant and optimal set point values. The values are constant for most of the combustion cycle. When the temperature starts to drop during the char burn-out phase the CO concentration increases at the very end of the combustion cycle. The length of the char combustion phase is of high importance for the calculated average CO-concentration – a long char combustion time would increases the average CO concentration.

These initial tests contributed to improvement of the control system regarding: 1) Optimization of the parameters in the control unit to avoid large fluctuations in phase two, 2) Optimization of the ratio between the flow rate of secondary and tertiary air in phase two, 3) Demonstration of a more stable combustion was achieved when using T10 instead of T8.

Particle emissions

The experiments showed a wide variation in the measure particle emissions due to various problems with the control system and the PM collection system. However, when the control system worked well the particle emission level were close to test results of about 18 m3/Nm3 achieved during tests at the Technological Institute. The PM were collected separately for the three phases and a significant difference in PM appearance were seen for phase 2 and 3. In phase two the collected particles were black (soot and condensable char) while in phase 3 the limited mass of particles were almost white.

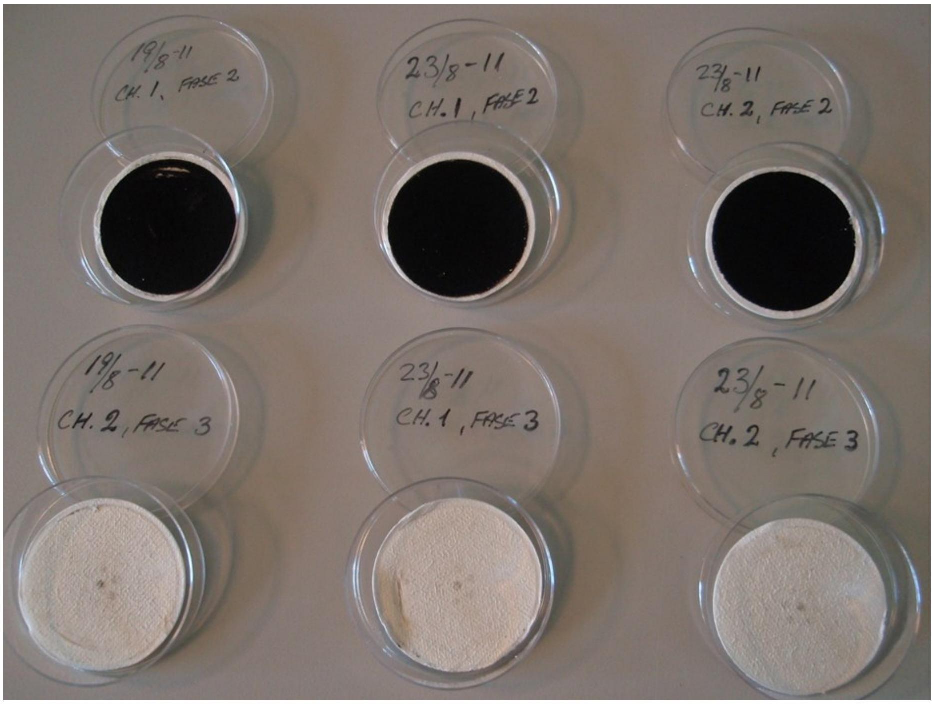


Figure 4.4. Particles collected on filters for combustion phase 2 (top) and phase 3 (bottom).

The tests also showed that at bad firing condition – meaning a high concentration of PM – the condensable particles were partly condensed in the tube connecting the chimney and the particle collection filter. It was therefore decided to reconstruct the particle collection system and built an dilution tunnel based on the Norwegian standard (see chapter 6).

Based on the observation and results of this first test period at DTU and HWAM the control system was updated before it was tested in private wood stove houses (see chapter 5 Field tests).

5. Field tests

Before introducing this new control system to the market, it was decided to test the prototype of the control system in field tests on a number of wood stoves operated by ordinary wood stove owners and thereby test the influence of private stove users practices on emissions and energy efficiency.

5.1 Objectives

The objectives of the field tests were:

- To evaluate to which extent the prototype IHS-control system was capable of controlling the combustion process sufficiently optimal under the different conditions found or selected for these tests.
- To obtain specific experience on the conditions and situations where the control software can be improved towards the aim of maintaining a clean efficient combustion throughout the firing cycle in the wood stove.
- To get subjective feed-back from different stove operators about performance and functionality in everyday use under different installation conditions
- To evaluate to which extent lab test results on efficiency and CO-emission are comparable to similar measurements obtained during field tests.
- To evaluate to which extent the Thermostat function integrated in the IHS-control is actually able to maintain the preferred rum temperature.

5. 2 Stoves and test sites

All together six new IHS-controlled stoves from Hwam A/S was used for the field tests – one for each test site. Three different stove models were selected; model 3120, model 3640 and model 3630 (Figure 1 and 2). The main difference between the models was the size. Model 3120 is the smaller in size with a nominal heat output of 4.5 kW while models 3630 and 3640 have a nominal heat output of 6 kW. The only difference between the two latter is that model 3640 is without side glasses. For the laboratory test at DTU model 3640 is used.

