UNIVERSITY OF KUOPIO

REDUCTION OF FINE PARTICLE EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION
Workshop in Kuopio on May 22 – 23, 2006

Kati Hytönen and Jorma Jokiniemi (Eds.)
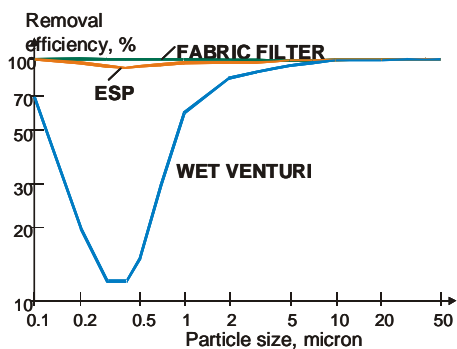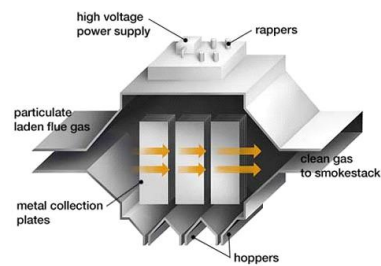
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Tiivistelmä

Puun pienpoltto on merkittävä pienhiukkasten päästölähde. Tavoitteena oli selvittää, miten puun pienpolton pienhiukkaspäästöjä voisi vähentää Suomessa tehokkaasti. Vähennyskeinot jaettiin kahteen osa-alueeseen: poltto- ja käyttöteknisiin keinoihin ja savukaasun puhdistustekniikoihin. Panospolton päästöjä pitäisi ensisijaisesti vähentää edistämällä hyviä tulisijojen käyttötapoja ja pitemmällä tähtäimellä parantamalla laitteiden polttotekniikkaa. Puun pienpoltossa käytettävien savukaasun puhdistuslaitteilla pitäisi olla hyvä hiukkasten erotustehokkuus; lisäksi niiden tulisi olla edullisia, pieniä kooltaan ja helppoja huoltaa. Käyttökelpoisimmat puhdistuslaitteet puun pienpolton savukaasuille ovat sähkösuodatin, lämmönvaihdin ja katalysaattori. Epäsopivilta vaikuttavat savukaasupesurit, erotuskammiot ja syklonit.

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Title
Reduction of Fine Particle Emissions from Residential Wood Combustion. Workshop in Kuopio on May 22-23, 2006.

Abstract
Residential wood combustion (RWC) is considered to be a significant source of particles in ambient air. The aim was to find out measures to reduce the fine particle emissions from RWC efficiently in Finland. The reduction was discussed in two sections; "Reduction of Fine Particle Emissions by Combustion Technology and Operation" and "Reduction of Fine Particle Emissions with Flue Gas Cleaning Devices". Primarily, the fine particle emissions from batch burning devices should be reduced by promoting good operation and in the long run by improving the combustion technology. Flue gas cleaning device used in RWC should have good particle removal efficiency; in addition it should be inexpensive, small and easy to use and maintenance. The most potential flue gas cleaning devices for RWC could be electrostatic precipitators, heat exchangers and catalytic converters in contrast to scrubbers, separation chambers and cyclones, which don't seem to be feasible for the reduction of fine particle emissions from RWC.

FOREWORD

This report is part of a research project named "Reduction of Fine Particle Emissions from Residential Wood Combustion". The report is based on a workshop which was held in Kuopio on 22nd and 23th of May, 2006. The structure of the report follows the one of the workshop. The report is divided into two sections; the first is "Reduction of Fine Particle Emissions by Combustion Technology and Operation" and the second is "Reduction of Fine Particle Emissions with Flue Gas Cleaning Devices".

The project was part of the Tekes technology programme Small-Scale Production and Use of Wood Fuels 2002-2006. Research partners in the project were University of Kuopio and VTT Technical Research Centre of Finland, and company partners were Tulikivi Ltd., Nunnanlahden Uuni Ltd., Kermansavi Ltd. and Harvia Ltd. Accountable manager of the project was Professor Jorma Jokiniemi from University of Kuopio, Department of Environmental Science. The members of the management group of the project were Jorma Jokiniemi (University of Kuopio), Heikki Oravainen (VTT Technical Research Centre of Finland), Marjatta Aarniala (Tekes), Pekka Horttanainen (Tulikivi Ltd.), Johannes Uusitalo (Nunnanlahden Uuni Ltd.), Juha Timonen (Kermansavi Ltd.) and Pertti Harvia (Harvia Ltd.).

Besides the persons in the management group, following persons contributed the project: Kati Hytönen, Pia Kilpinen, Olli Sippula, Valtteri Suonmaa and Jarkko Tissari (University of Kuopio), Veli Linna, Pasi Makkonen, Mikael Ohlström and Kai Pietilä (VTT Technical Research Centre of Finland), Mika Ruusunen (University of Oulu), Seppo Tuomi (Work Efficiency Institute TTS), Ari Laitinen and Pertti Taskinen (Tampere University of Technology). The report was compiled by Kati Hytönen.

CONTENTS

1 INTRODUCTION

Residential wood combustion (RWC) is considered to be a significant source of particles in ambient air. According to The Finnish Environment Institute (SYKE), the proportion of fine particles emitted from RWC is tens of percents of the total emission in Finland (Karvosenoja and Johansson, 2003). RWC produces both gaseous and particle emissions which are harmful to health. The amounts of emissions of carbon monoxide, hydrocarbons and fine particles from RWC depend, among other things, on fuel quality, burning appliance, appliance operation and possible flue gas cleaning technology used.

The knowledge of the RWC emissions has improved a lot lately. Recently a research project called "Fine particle emissions in small scale wood combustion" (Tissari et al., 2005) was completed. The study was carried out by University of Kuopio, VTT Processes, Work Efficiency Institute (TTS) and 9 manufacturers of boilers and batch burning appliances. The main financier was Finnish Funding Agency for Technology and Innovation (Tekes). The size, number, chemical compositions and mass of fine particles emitted from various residential wood burning appliances were studied. Formation of fine particles and effect of burning conditions on emissions were studied in flow reactor tests and with modelling. Moreover, the impact of the amount and size of logs on the emissions of various batch burning appliances were studied by Tissari et al., 2006. Nevertheless, to be able to reduce emissions, more information about emissions and their formation is still needed.

The emissions from RWC can be reduced through more complete combustion and/or by using flue gas cleaning devices. The improvement of burning relates to fuel quality, burning appliances and appliance operation. Flue gas cleaning devices are an option when the emissions can't be reduced otherwise. Flue gas cleaning devices have been mainly used for wood combustion in MW scale. In some countries there are cleaning devices also for residential wood burning appliances, but they haven't been used in Finland and there's no experience whether they function in the weather conditions like in Finland. Several flue gas cleaning techniques are under development in Finland (Aho, 2005; Oravainen, 2005), but the general view of their performance in various conditions has been lacking.

The aim of this workshop was to find out measures to reduce the fine particle emissions of RWC efficiently in Finland; both flue gas cleaning techniques and various means to improve wood burning were under discussion. On the basis of the results of the workshop, the resources can be directed to useful techniques or to potential techniques, which have not yet been investigated thoroughly.

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Session I: Reduction of Fine Particle Emission by Combustion Technology and Operation

2 THE INFLUENCE OF WOOD FUEL CHEMICAL COMPOSITION ON PARTICLE EMISSIONS

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2.1 INTRODUCTION

The fine particles in residential wood combustion are in general formed of three different constituents. First, soot particles are formed in the flame from aromatic hydrocarbons. Part of the soot particles remain unburned and are released to the flue gas. Secondly, part of the ash forming mineral matter is volatilised from the wood fuel into the flue gas. When the flue gas cools, the ash vapours condense and form fine particles. Thirdly, hydrocarbon vapours are released to the flue gases which condense when the flue gas cools. The hydrocarbons condense typically on the surfaces of particles already existing in the flue gas, creating a tarry or liquid layer on the particles.

The major cause for formation of fine ash particles is different to that of formation of soot and hydrocarbon particle matter. The soot and hydrocarbons are formed due to incomplete combustion conditions, mainly because of local fuel rich areas in the combustion zone and imperfect mixing in the combustion chamber. However, the major cause for fine ash particle formation is the volatile form of the mineral compounds in the wood fuels. The studies have shown that especially potassium, sodium and zinc together with sulphur and chlorine are enriched in fine particles (dp < 1 µm) while for example calcium, magnesium and silicon remain almost totally in the bottom ash or form coarse particles (dp > 10 µm) (Valmari et al., 1998; Sippula et al., 2006a).

2.2 THE EFFECT OF FUEL ASH ON PARTICLE EMISSIONS

In small scale wood combustion there are large variations in particle emissions and also the chemical composition of fine particles vary considerably. In batch wise burned combustion the particles contain usually large amounts of soot (elemental carbon) and hydrocarbons. In modern continuously operating appliances, due to more complete combustion conditions, the fine particles are formed mostly of ash species. Sippula et al. (2006a) performed a study in which 11 different pellet fuels with varying ash contents were combusted in a modern top-feed pellet stove. In the study, the fuel ash content correlated linearly with the fine particle mass (PM1.0) emission (Figure 1). However, the chemical analyses revealed that the higher ash content increased not only the fly ash emission but also the products of incomplete combustion (elemental carbon and organic carbon). Figure 2 shows the chemical compositions of fine particle mass emitted from pine stem, birch stem and willow bark combustion (Sippula et al., 2006a).
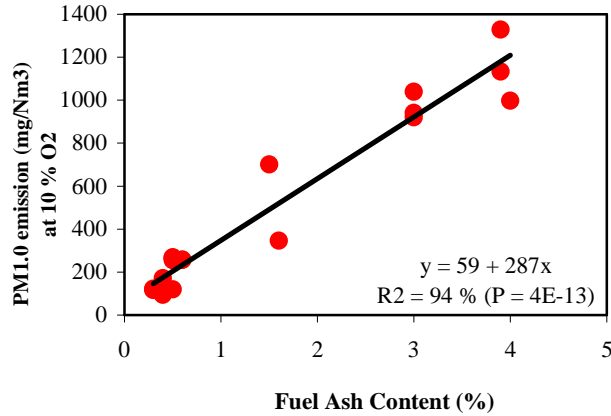
Figure 1. *Fine particle mass emission (PM1.0) from a pellet stove as a function of fuel ash content (Sippula et al., 2006a).*
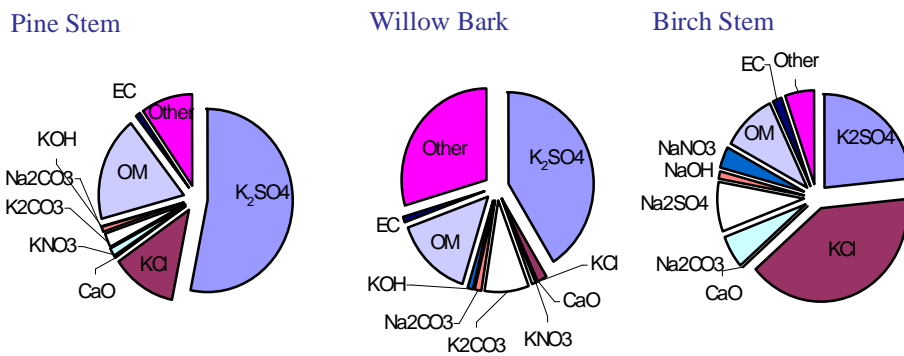
Figure 2. *PM1.0 chemical compositions from a pellet stove operated with different fuels (Sippula et al., 2006a). The chemical fractions are determined by combining results from chemical and gravimetric analyses with flue gas equilibrium calculations. EC is elemental carbon and OM is organic material.*

The effect of biomass fuel ash composition on particle formation has been characterized to some extent. The main findings are that high chlorine content increases release of different metals from the fuel to flue gas (Lind et al., 2006; Miller et al., 2006; Baxter et al., 1998; Sippula et al., 2006b) and thus, formation of fine fly ash particles. This is because chlorine tends to form metallic chlorides (as KCl, $NaCl$, $ZnCl_2$) which have high vapour pressures. However, a sufficient high sulphur amount in the fuel may change the reaction pathways. In this case metallic sulphates, which have reasonably lower vapour pressures, are formed by sulphation reactions (Equations 1-2).

$$2KCl + H_2O + SO_2 + \tfrac{1}{2}O_2 \leftrightarrow K_2SO_4 + 2HCl \qquad [1]$$
$$2KOH + SO_2 + \tfrac{1}{2}O_2 \leftrightarrow K_2SO_4 + H_2O \qquad [2]$$
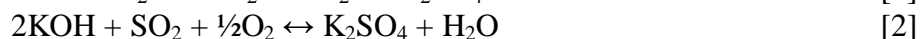
The recent studies made on effects of sulphur and chlorine on particle formation in wood combustion indicated that chlorine tends to increase especially the volatilization K, Na, Zn and Cd. As a result more than 2 fold particle mass concentration was observed when the flue gas chlorine concentration was increased from 9 ppm to 80 ppm (Sippula et al., 2006b). The

experiments have also shown that by adding sufficient amount of sulphur to the fuel the effect of chlorine on particle formation could be removed. (Lind et al., 2006; Sippula et al., 2006b).

A second important mechanism observed in the volatilization of ash compounds is the capture of alkali metals on silicates, aluminium oxides and aluminosilicates. It has been observed that fuels or fuel mixtures rich in silicates or aluminium do not release as much alkali metals to flue gas as ones without. Especially the aluminosilicates have been found to act effectively in decreasing the release of alkali metals (Aho and Silvennoinen, 2004; Tran et al., 2005). As an example, Tran et al. (2005) have proposed chemical reactions (Equations 3-5) between kaolin and potassium vapours which lead to formation of potassium alkali silicates, which are solid in typical combustion temperatures.

$$Al_2O_3 - 2SiO_2 + 2KCl + H_2O \rightarrow 2KAlSiO_4 + 2HCl \qquad [3]$$
$$Al_2O_3 - 2SiO_2 + K_2SO_4 \rightarrow 2KAlSiO_4 + SO_3 \qquad [4]$$
$$Al_2O_3 - 2SiO_2 + 2KOH \rightarrow 2KAlSiO_4 + H_2O \qquad [5]$$

2.3 THE APPLICATION OF AVAILABLE DATA IN WOOD COMBUSTION

A few chemical methods have been developed to remove the fine particle forming vapours from the flue gases. The applications have been mostly tested in the large scale combustion environment and their main purpose is usually to prevent formation of corrosive deposits in boilers or reduce agglomeration of bed material in fluidized bed combustion. However, the same mechanisms could possibly be used to prevent fine particle formation.