The five of the test sites were selected among a population and the selection of the sites was based on various installation specifications including room size, needed heat effect, chimney type and height. The sixth test site (the reference site) belonged to one of the project participant from DTU.

Detailed information on the five selected test sites is given in Internal document 3.

5.3 Procedures

At each test site continuous measurements of O_2, CO_2, CO and flue gas temperatures were conducted with both the existing stove and the new HWAM IHS stove Figure 5.1). For the same wood stove users the measuring period for each stove was one week. All the tested IHS wood stove models were equipped with a prototype of the automatic control system.

The person handling the firing on the test site was instructed to use the stoves as usually – that means using the same kind of wood and firing in the same way. Furthermore the stove user was asked to use uniform wood types like hardwood or softwood, weight the wood before each firing period, and to note the weight and time in a log book.

The measurements were conducted in February and March 2012.

Figure 5.1 Illustration of a test set-up in a private household.

Data treatment:

A correction of the CO concentration to 13% O_2 was calculated to eliminate the influence of varying dilution degrees of the flue gas.

$$\mathrm{CO}\ (13\ \%\ \mathrm{O}_2) = \mathrm{CO} \cdot \frac{21\text{-}13}{21\text{-}\mathrm{O}_2}$$

The combustion efficiency was calculated based on the flue gas heat loss (Q_a), partially converted species (only CO, Q_b), and un-combusted residuals in the ash (0,5 assumed).

$$\eta = 100 - \left(100 \cdot \left(\frac{Q_a}{H_u}\right) + 100 \cdot \left(\frac{Q_b}{H_u}\right) + 0.5\right)$$

5.4 Results

For all test sites an improved efficiency was obtained when using the IHS-stove, also lower CO emissions were measured for most of the sites.

Test site 3.1
The characteristic for this site was that a chimney fan was used resulting in a very high chimney draft and thereby high excess air for both the existing stove and the IHS stove. The control system is optimized for 12 Pa and the control system could not compensate for the high draft in this chimney. Therefor only a small improvement in the efficiency was seen for this site.

Test site 3.2
Both efficiency and CO emissions were significantly improved for this site when using the IHS stove. The only problem the user registered was increased soot formation and blackened on the stove front window when using Baltic pine wood – the problem did not occur when beech wood was used.

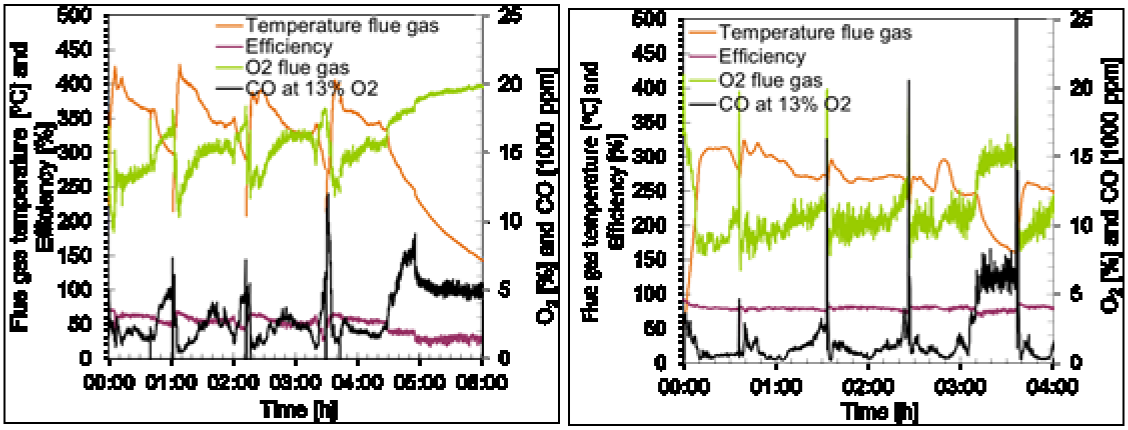
Test site 3.3
This user fired generally with used wood with a high content of water (18-25 %) resulting in delayed ignition or failed and consequently very high emissions of smoke and CO was seen. The higher CO emission from the IHS stove was due to very wet wood logs used in the period where the IHS stove was applied. However, the efficiency was improved from 62 to 75 %.

Test site 3.4
No special or untypical observations were found for this site. This user was good at firing and achieved a good combustion for the existing stove and the results from this site can be considers to be the most applicable for comparing a manually controlled stove and the IHS stove. The efficiency for this site increased from 71 to 79 % and the CO emission was reduced by around 40%.

Test site 3.5
This use had a very bad firing practice. To little combustion air was introduced in combustion phase one and two resulting in bad combustion and high emissions of smoke and CO. Also for the new stove the bad firing practice was carried on. Typically the front door was open and a small amount of wet wood was used. However, a significant improvement of the efficiency was observed and the CO emission was reduced.

Reference site
This user had focus on obtaining a clean burning. The measurements showed that both the temperature and O2 concentration was high in the combustion chamber. This site is an example of a firing practice where a too high excess air is used during the entire combustion cycle. That means the efficiency was very low for the manually controlled stove – and increased from around 60 % to 80 % when the user changed to an IHS stove.

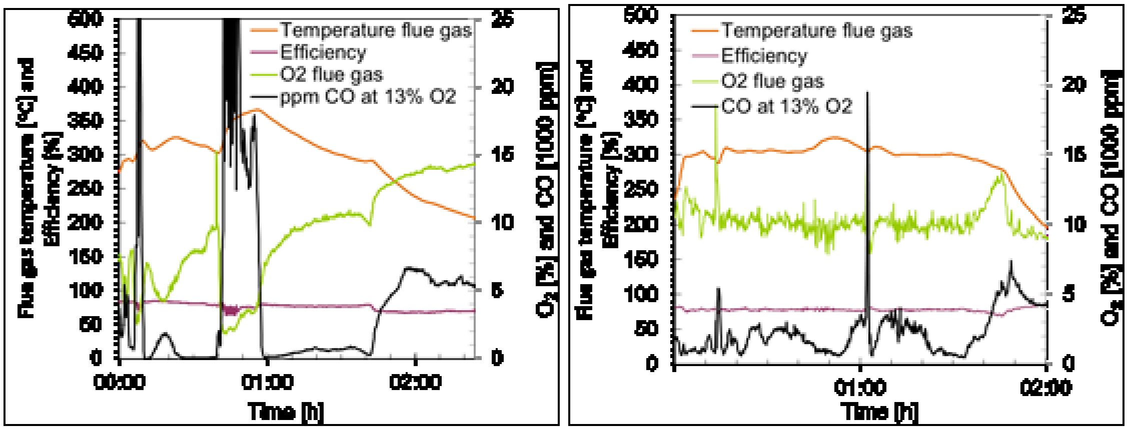
Figure 5.2 and 5.3 show measured gas concentrations and temperatures for the reference site and test site 3.4 illustrating two situations: 1) Too high excess air during the entire combustion cycle and 2) too little air during the flame phase and too much air during the char combustion phase.



a) b)

Figure 5.2. Reference site: Field test measurement conducted with a privately operated wood stove with the user applying a manually controlled stove a) and an automatic IHS stove b) (four combustion cycles).

By using the automatic control of the combustion air, almost constant temperatures and O_2 concentrations were obtained. The O_2 concentrations varied from 9% to 12% and the temperature from 230°C to 290°C during the flame phase. Because of the low heat output of the remaining char in cycle 4, the temperature gradually drops and the CO concentration starts to increase at the end of the char combustion phase. The tests conducted at this site showed that the efficiency increased from about 60% to 80% and the CO concentration was reduced by approx. 50% when the wood stove user switched from a modern manually controlled stove to an automatic IHS stove.



a) b)

Figure 5.3. Test site 3.4. Field test measurement conducted with a privately operated wood stove with the user applying a manually controlled stove a) and an automatic IHS stove b) (two combustion cycles).

When the same user applied an automatic IHS controlled stove (Figure 5.3), very constant flue gas temperatures, O_2 and CO concentrations were obtained. Especially in the flame combustion phase, a significant reduction of the CO concentration was seen.

5.5 Conclusions

These field tests clearly showed that other parameters than the design of the wood stove influences the combustion process and thereby the efficiency and the emission of harmful. In prioritized order the most important factors are: 1) the firing practice, 2) the water content in the wood logs, 3) the chimney draft and 4) the wood type. The resulted shows that in most cases the IHS controlled stove is able to improve the efficiency and reduces the CO-emissions compared to the manually controlled stove by eliminating bad firing practice. Furthermore the tests indicated that there the control system could be further improved and optimized in order to better handle different wood stove types and high chimney drafts.

6. The wood stove experimental set-up at DTU KT – Phase two

After the first laboratory tests at DTU and HWAM and the field tests, a first version of the commercial control system was launched on the market in 2012. For further investigation of the control system and the formation of air pollutants especially PM emissions, a second phase of experiments were conducted at DTU Chemical Engineering using the commercial control system.

6.1 Modification of the set-up

In order to avoid condensation and deposition of particles in the sampling system and thereby to obtain more reliable and standardized PM emission measurements the experimental set-up at DTU was modified and added a dilution tunnel (based on the Norwegian Standard) and two PM collection filters in parallel, see Figure 6.1.