The present knowledge indicates that silicon and aluminium based sorbent minerals are most effective in removing alkali metal vapours. In addition, it is preferable to have sufficient amount of sulphur in the fuel. Up to writers' knowledge, sorbents based on both mechanisms are already in commercial use in large scale combustion units. However, a mixed combustion of different fuels is often economically more feasible. The studies made in laboratory scale combustors and in large scale boilers indicate that mixing of fuel with high silicon and sulphur content to a fuel with relative high alkali content (e.g. wood) can prevent the release of alkali vapours to the flue gas considerably. For instance the co-combustion of coal with potassium rich straw has been reported to decrease sharply the release of alkali metal vapours (Glazer et al., 2005). Similar indicative results have been observed by adding small amounts of peat to wood fuel in fluidized bed combustion (Lundholm et al., 2005; Lind et al., 2003). Also in small scale combustion, the knowledge on optimal fuel chemical composition gives an option to create fuel mixtures with lower particle emissions.

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3 FACTORS AFFECTING COMBUSTION AIR FEED AND MIXING IN SLOW HEAT RELEASE STOVES

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3.1 INTRODUCTION

The use of wood as a fuel is constantly growing in Finland. In 2005 the use of wood in private houses and in farms was 12.2 TWh, of which most was used as wood logs in stoves. In the National Energy and Climate Strategy target for 2010 is 20 TWh. As wood is classified as a renewable energy source, use of wood as a fuel does not increase carbon dioxide emissions. In small scale other emissions, such as carbon monoxide, organic hydro carbons and particle emissions, form a problem to be recognized. Good firing habits and proper air feed and staging can significantly decrease emissions (Ministry of Trade and Industry Energy Department, 2005; Tissari et al., 2005; Pietilä, 2005).

The air staging was introduced in Finnish commercial stoves at the end of 90's. Nowadays several Finnish stove manufacturers have used air staging in their stoves. In both air feed systems primary air is fed under the grate and secondary air is introduced to fire chamber from the sides of the grate or from the walls of the fire chamber. Main idea in both systems is that primary air is used to gasify the wood fuel and secondary air is used to burn the pyrolysis gases (Tulikivi, Nunnauuni).

3.2 AIR FEED AT DIFFERENT BURNING STAGES

Burning of wood logs in a stove is batch combustion process, which includes four main stages:

- ignition
- pyrolysis
- burning and
- char burning.

As the process progresses from evaporation of the moisture to the burning of pyrolysis gases and char coal different amounts of air is needed to attain good efficiency and low emissions. The result of the burning is also dependant of combustion conditions such as temperature of the fire chamber, mixing of the combustion air and flue gas, quality of the fuel and staging of combustion air (Pietilä, 2005).

Primary and secondary air need varies at different burning stages. At ignition stage air is mainly fed under the grate, because all the reactions happen at the fuel bed as the temperature of the fire chamber is not high enough for burning reactions. Ignition stage is usually visible with first batch. Next batches ignite fast and ignition stage is very short. At pyrolysis stage wood starts to degrade and form pyrolysis gases. At this point the emphasis is on the secondary air as the primary air only works to accelerate pyrolysis. A good balance between primary and secondary air is needed to control the pyrolysis so that there is enough secondary air to burn the gases. Most of the emissions in batch combustion form at pyrolysis stage. Emissions are mainly carbon monoxide, organic hydrocarbons and particles. After pyrolysis stage comes burning stage, where burning gradually slows down. As the burning stage progresses less pyrolysis gases form and less secondary air is needed until char burning stage is reached, where only char burn and there is no formation of pyrolysis gases. At this point only primary air is needed to burn the char. Burning stage usually produces least emissions as the formation of pyrolysis gases and need of secondary air are decreasing. At char burning stage emissions are mainly carbon monoxide and particles (Tissari et al, 2005; Pietilä, 2005).

3.3 FACTORS AFFECTING COMBUSTION AIR NEED AND MIXING

An experimental study was made to determine the effect of different factors to the air need and to the quality of burning. The tests were made according to a Taguchi design of experiments. Carbon monoxide emissions and efficiency of the stove were used as criteria for the tests. The following factors were studied:

- Moisture of fuel: 10 w-% and 25 w-%.
- Mass of batch: 1 kg, 2 kg and 3 kg.
- Size of wood logs: small and large, where smaller had 30% more surface area.
- Air feed at burning stage: 550 l/min, 800 l/min and 1100 l/min total air feed.

The tests were made in a 1500 kg stove, where primary and secondary air was separated (Figure 3). The combustion air feed was forced (Pietilä, 2005).
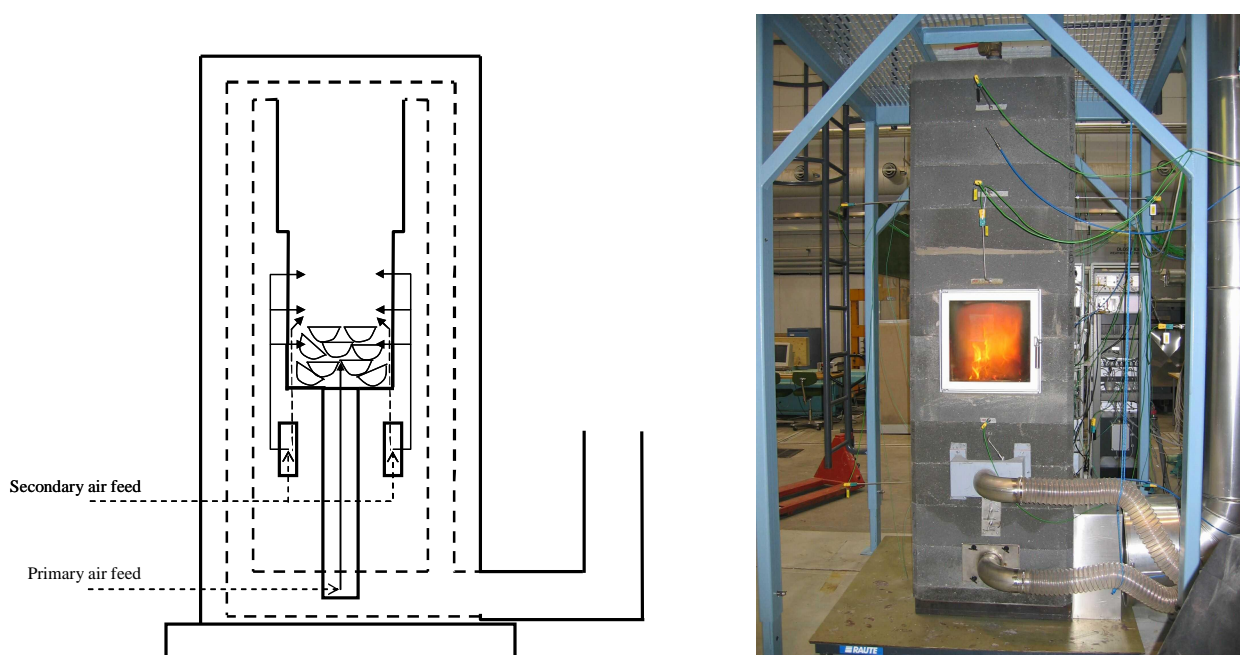
Figure 3. *Test stove. Primary and secondary air feed is forced.*

Moisture of wood fuel was tested on two levels: with 10 w-% and 25 w-% moisture content. Moisture was observed to have big effect on efficiency and emissions. The construction of the grate limited pyrolysis, which caused high moisture content of the wood to slow down burning and lower the temperature in the bed and fire chamber. Therefore high moisture content decreased efficiency of the stove, but also caused high CO emissions. With low moisture content burning was intensive and conditions were good for clean burning. High moisture content of the fuel needed more primary air to keep on the burning. With low moisture content more secondary air was needed. Generally excess air factors and CO emissions were higher with moist wood (Pietilä, 2005).

Mass of batch was tested on three levels: with 1 kg, 2 kg and 3 kg batches. Optimal batch size was dependant on the size of fire chamber. 1 kg batch was too small for this fire chamber and no good results were achieved with any of the air feed amounts. Intensity on the burning was not high enough to enable mixing of the pyrolysis gases and combustion air. More intensive burning, better mixing and therefore best results were reached with 2 and 3 kg batch sizes, which also required larger amount of combustion air. The air need was greater with 3 kg batch than with 2 kg batch (Pietilä, 2005).

The effect of wood log size on burning was tested on two levels, where smaller sized wood logs had 30% more surface area than the larger wood logs. Smaller logs were about 0.5 kg when larger were 1 kg. Small and large logs were 25 cm long. Due to larger reaction area burning was more intensive with smaller wood logs. This enhanced burning of moist wood whereas dry wood burned too intensively, which caused high CO emissions. CO emissions were higher with dry wood and bigger batches (2-3 kg) and lower with moist wood and smaller batches, when wood log size was smaller. Excess air factors were 10% - 30% greater with smaller wood log size depending on the wood moisture and batch size (Pietilä, 2005).

Air feed amounts were selected for a wide range of test variables. Therefore optimal air amounts could not be reached in any of the tests. About 30% of the total air feed was fed as primary air and the rest was brought in the fire chamber as secondary air. Generally largest air feed, 1100 l/min, was enough for the 3 kg batch of dry wood, but the smaller amounts of air were not sufficient. Good air feed for the 1 kg batch was not found. The reason was the fire chamber and grate size, which were too large for small batch. Most of the primary air did not react with the fuel and only cooled down the fire chamber. Excess air factor ranged in the tests between 1.7 and 3.6 and CO emissions between 600 ppm and 2650 ppm reduced in 13% oxygen (Pietilä, 2005).

On the basis of the test results, a control system for batch combustion process was implemented. Carbon monoxide and carbon dioxide content of the flue gas was measured to optimize the supply of primary and secondary air feed. CO/CO_2 –ratio was used as a control criteria and good controllability was observed. Controller was tested with batch sizes ranging from 1.6 kg to 2.8 kg, where moisture content of the fuel was between 10 w-% and 20 w-%. Air feed was during most intense burning 1200 l/min at the highest, where the share of primary air was about 25%. During char burning stage primary air feed was 300 l/min and no secondary air was fed. Excess air factors ranged in the tests between 1.6 and 2.0. CO emissions were between 369 and 561 ppm reduced in 13 % O_2 (Pietilä, 2005).

3.4 CONCLUSIONS

Several factors affect the outcome of batch combustion process. Enough combustion air and good mixing of air and pyrolysis gases is needed to obtain clean burning. To obtain good mixing, intensive burning and staged air feed is needed, but with too intensive burning air feed might not be sufficient, which causes emissions. Moisture in the fuel decreases intensity of the burning whereas smaller wood log size increases it. Thus, the negative effect of moist wood can be downsized by using smaller logs in the burning. Result of the combustion can be controlled by optimizing air feed as long as the conditions in the fire chamber are favourable for clean burning.

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User manual for Tulikivi stove.

4 EFFECT OF AUTOMATIC CONTROL TECHNOLOGIES ON EMISSION REDUCTION IN SMALL-SCALE COMBUSTION

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Automatic control can be regarded as a primary measure for preventing combustion emissions. In this view, the control technology covers broadly the control methods, sensors and actuators for monitoring and controlling combustion. In addition to direct control of combustion process, it can also give tools for condition monitoring and optimisation of total heat consumption by system integration thus reducing the need for excess conversion of energy.

Combustion control is usually applied to achieve targets like steady heat output and constant oxygen level in flue gas. This means that disturbances, changes in fuel quality and heat load, are smoothed by the control actions reducing process variations. The control of the process behaviour is directly related to clean combustion since steady-state conditions in general are favourable for achieving lower emissions. It is also known that traditional control strategies aiming to minimise carbon monoxide content in flue gas can actually favour the conditions for the lower mass and number concentration of particles emitted (Johansson et al., 2004; Tissari et al., 2005).

One of the main aspects for successful combustion control is the feedback from the state of the process. This includes direct (Good et al., 1998) or indirect measurements (Ruusunen, 2001; Ruusunen et al., 2004; Ruusunen, 2006) from the variables to be monitored and controlled. With control algorithms, sophisticated air and fuel supply strategies can be then realised, as typically in larger (>100kW) combustion units. This can lead to a multiobjective optimisation problem to be solved, since maximisation of efficiency, maintaining a proper oxygen level and minimisation of certain emissions may require simultaneous but opposite control actions in different operating conditions. Partly for these reason, a new generation of control methods is arising at the area of combustion control (Kalogirou, 2003).

Unfortunately, the applicability of control technologies is still restricted in small-scale combustion mainly by the absence of:

- cost-effective instrumentation (sensors and actuators),
- reliable measurement technology for monitoring combustion variables,
- device and energy storage technology for controllers' own consumption,
- adaptable control methods for changing combustion environments,
- systematic process development towards more controllable combustion processes.

In a small-scale heat production the continuous and batch combustion are a common practice. Continuous process enables the implementation of a control system, demonstrated for

example in (Good et al., 1998; Hassler, 1998). In practice, these kinds of systems should be cost-effective and contain adaptation mechanisms for implementation also to older combustion devices, as mentioned earlier. Developments in electronics and sensor technology, for example small embedded systems and new sensor materials can solve many of the problems related to hardware of the control system; there are already commercial pellet burners (<20kW) utilising combustion temperature measurements and microprocessor-based control systems for feedback control.