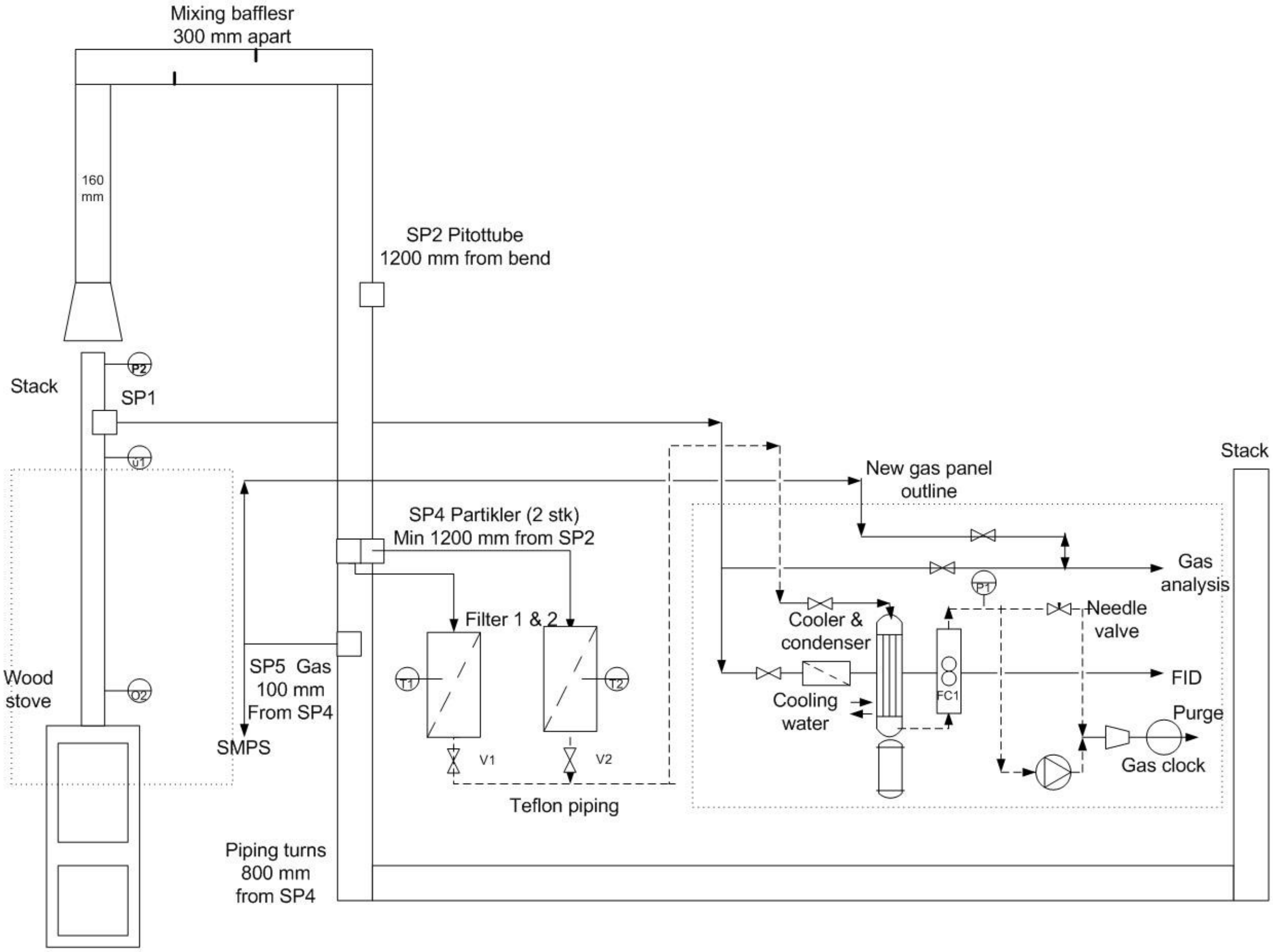


Figure 6.1 PI diagram of the research wood stove experimental set-up at DTU Chemical Engineering. The set-up includes: woodstove, stack, dilution tunnel, sampling sites, filters for particulate collection and panel for gaseous analysis.

For collecting and measuring the PM concentration and composition the following methods was used: 1) The Scanning mobility particle size analyzer (SMPS) for counting the particle number concentration (by light scattering) and their size (based on their electrical mobility), 2) Filter collection performed on the diluted flue gas for measuring particle mass, 3) PM Composition analysis of the fine particles collected in the filters. A two-step thermo gravimetric procedure was applied to determine the fraction of condensable organic carbon and elemental carbon/soot (see more details in Internal document 4)

6.2 Experimental plan and procedures

The aim of the experiments was to study the PM emissions for different combustion charges and phases and to investigate if further improvement could be made to the control system or the combustion chamber. The experiments were carried out between March 2013 and November 2013 at 8 different days and with 1 to 5 charges a day. In the first part of the experimental period the experiments were carried out at standard conditions and in the last part various modification of the combustion air inlets were tested.

The experiments have been conducted in a HWAM wood stove (3420) with the IHS control system using the set-up shown in figure 6.1. A number of manuals and notes were prepared to advise how to perform the experiments to ensure standardized experiments and reproducible results (Internal documents 5-10).

6.3 PM emissions

The results from the measurement of collected PM on filters generally show low PM concentrations. The range was typically between 1.8 g/kg wood and 0.6 g/kg wood with a decreasing emission trend for an increasing charge number.