Temperature control in a fixed fuel-bed and secondary combustion zone, including maintenance of optimal excess air, are potential actions to prevent formation of unburnt components and particle emissions, when coupled with automatic control. A few studies have shown reduction of particle emissions by a factor of 5, when the fuel-bed temperature and primary air feed are minimised, and the temperature maximised at the secondary combustion zone of small-scale combustion devices. This may result in unstable combustion conditions, where active control is needed since primary air must be kept at much lower level than normally. (Nussbaumer, 2003; Wiinikka et al., 2004)

Figure 4 shows an example about changes in a fuel bed and secondary combustion zone temperatures as a result of control actions. In this case, primary and secondary air feeds were controlled with a step change to new values in a 300kW stoker-boiler using wood chips. The box-plots suggest that the realised control action lowered fuel bed temperature with both dry and wet fuel. At the same time, temperatures at secondary combustion region slightly increased. Additionally, CO vol.-% with both fuel decreased by 40% compared to initial state.
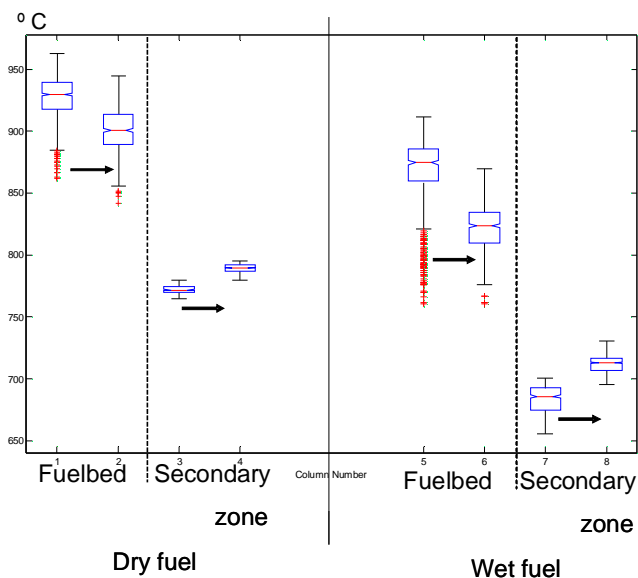
Figure 4. Measured temperature distributions (box-plots) in fuel bed and secondary combustion zone before and after step changes in primary and secondary air feeds in a 300kW stoker-boiler using wood chips as a fuel.

On the other hand, there are a few attempts to apply feedback control in batch combustion of wood. In these studies, the CO-emissions were compared to situation with manual and/or measurements and control. It was found that reduction of CO was between 15-40 percentages on the average, depending on combustion device and applied control strategies. In (Grönroos,

1995), the manual control of air dampers was based on CO-measurement and maximisation of temperature in the secondary combustion chamber of a stove. In (Ruusunen, 1999), signal processed information from SnO_2-sensor and mathematical CO_2-model was utilised with fuzzy rulebase to automatically control dampers of an iron stove. The most recent results were achieved with forced draft based system applied to a stove by using measured CO/CO_2-ratio based control criterion and fuzzy rulebase to automatically adjust air feeds during combustion (Pietilä, 2005). Experimental setups and results with the proposed control systems are presented in Table 1.

Table 1. *Examples of feedback control results applied to batch combustion of wood.*

Reference	Combustion device	Measurements	Draft	Reduction of CO %
Grönroos, 1995	Stove	CO, temperature	Natural	5-30
Ruusunen, 1995/1999	Iron stove	Modelled $CO+CO_2$	Natural	10-30
Pietilä, 2005	Stove	measured $CO+CO_2$	Forced	20-70

Another applicable use for automatic control is the utilisation of measurements for the condition monitoring of the small-scale combustion. Information about the instrumentation, the combustion efficiency and pollutants, especially their long-term trends, can be used to indicate for example

- fouling of heat exchange surfaces and air ducts,
- health status of a combustion device, its sensors and control equipments,
- quality of the fuel,
- misuse of a combustion device.

Usage of historical knowledge about process behaviour could enable preventive maintenance actions also for small combustion units. Of course, condition monitoring requires the measurements, statistical analyses, and connection to a proper maintenance policy (Wang, 2002) to be followed. Applying the condition monitoring and diagnostics to feedback loop makes possible the automatic, condition based preventive actions. These may include for example use of automatic cleaning, leading then to emission based maintenance (Fiedler, 2004).

Automatic condition monitoring and maintenance has potential to affect annual efficiency and amount of pollutants. For example, 1 mm thick layer containing soot and tar at heat exchange walls may raise the fuel consumption by 10% (Wahlroos, 1980). On the other hand, air duct fouling can remarkably increase the amount of combustion emissions because of too low excess air level (Berg, 2001; Fiedler, 2004).

A higher level control method for indirect reduction of pollutants by means of energy saving is system integration. To accomplish this target, separate control systems should act together producing thus additional information for each other. This way a broader perspective about the energy need or usage can be available. In the small-scale combustion environment, this could include situation presented in Figure 5. There, the principle of system integration is shown at the household level, in the form of a building automation system.
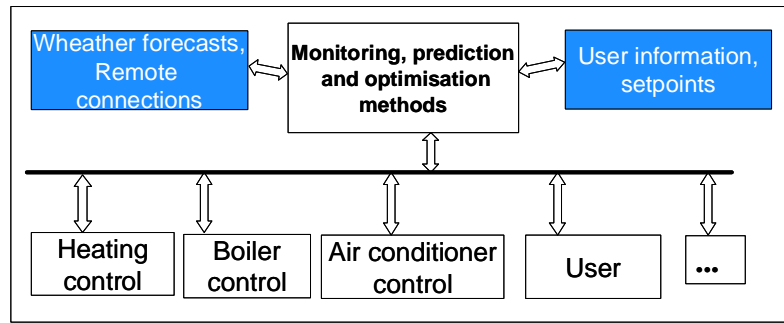
Figure 5. *The principle of integrated optimisation system of energy usage at building automation environment.*

Compared to separate controllers, an integrated control approach shown above can more efficiently optimise energy conversion at the building level. For example, the long-term optimisation of the energy usage may differ from the short-term targets requiring higher level control. It is estimated that in this way energy savings around 10-40% could be achievable (Paiho, 2002). However, many issues still exist at implementation of the system integration to the household scale, including incompatible standards and hardware interfaces.

As a conclusion, automatic control has already shown its potential in small-scale combustion. The potential, but still unrealised advantages of automatic control in this scale are the adaptation to changes in combustion conditions (fuel, environment, device, user) and the continuous optimisation of the air/fuel ratio. Modern control technology also covers combustion condition monitoring, diagnostics, and the higher level optimisation of the energy consumption with system integration. In theory, these primary measures maximise the overall efficiency, enabling a significant reduction in fuel consumption and thus total emissions per small-scale combustion unit, specifically at the annual level.

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5 TULISIJA TECHNOLOGY PROGRAMME FOR WOOD FIRING TECHNOLOGY (1997-1999) -AN OVERVIEW

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Tulisija, a three-year research programme for wood combustion technology was launched in the beginning of 1997 by Tekes, the National Technology Agency of Finland, together with companies manufacturing small scale fireplaces. The aim of the Tulisija programme was to assist the participating companies to develop new fireplace designs with improved control of the combustion process and the flue gas emissions.

Four specific targets were defined for the programme:

- To develop advanced computer simulation to evaluate fireplace designs from the viewpoint of combustion and formation of pollutants. The main emphasis was on the study of unburned gaseous emissions (CO, C_xH_y) but also emissions of nitrogen oxides (NO_x) were taken into account.
- To create a measuring and test facility for controlled tests of commercial equipment by the manufacturers and for well defined tests and measurements to validate the CFD model being developed.
- To create modelling facilities for calculating the heat transfer in the fireplace structures. This model would allow comparing the usability of various fireplace materials and structures in different parts of the fireplace for optimum heat transfer.
- To promote national networking and to utilise international co-operation in the area of small scale wood firing.

In total, eight companies participated in the programme. They were Harvia Oy, Kerman Savi Oy, Nunnanlahden Uuni Oy, Optiroc Oy/ Finnish Brick Industry Association, Tulikivi Oyj, Tunnelma Uuni Oy, Turun Uunisepät Oy and Puulämpö Suomi Oy. Research laboratories involved were Tampere University of Technology, VTT Energy, VTT Building Technology, and Åbo Akademi University, which also undertook, together with Tekes, the co-ordination of the programme.

Eleven research and development projects were part of the Tulisija programme (Figure 6). This included five modelling projects, two projects dealing with experimental work and creating the measuring and test facility, and four corporate projects. The total funding including the corporate projects was 24 million FIM, the research part of it being around 7 million FIM.

The Tulisija programme managed to achieve all of its principal goals. New useful modelling tools were developed for optimising furnaces in order to reduce emissions of pollutants and improve heat transfer.

Extensive measurements resulted in a unique set of detailed experimental temperature and gas concentration data from a small scale wood furnace. The phenomena of wood batch firing are better understood than before the programme.

A network of researchers and R&D personnel in the industry was created. Valuable international contacts were established and scientific co-operation was increased.

The programme published more than twenty technical reports and scientific journal articles. The programme was presented at a number of international seminars and also at radio and television and by numerous newspaper articles.

Some results of the programme are presented in Figure 7 and Table 2.
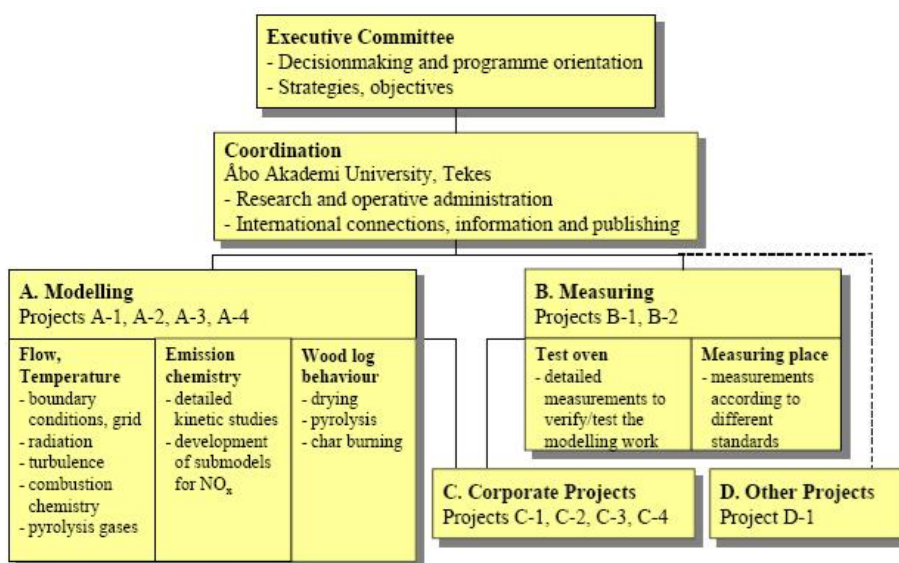
Projects

Modelling

A-1: The behaviour of fuel
VTT Energy, Jyväskylä

A-2: Computational fluid dynamics simulation of combustion in small scale wood ovens
VTT Energy, Espoo

A-3: Computational fluid dynamics simulation of combustion in small scale wood ovens and modelling of emission chemistry
Åbo Akademi University, Turku

A-4: Modelling of heat transfer in fireplace walls and constructions
Tampere University of Technology

Measuring

B-1: Detailed emission and temperature measurements in the TULISIJA test oven
VTT Energy, Jyväskylä

B-2: Measurement environment for fireplace testing
VTT Energy, Jyväskylä

Corporate projects

C-1: Clean combustion
Nunnanlahden Uuni Oy

C-2: Reduction of emissions from soapstone fireplaces
Tulikivi Oyj

C-3: Development of a new modular method for fireplace manufacture
Tunnelma Uuni Oy

C-4: Replacement of energy intensive raw material with recycled industrial waste and further development of combustion processes in fireplaces
Kerman Savi Oy

Other projects

D-1: Instructions for dimensioning and design of fireplaces for optimum living atmosphere in residences
VTT Building Technology, Espoo

Figure 6. *The organisation and the projects of the Tulisija programme.*
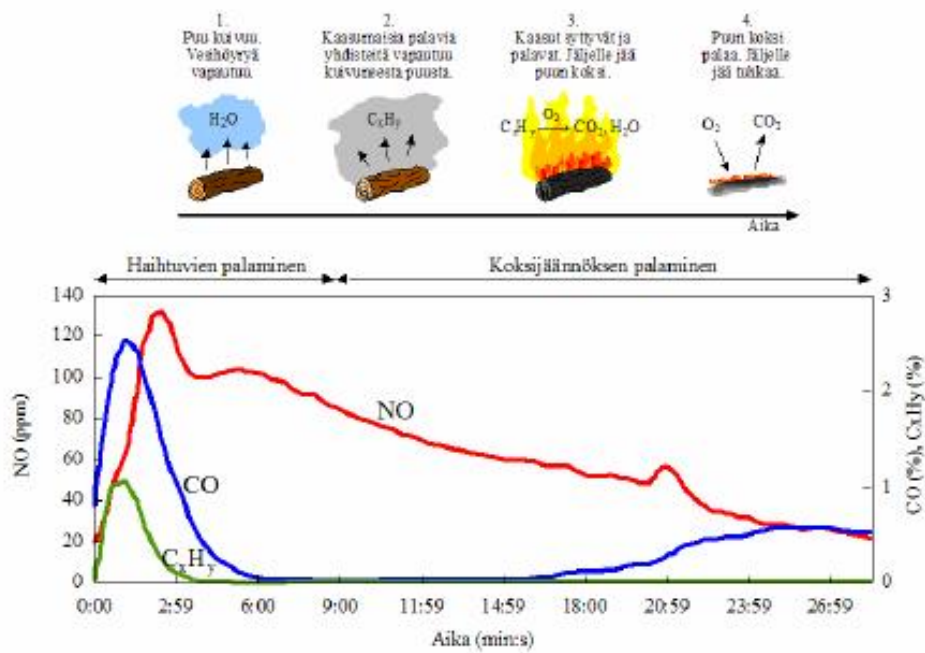
Figure 7. *The combustion cycle of a wood batch: the different phases of the combustion and the emissions of hydrocarbons, carbon monoxide, and nitrogen oxides during the different phases, measured in the Tulisija test oven.*

Table 2. *Values which the Tulisija CFD code can predict and their estimated accuracy at the end of the programme.*