The charge average particulate emission from the 16 performed experiments, showed no significant difference for charge 1 to 3, while the single charge 4 yielded a very low particulate emission. The highest emissions measured in an individual experiment took place in charge 1 (2.2 g/kg_{dry}) and 2 (2.3 g/kg_{dry} and 3.0 g/kg_{dry}).

- Charge 1: 1.8 ± 0.2 g / kg_{dry}
- Charge 2: 1.8 ± 0.8 g / kg_{dry}
- Charge 3: 1.4 ± 0.4 g / kg_{dry}
- Charge 4: 0.5 g / kg_{dry}

The standard deviations associated with the average particulate emissions, may be caused by both experimental uncertainties and the measuring procedure (a very low particulate mass is collected). The observed PM levels correspond well with the NS 3059 test performed at the Danish Technological Institute in September/October 2008 for a 3410 without IHS (2.05 g/kg_{dry}) and are well below the requirements in both current legislation (10 g/kg_{dry}) and the Nordic Eco label, the Swan label (4 g/kg_{dry}).

When comparing the PM concentration determined by filter collection and the one calculated based on a particle number measurement, the latter are generally higher (despite the fact that particles above 660 nm are not included) but follow a similar trend with respect to which charges are higher in PM emissions than others.

In figure 5 an image of PM filters for four charges is shown. For the first charge the filters are black for both the first collection and for the second collection period indicating some soot formation in both the ignition phase and the flame phase. For the following charges the filters look much lighter for the first part of the combustion period, and for charge four the filter is brown for the whole combustion cycle. The PM composition analyses also support this observation – during the ignition phase mainly condensed organic compounds (COC) are formed while during the flame phase a mixture of COC and soot is formed. In the char combustion phase very small amount of PM was detected. The SMPS particle trends in figure 4 also support these results.

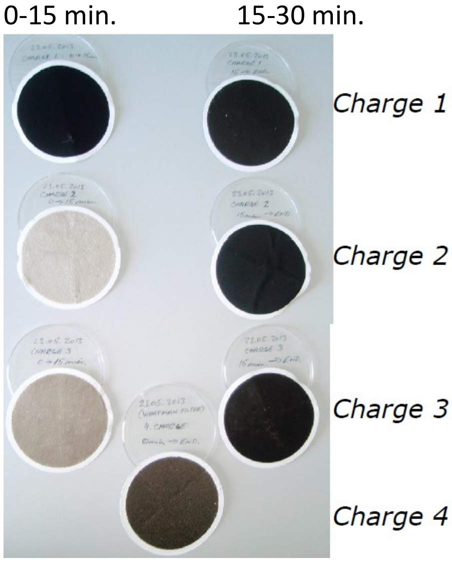


Figure 6.2. Examples of particle filters where particles are collected in different charges for the first 15 minutes and the following 15 minutes.

6.4. Emission trends

Figure 6.3 illustrates typically emission trends for different combustion charges and phases.
The highest fine particle emission was observed for the first charge when starting up a cold stove. For the subsequent charges only relatively small increases of the emissions and much lower PM levels were seen in the ignition phase and also, the ignition phases are relatively short especially for the second and third charges. During the flame combustion phase, low and constant emissions of CO, VOC and fine particles are observed. However, the emissions tend to be a little higher and more unstable in the first charge. A small fine particle peak occurs in the flame combustion phase for most of the charges.