	Pyrolysis	Char combustion

Gas flow field	• Correct main flow pattern
	• Location of swirls etc.: $\pm 0.1 \times 1$
	  (1 = characteristic dimension of furnace)
	• Velocity of main flow: $\pm 15\%$
		• Correct main flow pattern
		• Location of swirls etc.: $\pm 0.1 \times 1$
		  (1 = characteristic dimension of furnace)

Shape of flame	• Qualitatively correct shape	
Temperature	• Correct temperature field • Location of temperature maxima etc.: $\pm 0.1 \times 1$ • Local temperatures $\pm$ 200 °C	• Correct temperature field • Location of temperature maxima etc.: $\pm 0.1 \times 1$ • Local temperatures $\pm$ 100 °C
Distribution of main components (O_2)	• Correct concentration field • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 1.3 • Final concentrations in flue gases: Factor 1.3	• Correct concentration field • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 2 • Final concentrations in flue gases: Factor 2
(CO_2, H_2O)	• Correct concentration field • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 1.1 • Final concentrations in flue gases: Factor 1.1	• Correct concentration field • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 1.1 • Final concentrations in flue gases: Factor 1.1
CO distribution	• Qualitatively correct distribution • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 3 • Final concentrations in flue gases: Factor 3	• Qualitatively correct distribution • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 5 • Final concentrations in flue gases: Factor 5
C_xH_y distribution	• Qualitatively correct distribution • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 5 • Final concentrations in flue gases: Factor 5	
NO distribution	• Qualitatively correct distribution • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 5 • Final concentrations in flue gases: Factor 5	• Qualitatively correct distribution • Location of concentration maxima etc.: $\pm 0.1 \times 1$ • Local concentrations: Factor 3 • Final concentrations in flue gases: Factor 3

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6 THE EFFECT OF OPERATION ON FINE PARTICLE EMISSION FROM RESIDENTIAL WOOD COMBUSTION

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6.1 INTRODUCTION

Residential wood combustion (RWC) is known to be a significant source of pollutants, especially of fine particles. Among other things it has been proposed that RWC accounted for more than half of the stationary combustion, based on primary $PM_{2.5}$ (Particle Mass (PM) below aerodynamic size of 2.5 µm), emissions in Finland (Karvosenoja & Johansson, 2003) and RWC can locally account for as much as 20–90 % of the wintertime fine particle emissions (Muhlbaier Dasch, 1982; Boman et al., 2003). The small size of the particles may increase significantly the population's exposure to respiratory ailments and other health risks (Pope et al., 2002). The amount and composition of the emissions from the RWC have been shown to be inconsistent and dependent on many factors (Nussbaumer, 2003; Johansson et al., 2003). The most important factors are the type of appliance (Johansson et al., 2004; Johansson et al., 2003), the combustion conditions (Nussbaumer, 2003) and the way the heater is operated (Boman, 2005). Operational practices and appliances differ considerably in various countries. For example Finnish appliances are operated for a short time and at a high combustion rate in contrast to the lightweight metal stoves which operated at a low combustion rate, owing to requirement to generate heat for a long time at low power often used e.g. in warm countries.

6.2 EXAMPLES AND RESEARCH RESULTS

The effect of operation on fine particle emission are explicated and analyzed with help of several examples of research results. The examples are

1) Johansson et al., 2004: Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets

2) Tissari et al., 2003: Fine particle and CO emissions in an under-feed pellet burner.

3) Tissari et al., 2005: Emissions of wood log combustion for normal and smouldering conditions.

4) Jordan et al., 2005: Effect of airflow setting on the organic composition of woodheater emissions.

5) Muhlbaler Dasch, 1982: Particulate and gaseous emissions from wood-combustion fireplaces.

6) Tissari et al., 2006: The effects of appliance type and operation on the emissions from the residential wood combustion.

Johansson et al (2004) measured two old-type water cooled wood boilers (OB), two ceramic-lined modern wood boilers (MB), and three pellet burners (PB). OB was used with and without heat storage tank, with small and big batch size. MB has always heat storage tank, but used with natural draught or flue gas fan. Also in the measurements the several wood moisture contents was used. PB several power output was used as well as pellet burner with pilot flame and with electrical ignition. The main results were

- OB caused considerably higher emissions than modern wood and pellet boilers.
- Large wood batches caused about 4-fold PM emission compared to small wood batches from OB. When heat storage tank was used, emissions were similar level as small batches were used. Particle emission was reduced by 4 to about 20 times with heat storage tank.
- Flue gas fan have not significant effect on emissions from MB. The moist wood fuel (38% moisture content) caused over than three times higher PM emission and about two times higher number emission than more dry wood (26% moisture content) or dry wood.
- Typically the partial load increased emissions from PB. At 30% partial load PM emission was three fold from burner with pilot flame and four-fold from burner with electrical ignition. Generally, emissions from PB with electrical ignition were slightly lower than with pilot flame.
- Bark pellets caused higher mass concentration of particles, which is probably explained by the higher ash content of this fuel compared to pure wood pellets.

Tissari et al. (2003) measured fine particle and CO emissions from under-feed pellet burner (pilot flame) with 15 kW nominal output (continuous combustion) and 5 kW partial load (contain both working and interruption time). Averagely PM1 emission was about 10-fold during partial load compared to nominal output. During the interruption period mass and CO concentrations were very high, average mass about 40-fold and average CO about 20-fold than at the continuous combustion at partial power.

CO (Figure 8), number- and mass concentrations were equal in continuous combustion, but varied significantly during the interruption period. In the beginning of a break, mass concentrations increased and number concentrations decreased. At the end of break also the mass concentration decreases. The size distributions varied according to driving situation. The variation during the continuous combustion was minor. In continuous combustion the average number mean size was 120 nm and during the break 200 nm. Particles were composed mainly organic matter during the interruption time.
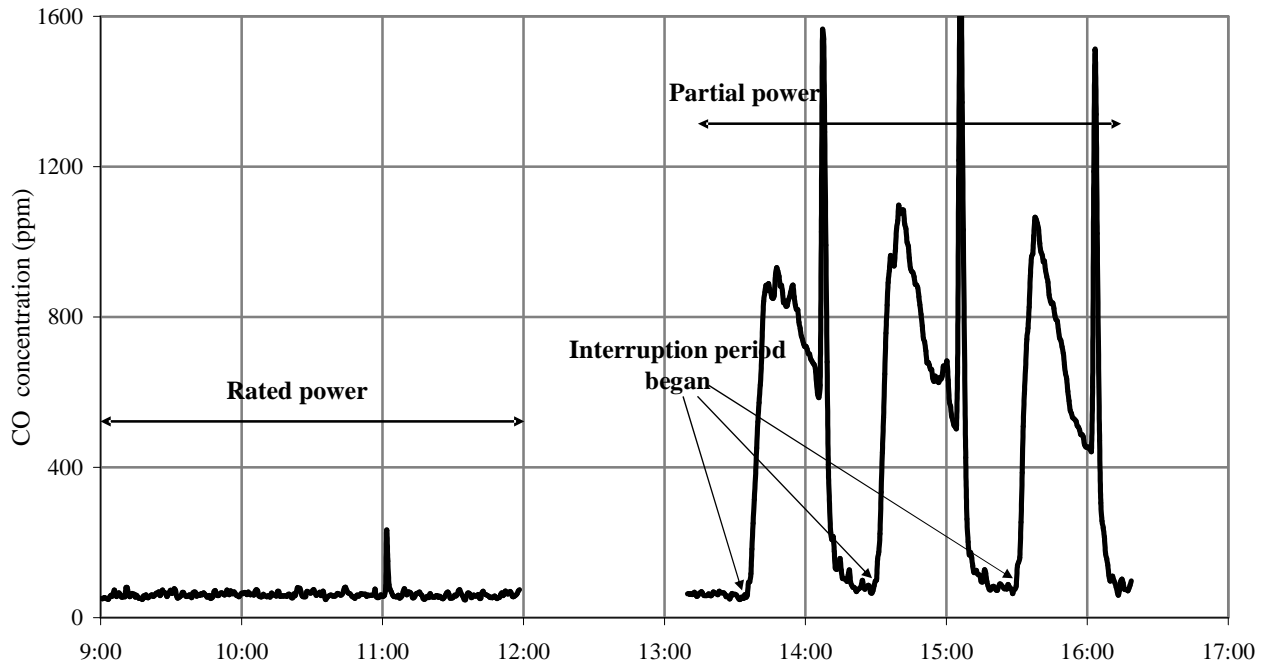
Figure 8. *The momentary CO concentration as a function of time from pellet combustion with pilot flame burner.*

In the smouldering combustion the combustion device was operated at a low combustion rate, owing to requirement to generate heat for a long time at low power often used from the stoves in the warm countries and also wood log boilers without heat storage tank. Only this kind of poor combustion conditions lead to complaints to the authorities in Finland. Tissari et al. (2003) measured emissions of wood log combustion for normal and smouldering conditions. The average PM1 emission at the start up phase and during smouldering were about 3-fold and OGC emissions about 4-fold compared to the normal combustion at an intermediate phase. The particle mass and OGC correlated very well during smouldering. Also according to the unpublished data from PUPO-health project from storing masonry heater the poor combustion produced very high emissions due to released uncombusted pyrolysis gases. Poor combustion also produced more gaseous hydrocarbon emissions, more particle mass, more organics in particles and larger particle size. Particle mass size distributions and SEM-figures from these measurements are presented in Figure 9 and 10.
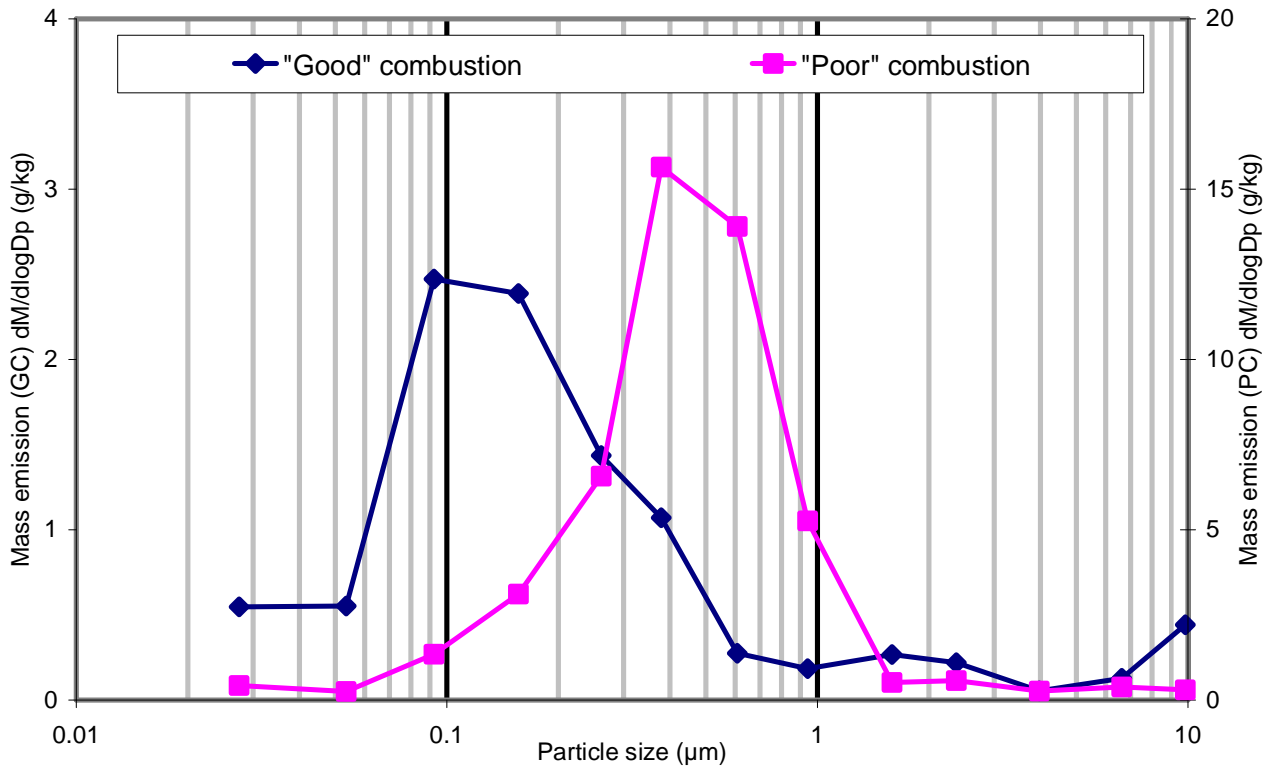
Figure 9. *Particle mass size distributions from poor and good combustion.*
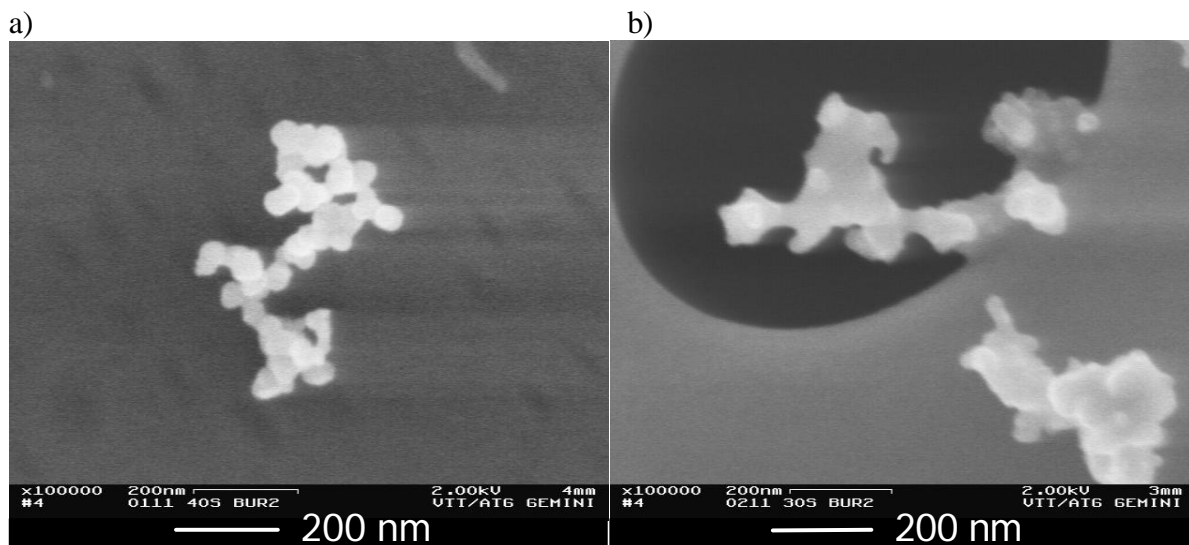
Figure 10. *SEM-figures from good (a) and poor (b) combustion (figures Jussi Lyyränen, VTT)*

Jordan et al. (2005) studied effect of airflow setting on the small wood heater (stove) emissions. An inverse correlation between particle emission and burn rate was observed for both heaters (S1 (old) and S2 (modern)) tested. It appeared that the PM reached a maximum at around 35-40 g/kg for most tests where the burn rate was less than 1.5 kg/h (poor combustion), irrespective of the heater model. The medium burn-rates (1/2-closed) using S2 produced PM intermediate between the two extremes, but for S1 they were not significantly

different from the closed conditions, indicating that oxygen-starved conditions are induced much more easily with this heater. In the closed setting PM emission was from S1 averagely 2.5 times higher and from S2 12.5 times higher than in the open setting.