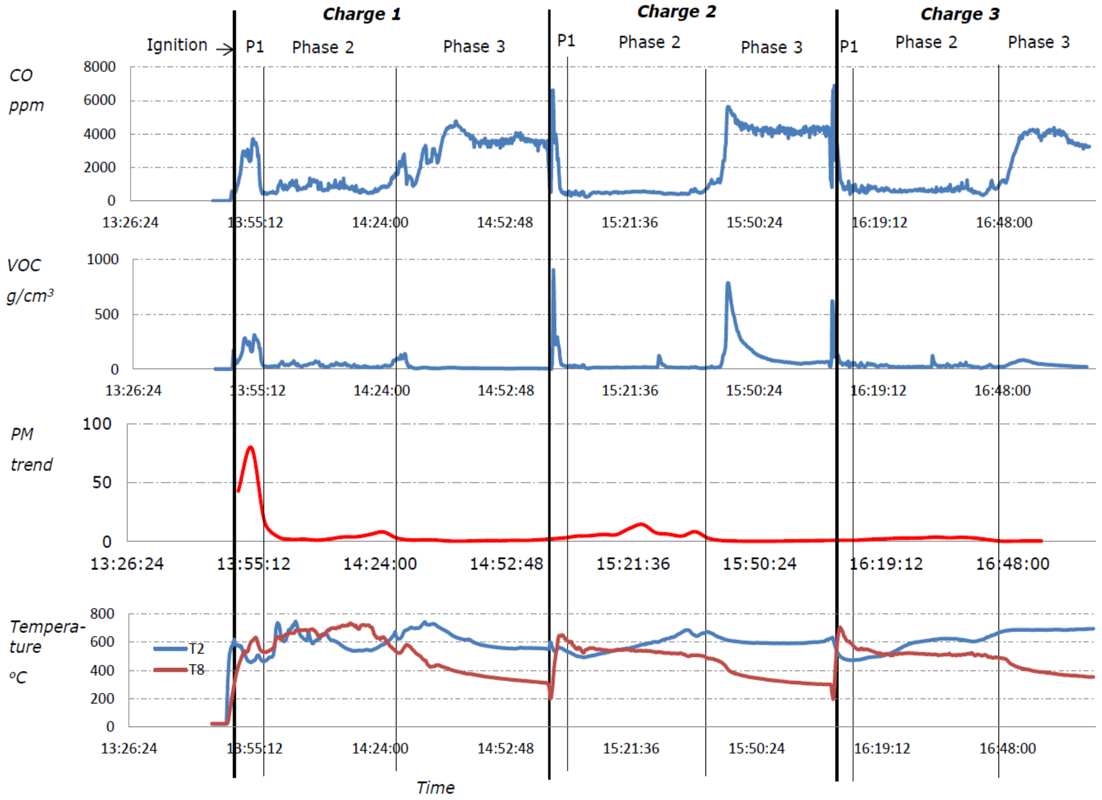


Figure 6.3. Emission and temperature trends for three charges illustrating the levels in the various combustion phases (P1: ignition phase, Phase 2: flame phase, Phase 3 char phase). T2: Temperature in the fire just above the grate, T8: Temperature in upper part of the free board.

Soot/elemental carbon formation takes place at elevated temperatures and oxygen lean conditions – the overall oxygen is generally above 9 % in the experiments, but insufficient mixing may cause local oxygen depleted zones and thereby soot formation.

Different approaches to control/target this late PM formation and thereby reduce the overall PM emission levels were investigated by modification of the introduction of primary, secondary and tertiary air. The largest influence was seen for reduced maximal primary air flow in phase 3 (and thereby increased secondary and tertiary air flows) where the PM emissions were reduced in all charges (1-3). Especially the emission of condensable hydrocarbons is reduced in these charges, indicating a better mixing and conversion above the fuel bed (Internal documents 11 and 12).

In Chapter 7 the results of the influence of the chimney draft, modification of the tertiary air inlets and the type of grate are descripted.

7. Further optimization of the combustion process

The IHS control system helps the wood stove to operate at optimized condition. However, the operating and design parameters, such as the chimney draft, the tertiary air injection mode, and the grate type, may affect the conditions during operation of the stove. In order to understand the influence of these parameters on the stove performance, series of experiments were carried out by varying the chimney draft, the tertiary air injection mode, and the grate type.

7.1 Influence of draft, combustion air and grate

Chimney draft

The chimney draft can be controlled by adjusting the distance between the top of chimney and hood of the dilution tunnel and the valve in the dilution tunnel simultaneously.

Three chimney drafts were tested: normal draft (around 12 Pa), low draft (around 5 Pa) and high draft (around 27 Pa). Testing for each draft was duplicated. In addition, the influence of the chimney draft on the air flow for the valves controlling the primary, secondary, and tertiary air was studied in a cold state (Internal document 13).

Tertiary air injection

In the original design, the tertiary air is introduced from the gap on the top of the backboard in the combustion chamber.

Four injection modes are realized by drilling holes in the back wall of the combustion chamber, as illustrated in Figure 7.1

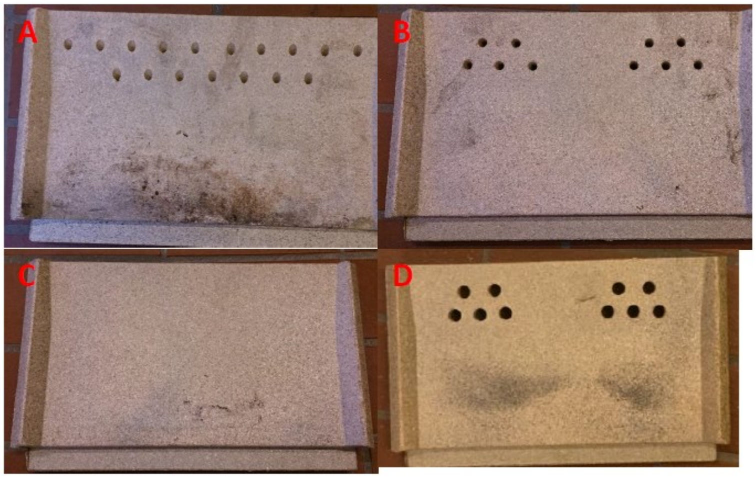


Figure 7.1 Illustration of four modes of tertiary injection.

In the mode C, the tertiary air is introduced from the top of the back wall as shown in figure 7.1. In the modes A, B and D, the tertiary air is partly introduced in the top and partly introduced from the holes in the lower part of the back wall. In this way, the locations of the tertiary air injection and the velocity of the tertiary air stream were varied, resulting in a change of flow pattern in the combustion chamber. It should be mentioned that the total injection area of the tertiary air injection will increase since the area in the top part keeps the same.