Muhlbaler Dasch (1982) studied emissions from fireplaces and observed that the log size seemed to have a greatest effect on particulate emissions. The test with split wood (pieces about 100 g each) facilitated a fast complete burn. The test run with 0.5 or 1.0 kg logs led to decrease burn rate, temperature, and flow rate and total particle emission was higher when large logs were used.

From the storing heater the operational practices have different effect on emissions. In the study Tissari et al. (2006) from Finnish appliances were observed in contrast to results from stoves or open fireplaces that doubling the batch size, emissions increased remarkably. The OGC emissions were 4.0, CO 2.2 and PM_1 1.9 times higher. Also emissions from big logs were lower than from small logs. Using equal batch sizes, emissions from small logs were for OGC 8.7-fold, for CO 2.3-fold, for N 1.4-fold and for PM_1 4.8 fold greater than from big logs. When small batch sizes were used, but the logs in them were small, still most emission rates were higher than when big batches and big logs were used: OGC was 1.5, N 1.8 and PM_1 2.5 times higher, though CO emission was nearly the same. The results seemed to show that log size affected emissions more than batch size.

6.3 SUMMARY

The operational practices have very clear effect on emissions and their composition. Each appliance has its own "best" operational practice. For all appliances the batch and log sizes as well as fuel quality are the main operational parameters which noticeably affect emissions. The old devices cause considerably higher emissions than modern devices. In general, heat storage tank applied for the wood boilers decreases emissions. When the modern pellet boiler is used, the prime factors, which affect emissions, are operational principle, operational power, output area of burner and temporarily power requirement. Typically the partial load increases emissions and the burner with pilot flame produces higher emissions than burner with electrical ignition. Using of the moist wood fuel increases emissions compared to dry one and also large wood batches caused higher emissions compared to small wood batches. Bark pellets causes higher particle emission due to the higher ash content of this fuel compared to pure wood pellets. From the light metal stoves and open fireplaces emissions are low at high combustion rate (air intake open or small logs used). From the storing masonry heaters, in contrast to stoves or fireplaces, the high combustion rate increases emissions and big logs decreased emissions. At the very low combustion rate (from the smouldering or poor combustion) the results are congruent with different appliances, i.e. this operation mode produces very high emissions

Generally, the operational practices of heaters differ significantly in different studies, which affect the amount and composition of the emissions, but surprisingly this subject has not been studied extensively. Especially from field measurement campaign, results have not been available. However, precise operational conditions in the field should be known, when evaluating real emissions and their influences.

6.4 CONCLUSIONS

The main factors for reduction of fine particle emission from residential wood combustion on operational practices are

- controlling partial load in the continuous combustion
- using modern boilers and heaters
- preventing smouldering or poor combustion
- using applicable batch size in batch combustion
- using suitable log size and combustion rate of each appliance
- looking after good conditions for combustion before ignition (batch combustion)
- promoting good operational practices with general information
- developing new reduction technologies

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7 OPTIMISATION OF AIR DELIVERY IN A SMALL HOUSE FURNACE

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7.1 INTRODUCTION

Small-scale batch-type wood combustion furnaces are widely used in heating of houses and saunas in Finland. Lately harmful emissions have been paid considerable attention, because remarkable amounts of fine particles are produced in combustion. It has been observed that the fine particles can cause serious health effects such as lung cancer etc (Salonen et al., 2006).

In small-scale batch-type furnaces carbon monoxide (CO), unburnt hydrocarbons (HC) and fine particles are the major emission components. At the beginning of year 2008 in Finland, a new emission standard is coming into force for new small-scale batch-type firewood combustion furnaces. According to the standard, the CO level must be below 0.17%. The aim of the standard is to limit the CO to a suitably reduced level. When comparing poor and good combustion, CO, HC and fine particle emissions are all reduced in the case of good combustion (Tissari et al., 2006). The CO level indicates well how complete the combustion is. However, in good combustion conditions there is no correlation between CO, HC and fine particle emissions.

The following factors influence to the amount of CO emissions in small-scale batch-type combustion:

- place of ignition
- moisture content of firewood
- size of firewood
- position of fire-woods in grid
- construction of furnace
- air delivery system

The goal of the research was to develop an air delivery system for a small-scale batch-type firewood combustion furnace in which CO emissions are as low as possible. Traditionally in this kind of furnace all the combustion air is supplied as primary air under the grid. In the new type of air delivery system a part of combustion air is supplied as a pre-heated secondary air over the firewood batch and rest of the air normally as a primary air under the grid. In this way pyrolysed gases from the fire woods burn out better and also other emissions will remain low compared to the emissions from furnace which has traditional construction. In the research the main objective was to find out and optimise a proper air supply ratio, how much

air needs to be supplied as the primary and secondary air into the furnace in order to reduce the CO emissions to the minimum level. In addition, considerable attention was paid to the previously listed factors which affect the formation of CO.

7.2 METHODS

The research was divided into the three stages. First, the amount of air needed and flue gas produced was calculated when a typical 5.0 kg firewood batch was burnt based on the birch's elementary analysis (Kurki-Suonio, 1980). Using a typical burning time and excessive air ratio of the firewood batch mentioned it was possible to calculate the average air flow during the combustion. Also the adiabatic temperature of the gas was calculated for estimation of the maximum flame temperatures which could appear, if radiation of the gas and soot is neglected.

Secondly, so called cold model of the small-scale batch-type combustion furnace, the real sized visualisation test model, was built up of transparent plastics in the laboratory of TUT. In this visualisation test model, the primary and secondary air flows were independently adjustable. There was a blower with which the pressure of the chamber was adjusted to the typical level appearing in the real furnaces. On both side walls there were secondary air holes from which the secondary air and visualisation smoke mixture jets came into the furnace as shown in Figures 11a, 11b. The number and size of the holes varied in the visualisation tests in order to know how the hole size influences the penetration of the jet. The basic idea of the use of secondary air jets was to enhance the mixing of pyrolysed gases and air and to enhance combustion by jets just above the firewood batch in the so called secondary combustion zone. Secondary air jets from both sides have to at least reach the middle part of furnace. Also the air flow through the hole was calculated for the different hole sizes based on the certain discharge coefficient (Daugherty et al., 1982) and the pressure difference over the hole (Fagerholm, 1986). This knowledge was used in the dimensioning of the secondary air pipes in the real furnace.
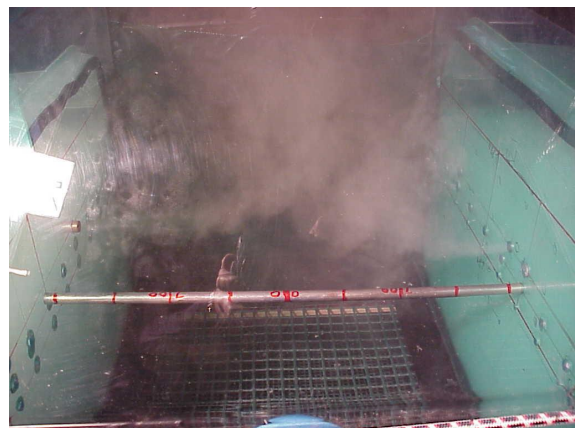

Figure 11. *General view of secondary air jets visualisation model at TUT on left (a), view of secondary air jets behaviour and measuring of penetration with rod in a certain test (b).*

Thirdly, many combustion tests were carried out with the real small-scale batch-type combustion furnace made at Tulisydän Oy by varying the primary/secondary air supply ratio. In the combustion tests, the place of ignition and the size of firewood were also tested. A test where there was a narrowed furnace at the grid level was tested in order to see the effect of free space between the furnace side wall and the firewood batch. Pyrolysed gases easily go near the side of the firewood batch to the flue gas channel without burning out and thus forming a lot of emissions.

7.3 RESULTS

7.3.1 Visualisation tests

The effect of secondary air hole size as a function of pressure difference over the hole at the 16 Pa chamber pressure below the surrounding pressure on the secondary air jet penetration is shown in Figure 12a. The calculated air flow through the different size of hole can be seen in Figure 12b.
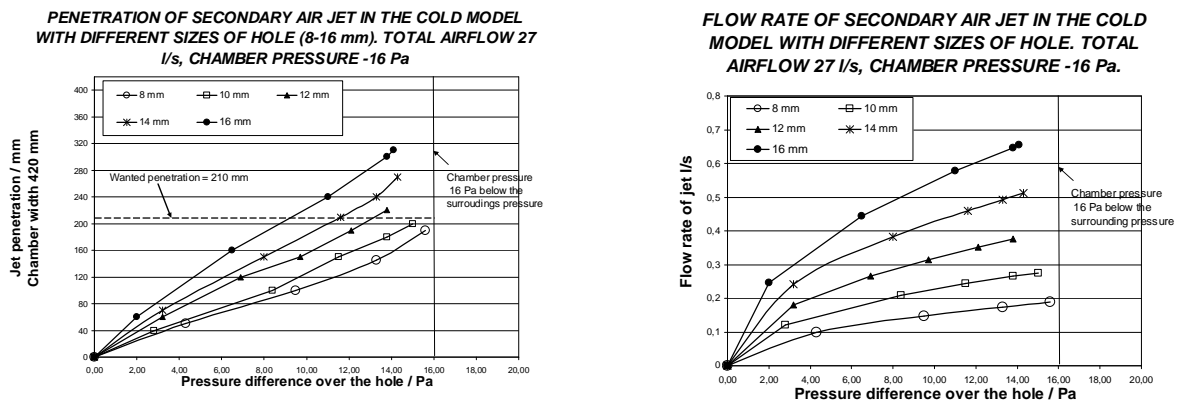
Figure 12. *Secondary air jet penetration on left (a), air flow through the different sizes of hole on right (b) at chamber pressure 16 Pa below the surrounding pressure.*

7.3.2 Combustion tests

According to the combustion tests made in order to reduce CO-emissions, the firewood batch has to be ignited from the top using small firewood splints as shown in Figure 13a. The firewood has to be as dry as possible and its size should be large enough to avoid the release of a large amount of pyrolysis gases. Also in the combustion tests it was observed that the fire woods should not lean to the sidewalls of furnace because they block the airflow near the batch and consequently combustion is inefficient in that area. Fire wood should be placed in the furnace in such a position that the combustion air is able to flow easily in the space between the logs. Then the combustion proceeds downwards fast enough and the whole firewood batch heats up and ignites properly. Also the grid must not be too wide so that the primary air could flow between the sidewall and the batch to the flue gas channel and extract the pyrolysed gases at the same time.

Since small-scale batch-type combustion furnaces use so called natural draught, in ignition and early combustion phase an unavoidable large amount of CO and HC is formed because a lot of pyrolysis gases are formed but the draught of air is still weak and hence the combustion is incomplete, as seen in Figure 13b. During the main combustion stage when the draught of air is large enough but not excessive, the pyrolysed gases burn out almost completely as can be seen in Figure 13b. If the draught is too strong it is possible that the pyrolysed gases go directly to the flue gas channel without burning due to too short a residence time in the hot combustion zone of the furnace.
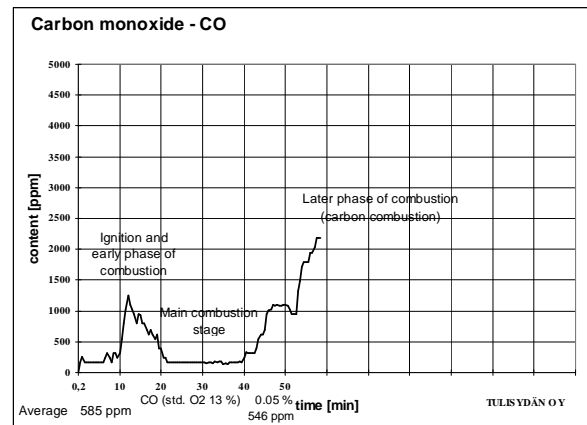
Figure 13. On the top of batch ignition and combustion proceeding downwards on left (a), CO-emissions in different combustion stages on right (b).

Using the secondary air supply above the firewood batch ensures that the pyrolysed gases will have sufficient air for combustion. Also the secondary air should be preheated as hot as possible so that it does not cool unburnt gases in the reaction zone and hence slow the combustion reactions. This kind of situation can happen in the later phase of combustion when the residual carbon of fire woods form CO and this does not burn properly because the temperature of gas mixture is too low. In this stage a lot of CO can be produced as can be seen in Figure 13b. The preheated secondary air supplied near the embers promotes the CO burn out.

By varying the primary/secondary air ratio in many of the combustion tests made at Tulisydän Oy, the number distribution of tests which yield a certain CO concentration was obtained (Figure 14a). Based on the results, it was found that when the primary/secondary air ratio is about 0.5, i.e. the secondary air flow over the batch is about double compared to the air flow through the grid, the optimised situation is reached in respect to the CO-emissions. In this case, the average from the ten tests obtained was 0.081 % CO which is less than the target level of the project (0.1 %) and clearly below the new emission standard level mentioned before (0.17 %). According to the reference (Hyytiäinen et al. 2007), if the secondary air is not used at all and all the combustion air is supplied as a primary air, the CO-emissions will be about three times higher. The flame which gets secondary air has different structure compared to the structure of flame in the traditional furnace. As can be seen in Figure 14b, the flame over the firewood batch becomes narrow at the beginning but after that it spreads in upstream due to secondary air jet flows and gases expanding at high temperature combustion.

COMBUSTION TESTS

6 off 16 mm holes/sidewall, Narrowed furnace on the grid level, Average content of CO 0.081 %, 10 tests
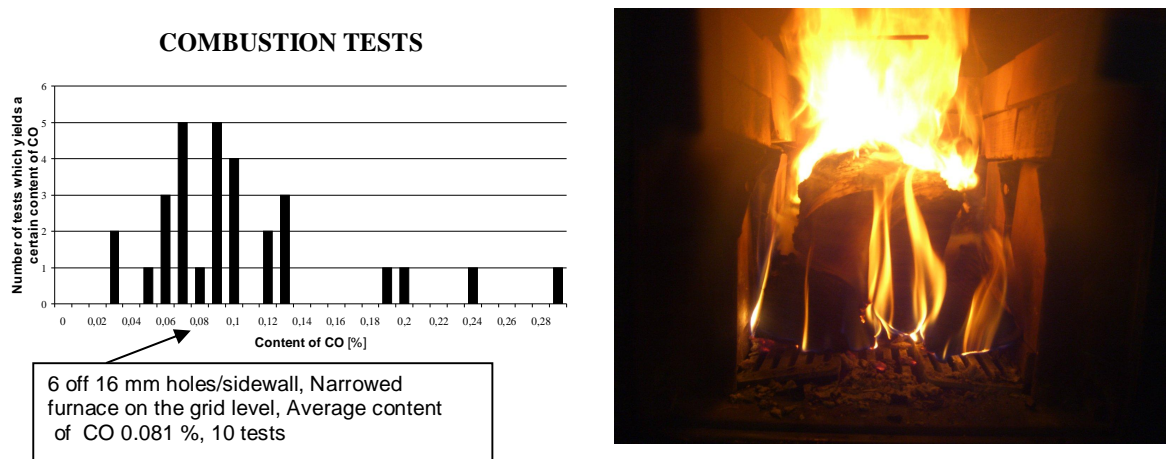
Figure 14. Number of tests at certain primary/secondary air ratio as a function of CO-emission on left (a), the flame structure in using secondary air on right (b).

7.4 CONCLUSIONS

CO-emissions have been reduced by more than 65 % from the original level by developing a new and optimised air delivery system into a small-scale batch-type combustion furnace using knowledge of visualisation tests results. Based on the knowledge of other emission component behaviour with respect to CO, such as HC and fine particles, it can be concluded that they have also been reduced in the same way without doing different measurements.

Also the way of using this kind of furnace influences the emissions produced considerably. Emissions formed as a result of incorrect use of furnace can be many times greater than the emissions from well operated furnace. With this in mind, informing users how to use furnaces correctly is also very important.

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Session II: Reduction of Fine Particle Emission with Flue Gas Cleaning Devices

8 TECHNOLOGIES FOR CONTROLLING FINE PARTICLE EMISSIONS

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8.1. INTRODUCTION

A dust or ash removal system is usually needed to control the quantity and, in some cases, the characteristics of particles going to the stack. The most important factor in determining the type of fly ash collection technology to be used is the permissible particulate outlet emission concentration in mg/Nm^3.

If an invisible plume is required, this requires an outlet emission of typically 50 mg/Nm^3 (O_2, dry) or less. For a high dust formation fuel, the inlet burden to the flue gas cleaning plant could be as high as 30 g/Nm^3. To give an invisible outlet plume, the collection/filtration efficiency of a plant would therefore be:

$$\text{Efficiency } [\%] = (E_{in} - E_{out}) / E_{in} \text{ x } 100 \qquad (6)$$

where E_{in} inlet dust concentration (30 g/Nm^3)
            E_{out} outlet dust concentration (0.05 g/Nm^3)

Therefore: Efficiency required = (30 - 0.05) / 30 x 100 = 99.83%

The penetration of fine particles through a particulate removal system is also an important attribute, and can be given as:

$$\text{Penetration } [\%] = 1\text{- Efficiency } [\%] = 1 - [(E_{in} - E_{out}) / E_{in} \text{ x } 100] \qquad (7)$$

In the case of electrostatic precipitators (ESPs), the penetration maximum (or the minimum level of filtration efficiency) is lowest for fine particles between 0.1-1.0 μm (aerodynamic diameter), as can be seen from Figure 15. Even where the total collection efficiency is over 99% of the total particle mass, efficiency in respect of ultra-small particles is often only 90-95%. Due to the small size and their small share of the total particulate mass, the effect of these fine particles is small on total penetration or filtration efficiency. However, the smallest particles are believed to be the most dangerous for human health, which is why it is important to achieve as high collection efficiencies as possible for ultra-small size classes.

Other important factors are the particulate inlet concentration before the removal system, flue gas volumetric flow rate, the flue gas temperature, and fly ash constituents and properties. Once these basic design parameters are known, an estimated entire life cost (capital investment, operating costs, and maintenance costs) can be calculated for each available

technology, and the technology with the lowest costs can be selected.
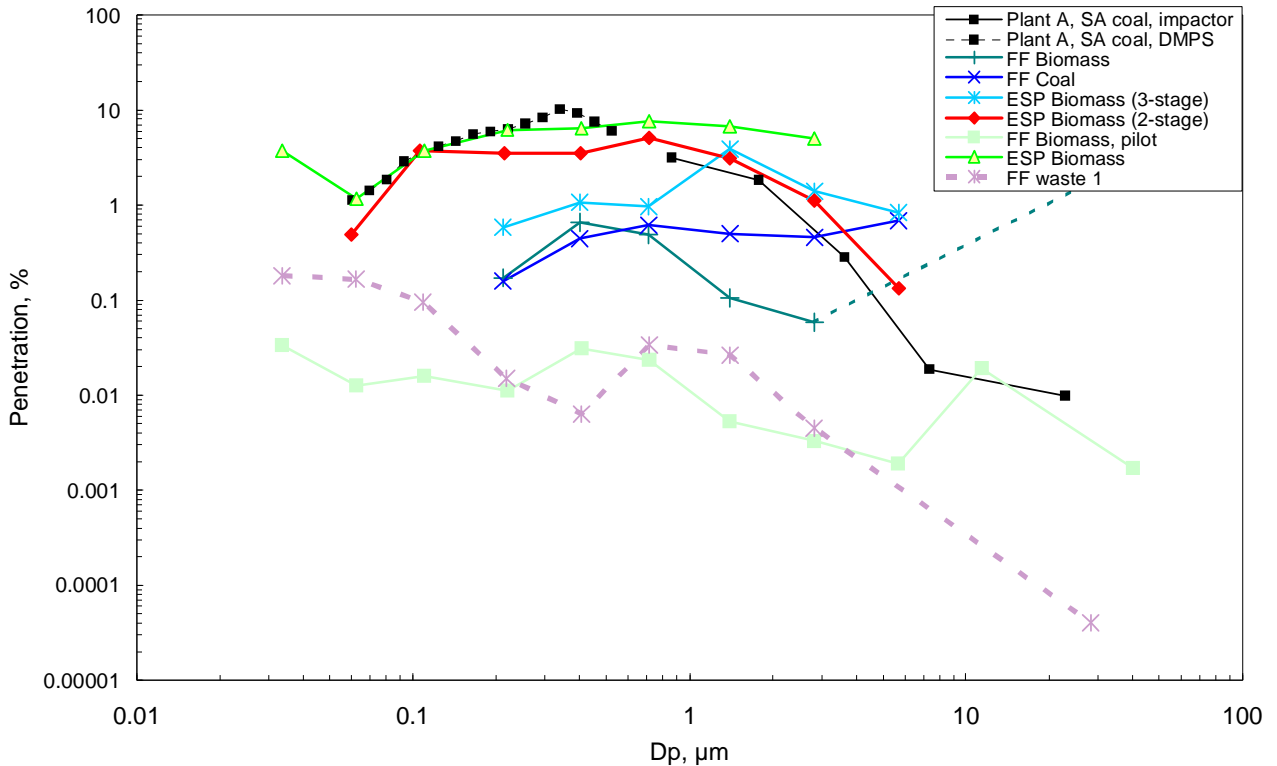
Figure 15. *Measured filter efficiencies at different types of power plants (Hokkinen et al. 2005).*

8.2 TECHNOLOGIES

The choice of fly ash collection technology for modern heat and power generation systems is usually between electrostatic precipitators and fabric filters. Both ESPs and fabric filters are highly efficient, with design efficiencies in excess of 99.5%. The efficiency of both types can be further improved by flue gas conditioning.

Other alternatives include mechanical or inertial collectors, and wet systems (scrubbers).

8.2.1 Mechanical/inertial collectors

In the past, industrial plant operators tended to fit cyclones for particulate removal. More recently, fabric filters have become increasingly popular in a number of industrial processes. Cyclones represent a robust technology capable of handling the cyclical operation and load changes typical of these types of plants. However, they offer only moderate efficiency compared to ESPs or fabric filtration, and cannot remove the finest particles from flue gas.

The efficiency of mechanical or inertial collectors is typically 50-99% for particles in the size range of 1.0-100 µm. An efficiency of 90% is typical for particles over 10 µm. Structure of a

mechanical fly ash separator is presented in Figure 16.

Cleaned gas (outlet)
Uncleaned flue gas (inlet)
Guide vane
Particles to receiver
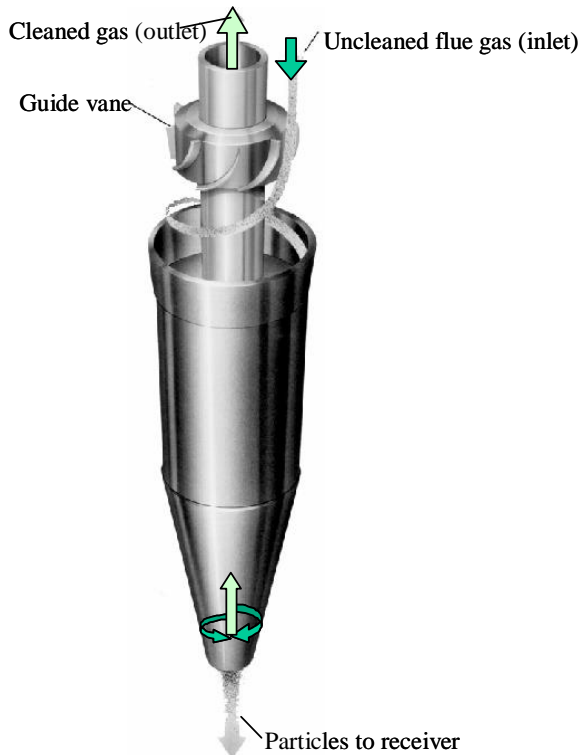
Figure 16. A schematic view of a mechanical fly ash separator.

8.2.2 Wet scrubbers

The most widely used type of wet scrubber is the venturi scrubber, in which water is injected into the flue gas stream to form droplets on to which fly ash particles impact, forming a wet by-product, which then generally needs to be disposed of.

The efficiency of wet scrubbing systems generally drops off at smaller particle sizes. They can also have high energy consumption, due to the use of sorbent slurry pumps and fans. Wet scrubbers also remove SO_2 from flue gas, and many units are designed to control both SO_2 and particulates by utilising alkaline fly ash as a sorbent. Lime is frequently used to boost SO_2 removal efficiency. Other chemicals can also be used.

Removal efficiency is typically between 90-99.9% for particles in the 0.5…>100 µm size range. Structure of a wet fly ash separator is presented in Figure 17.
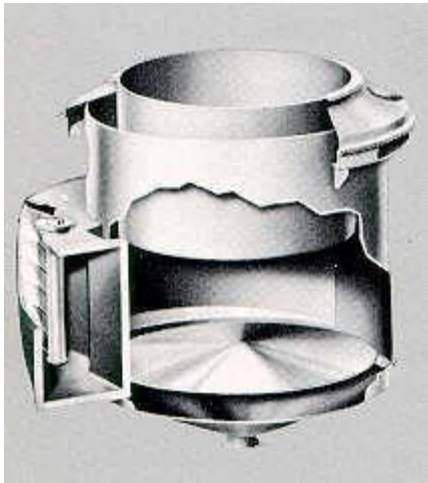
Figure 17. *A schematic view of a wet fly ash separator.*

8.2.3 Electrostatic precipitators

Electrostatic precipitators (ESPs) are widely used as the main technology for controlling particulate emissions, and this is expected to continue for the next couple of decades. The choice between ESP and fabric filtration generally depends on fuel, plant size, and boiler type and configuration.

An ESP captures dust particles by ionising the flue gas in high-voltage coronas that charge the particles. An electrical field is used to move the particles onto large, earthed, flat collecting electrodes, which are rapped at intervals to dislodge the dust, which falls into collection hoppers and is subsequently removed by a dust handling plant (Figure 18).

Cold-side (dry) ESPs fitted with fixed or rigid electrodes and located after the air pre-heater, operating at between 130 and 180 °C, account for the bulk of the current market. Units with moving electrodes are becoming more widely used, however.

Hot-side (dry) ESPs, located before the air pre-heater operating in a temperature range of 300-450°C, are used mainly in the USA and Japan. In these units, a liquid film is maintained on the collection plates using spray nozzles, which eliminates the need for rapping, as the liquid film removes any deposited fly ash particles. This also eliminates problems with re-entrainment, fly ash resistivity, and the capture of fine particles. However, wet ESPs require saturation of the flue gas stream with water, generate wastewater and sludge, and operate only at low temperatures.