Type of grates

Three types of grates were tested: a blank grate, a plate without holes on the blank grate and a plate with holes on the blank grate. The two plates are shown in figure 7.2.

Figure 7.2 Illustration of the plates with and without holes.

For the blank grate, the primary air is in contact with the wood logs and char directly. For the plate with holes, the direct contact is smaller. For the plate without holes, the direct contact is very limited.

7.2 Results

Influence of chimney draft

In general the IHS control system was adapting well to different chimney drafts and was working at both high and low drafts. However, the combustion process was not as optimal as at the standard chimney draft (around 12 Pa). For the low draft a longer ignition time was observed for the first charge resulting in higher VOC emissions. For the high draft different combustion pattern occurred. For some of the experiments a very long ignition time was seen and a lot of smoke was formed; in general it seemed more difficult to obtain a stable combustion with the high chimney draft.

The test results showed that the draft has a large influence on the thermal efficiency(Table 7.1).

Table 7.1 The effect of the draft on the thermal efficiency

Draft (Pa)	Average efficiency (%)
6.3	78.6
12.8	76.9
27.2	69.1

The efficiency decrease significantly when high drafts were applied. The trend is caused by the fact that the amount of air increases when the draft increases due to the higher pressure difference between the atmosphere and the combustion chamber, which is verified by the cold tests of the relationship between the draft and flow rate through the controlling valves shown in Figure 7.3. The high flow of air results in a larger volume of flue gas and a higher energy loss from flue gas. This is confirmed by that fact that the average oxygen concentration is higher for the high draft than the case of low draft.

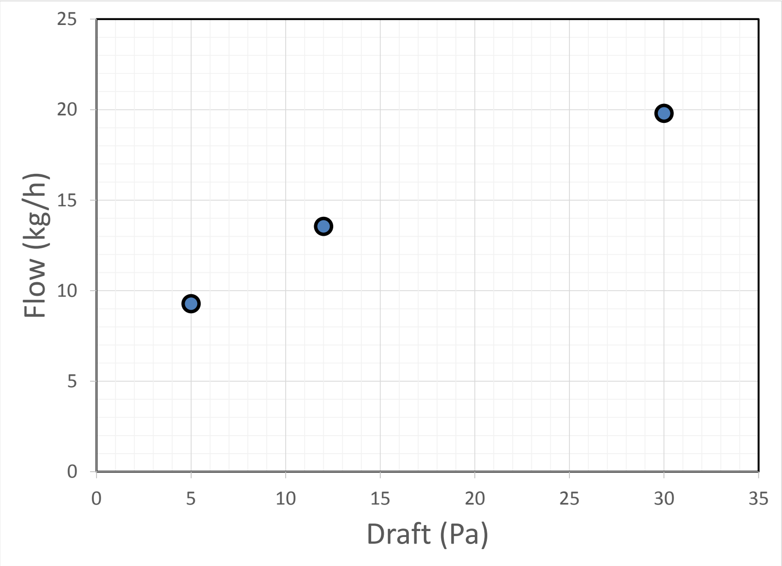


Figure 7.3 The example of the influence of the draft on the air flow of the valve when fully open (Internal document 13).

Furthermore, the influence of the draft when stating-up the stove was investigated by applying either a constant draft or a natural draft form the beginning of the firste charge. The measurements showed faster ignitions, lower CO-concentrations, and higher chamber temperature for the first cycle when applying a constant draft (12 Pa) form the beginning. For the natural draft a higher emissions of condensable organic compound was seen in the ignition phase for the first charge (Internal document 14).

Influence of tertiary air injection mode

The results show that the fine particle (PM) emissions are affected by the tertiary air injection mode. The PM emissions and their compositions (soot and condensable organic compounds (COC)) in the four tertiary air injection modes are summarized in Table 7.2

Table 7.2 The influence of the tertiary air injection mode on PM emissions

Mode	(g/kg fuel,dry)	Phase 1	Phase 2	Phase 3	Phase 4	Average	Standard Dev.
A	COC	1.44	0.60	0.47	0.07	0.65	0.57
	Soot	1.70	1.92	1.01	2.15	1.70	0.49
	Total PM	3.14	2.52	1.48	2.23	2.34	0.69
B	COC	2.06	N/A	0.29	0.31	0.89	1.02
	Soot	1.34	N/A	0.12	0.22	0.56	0.68
	Total PM	3.40	N/A	0.41	0.53	1.45	1.69
C	COC	0.39	0.41	0.13	0.33	0.32	0.13
	Soot	1.08	1.53	1.63	1.21	1.36	0.26
	Total PM	1.47	1.94	1.76	1.54	1.68	0.21
D	COC	0.33	0.37	0.18	1.65	0.63	0.68
	Soot	1.07	1.39	0.45	1.36	1.07	0.44
	Total PM	1.40	1.76	0.63	3.01	1.70	0.99

The results indicate that mode B has the lowest average total PM emissions of all modes. However, the standard deviation of the total PM emissions is the highest in this mode. For mode C, the standard deviation is the lowest though the average value is slightly higher than mode B. It seems that the gas velocity of the tertiary air injection points has a large influence on the PM emissions of the wood stove. The higher the gas velocity is, the lower PM emissions are. The high gas velocity of the tertiary air stream results in a high turbulence in the combustion chamber and better combustion in the freeboard. The good combustion reduces the formation of soot and the organic volatile compounds, i.e. condensable particles.