Removal efficiency is usually between 99->99.99% for particles in the 0.01- >100 µm size range.
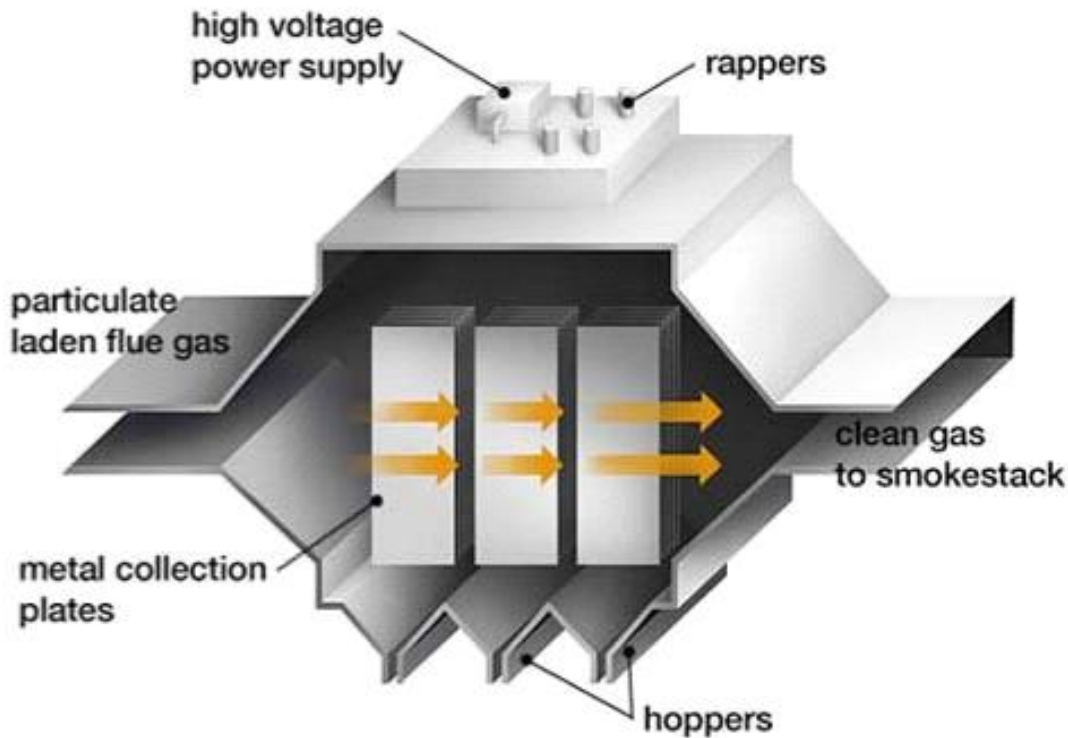
Diagram courtesy of http://www.zet.com/techrefs_overview_fr.html

Figure 18. A schematic view of a dry electrostatic precipitator (ESP). Courtesy of http://www.zet.com/.

8.2.4 Fabric filters

Fabric filters (FFs), which generally operate at between 120 and 180°C, have become more widely used since the 1970s, especially in industry. Installed in a baghouse, a fabric filter captures dust particles by forcing the flue gas to pass through a permeable fabric causing the particles to be collected on the surface of the fabric (Figure 19). The dust is then removed from the filter bag by means of a cleaning mechanism and deposited in collection hoppers.

There are three types of fabric filters. The most commonly used type is the pulse jet filter, in which a pulse of compressed air is introduced down the inside of the bag to dislodge the dust accumulated on the outside of each bag. Other types of filters using shaker mechanisms or reverse gas flow have been installed in the past, but are more expensive than pulse jet filters and require considerably more space.

Overall, the technology is relatively simple compared to ESP. Outlet emission is generally less than 50 mg/Nm^3 for a well-designed system, resulting in an invisible plume.

Fabric filters are increasing their market share, mainly in the process industry. New developments in chemical addition (activated carbon, lime) to form a chemically reactive filter cake have been commercialised, and filter elements with catalytic properties are also now available.

Removal efficiency is >99- >99.99% for particles in the 0.01- >100 µm size range.
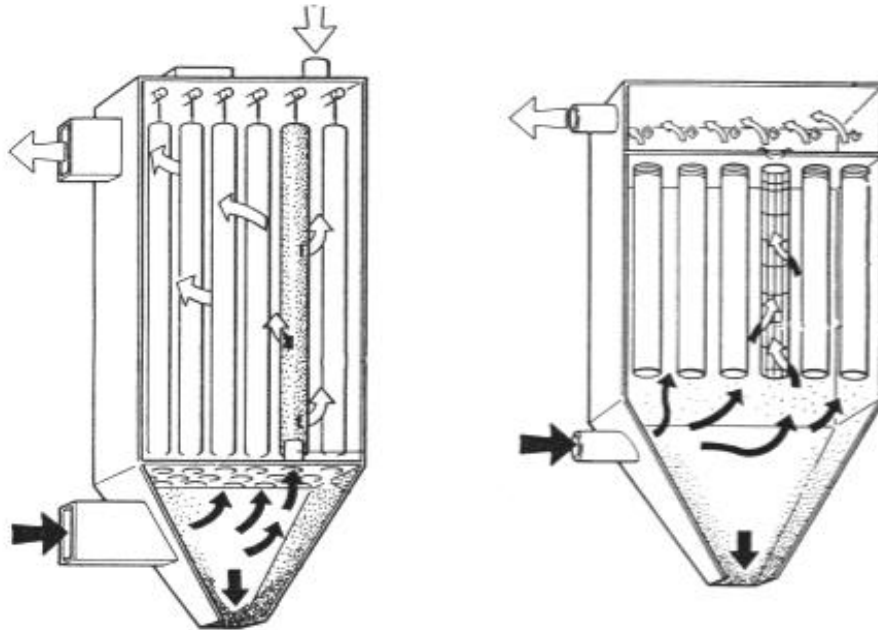
Figure 19. *A schematic view of a fabric filter (FF).*

8.2.5 Comparison of ESPs and Fabric Filters

The difference between the two technologies usually becomes much more apparent when very low emissions are required, and is normally reflected in a lower entire life cost for fabric filters. In addition, fabric filter plant performance is not usually affected by variations in coal quality, whereas ESP performance can be affected significantly. Another advantage of fabric filters is that a clear stack can be obtained under all operating conditions, including start-ups, whereas ESPs do not usually capture oil soot from start-up oil burners, resulting in a temporarily dirty stack (Table 3).

Another alternative is to install fabric filter plant downstream of existing ESP equipment. This has been carried out successfully in the USA and at Swanbank 'A' Power Station near Ipswich in Australia, where fabric filters from an older de-commissioned station were installed downstream of operational ESPs, resulting in 'clean stack' outlet emissions.

Helsinki Energy in Finland uses fabric filters at its Salmisaari power plant to remove the particulates formed in its semidry flue gas desulphurisation (FGD) process. Flue gas passes through an ESP prior to the FGD unit. This approach has resulted in very low particulate emissions, as low as 1 mg/MJ. Using ESP and fabric filter technology in this way makes it possible to optimise both systems for specific sizes of particles, and reduces the requirement for fabric filter efficiency.

Table 3. A comparison of ESP and FF properties (Ohlström et al. 2005). A "+" sign means better applicability and a "-"sign means worse applicability compared to the other technology.

	ESP	FF
Investment cost	-	+
Operation and maintenance costs	+	-
Pressure loss	+	-
Collecting efficiency - TSP - Fine particles - High-resistive dust	+ - -	+ + +
Moisture	+	-
Corrosion	-	+
High temperature	+	-
Glowing particulates	+	-
Acids and ammonia	+	-
Exploding gases	wet ESP	-
Removal of SOx, HCl, HF, etc.	-	+

8.3 SUMMARY

In large-scale boilers the specific emissions of PM2.5 fine particles are even less than hundredth part of the emissions of small-scale (10–50 kW) boilers, i.e. 0.5–50 mg/MJ compared to 50–600 mg/MJ (Ohlström et al., 2005; Ohlström, 1998). The specific emissions of fine particles depend most of all on particle separation device(s) used. The used fuel or combustion technique does not have as great influence.

The most effective separation device for fine particles is fabric filter. Recent measurements show that after fabric filter the share of PM1 in flue gas is only 1–10% of the total particle mass that is mainly composed of coarse particles/material released from filter or from exhaust gas duct.

Finnish measurements also show that collection efficiencies of 98–99.9% from total particle mass can be achieved using both ESP and FF technologies. Measurement data indicates that fabric filters are best at removing the smallest particles. Fabric filters offer an efficiency of over 99% (by mass) for fine particles, while ESPs offer somewhat lower performance in respect of fine particles between 0.1–1 µm (by aerodynamic diameter), at between 90% and 99%.

The problem considering small-scale wood combustion is that fabric filters and ESPs cannot currently be (economically) used for removing fine particles below 10 or 5 MW size classes. In addition, fabric filters must be protected against sparks when burning biomass.

In Table 4, the advantages and disadvantages of different particulate control technologies are summarised.

Table 4. *Advantages and disadvantages of particulate control technologies.*

Device	Minimum particle size [µm]	Collection efficiency [%*] (Flagan & Seinfeld 1988)	Measured collection efficiencies in Finland [%*]	Advantages	Disadvantages
Separation chamber (generally used as pre-separator)	>20	<50	not available	low pressure drop, relative simplicity and few maintenance problems, dry collection and disposal,	low collection efficiency, do not separate fine particles, inability to handle sticky materials
Cyclone (generally used as pre-separator)	5–25	50–90	60–85	simple construction, no moving components, little maintenance, low investment and operating costs, constant pressure drop, saves room, beyond temperatures control, dry relief during wet cyclone	low output for low particle diameter, bad performances at charge, emission of effluent at wet cyclone, erosion sensitive and constipation danger to the entrance, possibly noise nuisance
Multicyclone	5		75–98	simple construction, constant pressure drop, continuous particulate removal, separates big particles quite efficiently	low collection efficiency for low particle diameter, constipation danger to the entrance for high dust and moisture concentrations, for low temperatures and for sticky materials
Wet scrubbers:			not available	simultaneous removal of gaseous and particle emissions, relatively little maintenance, rather high disposal efficiency, insensitively for fluctuating gas flows, capability for cooling and cleaning hot and wet flue gases and to neutralise corrosive gases/mists, decreased dust explosion risk, efficiency control	corrosion and erosion problems, increased sewage disposal costs, potentially high pressure drop, low collection efficiency for fine particles (<1 µm), possibly even increasing the smallest particles, freezing problems in cold climate
Spray tower	>10	<80			
Dynamic scrubber	>2,5	<80			
Collision scrubber	>2,5	<80			
Venturi scrubber	>0,5	<99			

* from total particle mass

Table 4. *(continues)*

Device	Minimum particle size [μm]	Collection efficiency [%*] (Flagan & Seinfeld 1988)	Measured collection efficiencies in Finland [%*]	Advantages	Disadvantages
Electrostatic precipitator	<1	95–99+	99,2–99,9 (<2,5 μm particles: 96,9–99,1 and <1 μm particles: 95–99)	>99% overall efficiency, collects also fine particles, wet and dry separation, low pressure drops and relatively low energy demands compared to other efficient methods, continuous operation with minimum maintenance, relatively low operation costs, operation capability at high temperatures (up to 700 °C)	high capital costs, sensitive to fluctuating dust loads and gas flows, difficulties with the collection of particles with extremely high or low resistivity, relatively large space requirements, special precautionary requirements from high voltage during maintenance, collection efficiency can decline gradually and unnoticeably
Fabric filter	>0	>99	<2,5 μm: 99,9 <1 μm: 99,7	very high collection efficiencies (99.9%) both for coarse and fine particles, dry recovery of collected material for subsequent processing and disposal, relatively simple operation, no corrosion problems, high collection efficiency of submicron smoke and gaseous contaminants through the use of selected fibrous or granular filter aids, declining performance is well detectable	rather high maintenance requirements and operation costs (fabric changes between 2-4 years), shortened fabric life at elevated temperatures and in the presence of acid or alkaline particulate or gas constituents, sensitivity to filtration velocity, hot gases must be cooled down, glowing, sticky or big particles need pre-separation (explosion and fire hazard), the effect of relative humidity (condensation), the effect of chemicals, bypassings during failure situations

* from total particle mass

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9 USING CONDENSING HEAT EXCHANGERS AS FINE PARTICLE COLLECTING DEVICES - PRELIMINARY LABORATORY MEASUREMENTS

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9.1 INTRODUCTION

Heat exchangers can be described as devices which transfer heat between two fluids, e.g. between flue gas and coolant liquid. These devices are commonly used in chemical process technology, industrial energy production, cooling devices and air conditioning devices. In energy production they can be used to recover waste heat from flue gases which raises the overall energy efficiency of the plant or process.

In small scale combustion, which in this paper describes as the combustion in stoves, small boilers, pellet burners, fireplaces etc, the flue gases normally are relatively hot. In continuous combustion, the average temperatures vary in a range from 140 to 190 °C, while the average temperature in batch combustion is approx. 210 °C, but can rise up to 350 °C in sauna stoves (Ohlström et al., 2006). In small scale combustion waste heat recovery is seldom applied.

Fine particle deposition in heat exchangers attached into flue gas systems is a known phenomenon, and is usually described as fouling. There are indications, however, that this deposition can also be used as relatively efficient way to collect particles from flue gases.

Lehtinen et al. (2002) has studied the use of a tube heat exchanger in particle recovery in Passive Containment Condenser (PCC) system used in nuclear plants. The PCC system is designed to remove excess core heat in the case of a severe accident but it can also be optimized to prevent some of the radioactive particle emission. In the study, it was found, that even with relatively high flow velocities (100 standard litres per minute), depositions up to 53 per cent of the mass concentration could be obtained. The results indicate that in that application the deposition was directly proportional to the water vapour content of the flue gas. This suggests that the major deposition mechanism in the condensing heat exchanger was diffusiophoresis.

Other studies with heat exchangers have been conducted by Shi and Harrison (2001) and Messerer et al. (2003). In the previous study Shi and Harrison introduced a method to reduce fine particle emissions of a heavy duty diesel engine with a water-cooled fluidized bed. The latter study was conducted with a plate-to-plate heat exchanger and in both studies over 90 per cent collection efficiencies of the mass emission were found. In these studies the major deposition mechanism was thermophoresis.

By optimising a heat exchanger for fine particle deposition and applying it into small scale combustion process, it is possible to obtain both waste heat recovery and reduction in the fine particle emissions. In this research we studied the deposition of fine particles in a glass heat exchanger with an 8 kW pellet burner.