The influence of the modes of tertiary air injection on the efficiency and CO emissions appears insignificant. However, it should be emphasized that the modification of tertiary air inject is only with a limited change of position and inlet gas velocity. More work is needed for optimizing the tertiary air injection.

Influence of grate type

It was observed that the influence of the type of grates is only significant in the char combustion stage. The direct contact of char with air will keep the char combustion rate and the temperature on the grate high as long as the primary air is open for the case of blank grate. In the late stage of char combustion, the primary air is closed, there is no significant deference for different types of grates.

7.3 Conclusions

The chimney draft has a significant effect on the thermal efficiency of the wood stove, due to the influence of the draft to the air flow. It is desirable to have a stable draft at a standard condition, i.e. 12 Pa. The type of grates in the wood stove has only insignificant effect on the performance of the wood stove. Modification of the mode of tertiary air injection may be an effective way to improve the combustion in the chamber and to reduce emission of CO and PM based on the results with limited range of modification. Further work is needed for optimizing the tertiary air injection.

8. Conclusion and future work

A first version of an automatically controlled wood stove, HWAM IHS, was developed and launched on the market in 2012. The automatic control system developed for wood stoves ensures optimal combustion conditions, thereby minimizing the emissions throughout a complete wood log combustion cycle. This improved performance has been verified by field tests in private homes where measurements showed significant reduced emissions and higher efficiency for the IHS stoves compared to manually controlled stoves. The tests also showed that in many cases it is impossible to tell by watching the wood stove fire if non-optimal combustion occurs. Also, in practice it is impossible to manually control the combustion air as fast and optimally as the automatically controlled air inlet valves.

Emission measurements at the research wood stove set-up at DTU Chemical Engineering showed generally low emissions of particles. The highest emissions of CO, VOC and PM were seen in the ignition while only a small particle peak was observed in the flame phase. The CO emission in the char combustion phase increased due to decreasing temperature in freeboard – but almost no particle emissions were seen this combustion phase.
For the further optimization of the state of art technology of the IHS stoves developed in this project, the improvement of the tertiary air injection has considerable potential, which may result in an improved combustion and reduced pollutant emissions.

Some important areas of future work include further development of control system sensors and measuring methods, and optimisation of the combustion process and chamber.

9. List of project activities

9.1 Internal documents:

1. CO-oxidation
2. The wood stove experimental set-up at DTU KT – phase 1 2011-2013
3. Field test rapport 2013
4. IHS-PM report - Woodstove particulate emissions 2013
5. Procedure for experiments of the wood stove 2014
6. Checking list of HIS wood stove 2013
7. Methods to estimate dilution factor, 2014
8. Calculation of the parameters in a batch combustor for solid fuels 2014
9. Sheet for PM measurements 2014
10. Sheet for Impactor measurements 2014
11. Testresultater fra brændeovnsforsøg med fortyndingskanal 2013
12. Particle measurements in phase 3 2013
13. Wood Stove - Initial Cold Experiments, 2015
14. Wood Stove - Heated Experiments, 2015

9.2 Presentations:

- Brændeovnsforhandlere (2012)
- Miljøstyrelsen (2012, 2014)
- DTU (CHEC Annual Day, 2013)
- European Biomass Conference and Exhibition (EUBCE) (2014, 2015)
- Nordic Flame Days (October 2015)
- Seminar on Real-world emissions from residential wood combustion Copenhagen (3 December 2015)
- Expert workshop - Highly Efficient and Clean Wood Log Stoves Berlin (29 October 2015)
- Alliance for Green Heat: Pellet Stove Design Challenge, Brookhaven National Laboratory (6-8 April 2016)

9.3 Articles

- Ingeniøren (2014)
- Dansk Kemi (2015)
- FIB (2013, 2015)
- DTU: DTU Avisen (2012), Dynamo (2015), DTU KT Annual report (2016)
- European Biomass Conference and Exhibition (EUBCE) (2014, 2015)
- Magasiner
- Radio

Manuscript preparation to Environmental Science and Technology (Based on the laboratory studies)

Manuscript preparation to Biomass and bioenergy (Based on principle and fields tests)

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[9] Pettersson, Esbjørn, Boman, Christoffer, Westerholm, Roger, Boström, Dan, Nordin, Anders, 2011, Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 2: Wood Stove, Energy & Fuels — 2011, Volume 25, Issue 1, pp. 315-323.