9.2 DEPOSITION MECHANISMS IN A CONDENSING HEAT EXCHANGER

Diffusiophoresis can be described as the movement of the particles in the flue gas due to the movement of condensing vapours. If the flue gas contains condensing gases such as water vapour, these start to condense on the heat exchanging surface if the temperature of the flue gas is lowered below the dew point of the condensing gases. This creates a partial pressure gradient in the gas for the condensing vapour which leads to the diffusion of the vapour towards the heat exchanging surface. The moving vapour molecules also induce a net force and thus a net movement to the fine particles in the flue gas. (Waldmann and Schmitt, 1966.) Diffusiophoresis is theoretically almost independent of the particle size, where the only exception is the transition regime. The theory for diffusiophoresis in the transition regime is still under development.

Thermophoresis is the movement of the particles due to the brownian diffusion of the surrounding gas molecules in a temperature gradient. The gas molecules in the higher temperature have a higher thermal motion which leads to a brownian diffusion of the molecules in a temperature gradient. These molecules induce also a net force and thus movement to the particles in the flue gas.

The difference between diffusio- and thermophoresis is that in diffusiophoresis only one component of the flue gas diffuses to the heat exchanging surface whereas in thermophoresis all components of the flue gas start to diffuse towards the surface. Diffusiophoresis is an affecting phenomenon only until the condensing potential of the flue gas is fully used, thus the vapours cannot condense any further. Thermophoresis can be obtained as long as the temperature gradient holds. In regular heat exchangers the temperature gradient at the end of the heat exchanger is close to zero (the temperature of the flue gas and the heat exchanger surface is almost the same). On the other hand diffusiophoresis can be optimised so that the condensing film on the surface helps to prevent fouling of the surface. At some point this fouling dramatically reduces the performance of the heat exchanger.

9.3 EXPERIMENTAL

The measurements were done using a tubular heat exchanger made out of glass. The parameters studied were the effects of the heat exchanger to the PM1 number and mass emission and the particle size distribution from an 8 kW pellet burner. The used heat exchanger is described in Figure 20 and the process flow chart of the experiments in Figure 21.

The gas parameters of the flue gas were measured with four devices, the ABB (Hartmann & Braun) Limas 14 UV, Uras 14 and Multi-FID 14 and the Gasmet Fourier Transfer Infrared spectrometer (FTIR). The components measured were water vapour content, CO_2, O_2, CO,

NO$_X$ and total hydrocarbon content of the flue gas. The water vapour content, CO$_2$ and the O$_2$ were measured with the FTIR so that the placement of the FTIR probe was changed every 40 minutes from before to after the heat exchanger and vice versa. The combustion process of the Wodtke burner as well as the performance of the heat exchanger was stabile enough to make this possible.

Particle size measurements were done using two particle sampling devices, the Dekati Electrical Low Pressure Impactor (ELPI) and the TSI Fast Mobility Particle Sizer (FMPS). The instruments were measuring from different sides of the heat exchanger at the same time. Approximately every twenty minutes the flow was turned with a four-way valve so, that the instruments changed sides of measurement. With this we could obtain steady monitoring of the process, and comparable samples from both sides of the heat exchanger. Comparing results obtained with ELPI and FMPS is not efficient due to the differences of the measurement principles. As with the gas components of the flue gas, also particulate emissions from the Wodtke burner were stabile enough so that not simultaneous samples from both sides was acceptable. Both instruments obtained one size distribution every five seconds.

The mass measurements were done accordingly, with the following changes. Both lines after dilution ended with a PM1-impactor, followed with a Gelman filter collection unit. The flows were controlled with needle valves. The filters were weighted both before and after the measurements. The results were calculated into mass emissions following the SFS-standard 5624. Also the number concentrations obtained with the particle sizing devices were calculated according to the same standard, resulting as an adaptive number emission figures.
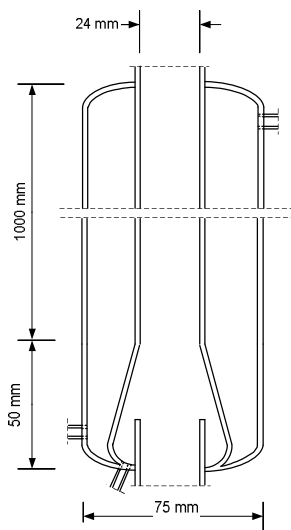

Figure 20. *Glass tube heat exchanger with a condense water collector.*
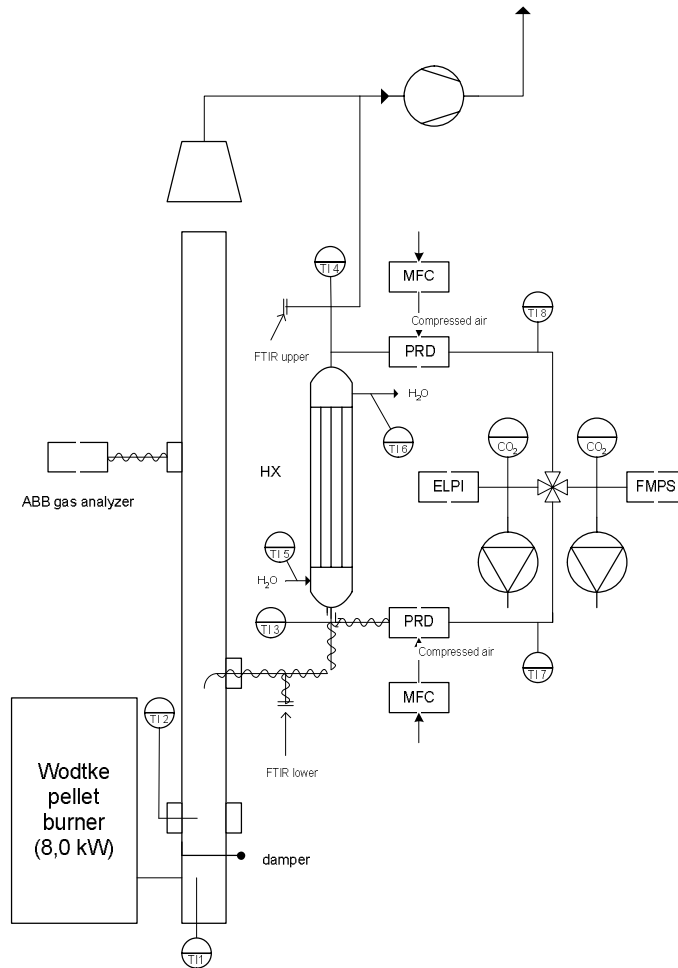
Figure 21. The process flow chart. Tubes for the partial flow from the main stack were made of standard vacuum parts (NW-25, inner diameter 25 mm). The sample lines before and after the heat exchanger were made of Ø12 mm steel pipe (collection probes Ø6 mm steel tubes). Line before the exchanger was heated to 150 °C. Sample lines after dilution were 120 cm of length. TI = temperarture indicator. FTIR = fourier transfer infrared analyzer. PRD = porous tube diluter. MFC = mass flow controller. ELPI = electrical low pressure impactor. FMPS = fast mobility particle sizer. HX = heat exchanger.

The variable used in this study was the flow velocity in the heat exchanger. Even though the water vapor content was already known to be a major influencing variable for deposition, we were not able to use that as a variable in these preliminary experiments due to technological difficulties with controlling the vapour content. The velocities used were 0.95 and 1.5 m/s, which both were on the laminar flow regime and correspond as flow velocities of flue gases in a common small scale combustion process.

The particle size distributions and number concentrations were measured on 5 days, of which 3 days with the higher flow velocity and 2 days with the lower flow velocity. The mass measurements were conducted on one day. The lengths of samples are presented in Table 5.

55

Table 5. The sample lengths for both mass number/size measurements and mass measurements.

Day	FMPS before / ELPI after (mm:ss)	FMPS after / ELPI before (mm:ss)	Mass measurements 23.3.	
			Flow velocity (m/s)	*Sample length (mm:ss)*
8.2.	17:20	16:54	1.5	20:00
	14:20	19:00		20:00
	18:54	13:35		18:50
	17:57	22:13		20:00
	25:57			20:00
9.2.[1]	19:57	15:30	0.95	20:00
	10:00	17:59		20:00
	20:00			20:00
13.2.	19:59	14:54		18:44
	18:58	19:16		20:00
	25:00			
15.2.	22:00	12:07		
	20:00	20:58		
	19:58	18:56		
	22:56	21:56		
	16:29	20:57		
	20:05	20:00		
16.2.	13:49	23:00		
	19:21	20:00		
	18:58	23:52		
	18:54	11:40		
	83:26:00	17:57		

[1] 9.2. Results were obtained only with ELPI, due to a malfunction with the dilution system of FMPS.

9.4 RESULTS

The Tables 6, 7 and 8 present the average properties of the flue gas. The temperature of the flue gas before the heat exchanger remained almost the same in all experimental settings, varying from 138.3 °C to 148.9 °C. Also the temperatures after the heat exchanger remained the same throughout the experiments. The heat exchanger lowered the temperature of the flue gas to a steady level of approximately 63 °C.

The flue gas was found to be relatively stabile in composition throughout the experiments, as found in the Table 7. The water vapor content was relatively low, keeping below 5 %-vol. The condensation in the heat exchanger lowered the vapor content so that the flue gas after the heat exchanger was found to have a steady vapor content of approximately 2.5 %-vol.

Table 6. *Average temperatures. The measuring points correspond to the ones indicated in the figure 21. s is the standard deviation of the values.*

Measuring point	1,5 m/s		0,95 m/s		Mass measurements	
	T (°C)	s	T (°C)	s	T (°C)	s
Stack connection (TI1)	196.6	8.9	195.2	9.1	201.1	4.6
Stack (TI2)	167.6	8.7	164.7	9.2	162.9	5.2
Before Exchanger (TI3)	148.9	5.8	143.7	5.4	138.3	2.6
After exchanger (TI4)	66.2	2.3	60.7	1.5	61.3	2.7
Coolant in (TI5)	6.9	0.3	6.9	0.2	7.0	0.3
Coolant out (TI6)	7.8	0.5	7.8	0.3	7.8	0.2
Lower sample line (TI7)	21.5	0.9	23.2	0.8	23.7	0.5
Upper sample line (TI8)	21.4	0.8	22.4	0.2	23.9	0.4

Table 7. *The average values of gas components of dry flue gas. s is the standard deviation of the values.*

Measurement	CO_2		CO		NO_X		O_2		Total HC	
	C	s	C	s	C	s	C	s	C	s
	(vol- %)		(ppm)		(ppm)		(vol- % %)		(mg(C)/m^3)	
1.5 m/s	4.2	0.7	123.5	71.9	34.6	5.7	16.0	0.7	31.7	17.0
0.95 m/s	4.3	0.7	135.0	51.8	34.9	5.5	16.1	0.7	35.4	15.7
Mass	4.5	0.8	144.6	60.2	34.1	6.2	16.1	0.8	36.6	14.7

Table 8. *Average water vapor content of the flue gas. s is the standard deviation of the values.*

Measurement	C_{H2O} before (*vol- %*)	s	C_{H2O} after (*vol- %*)	s
1.5 m/s	3.7	0.6	2.6	0.3
0.95 m/s	3.4	0.5	2.4	0.3
Mass	4.5	0.6	2.6	0.3

The particle deposition measurements regarding particle size distributions and number concentrations are listed in the Tables 9 and 10 and in the Figures 22 and 23. As seen in the table values, the mean diameter did not change, nor did the shape of the distributions change according to the geometric standard deviations. Mean collection efficiencies varied from 8 to 24 per cent of the total number emission, depending on the measuring device and the flow velocity. The differences observed in the latter can be explained with error margins, though. The differences between the two velocities are within the uncertainty limits of the measurements.

Table 11 and Figure 24 explain the observed changes in mass emission, where the collection efficiency staid in 7.5 per cent of the mass emission.

Table 9. *Total number emission, geometrical mean diameter and geometrical standard deviation of the average distributions calculated with the results obtained with ELPI. η = collection efficiency; Δ = change in the mean diameter.*

Day	Emission (#/MJ)			GMD (nm)			GSD	
	Before (×10¹³)	*After (×10¹³)*	*η (%)*	*Before*	*After*	*Δ*	*Before*	*After*
8.2.	8.19±1.04	7.02±0.80	*14*	51.8	53.6	*1.8*	1.69	1.72
9.2.	8.67±1.63	7.10±1.42	*18*	51.1	52.6	*1.5*	1.70	1.74
13.2.	8.62±1.29	6.93±0.89	*20*	48.6	50.1	*1.5*	1.66	1.69
15.2.	9.40±1.23	7.91±1.52	*16*	47.1	48.6	*1.5*	1.65	1.68
16.2.	8.69±1.99	6.15±1.39	*29*	47.1	48.8	*1.7*	1.67	1.70
1.5 m/s	**8.43±1.29**	**7.01±1.01**	*17*	**50.7**	**52.3**	*1.6*	**1.69**	**1.72**
0.95 m/s	**9.08±1.66**	**6.92±1.69**	*24*	**47.1**	**48.7**	*1.6*	**1.65**	**1.69**

Here $\times10^{13}$ denotes the exponent scaling of the emission columns.

Table 10. *Total number emission, geometrical mean diameter and geometrical standard deviation of the average distributions calculated with the results obtained with FMPS. η = collection efficiency; Δ = change in the mean diameter.*

Day	Emission (#/MJ)			GMD (nm)			GSD	
	Before (×10¹³)	*After (×10¹³)*	*η (%)*	*Before*	*After*	*Δ*	*Before*	*After*
8.2.	7.75±1.01	6.74±0.98	*13*	40.8	41.0	*0.2*	1.56	1.56
9.2.	-	-	*-*	-	-	*-*	-	-
13.2.	6.14±1.17	5.29±1.05	*14*	40.9	41.9	*1.0*	1.57	1.55
15.2.	6.88±1.17	6.17±1.05	*10*	41.0	42.2	*1.1*	1.56	1.54
16.2.	5.83±0.97	5.37±0.90	*8*	42.0	42.6	*0.5*	1.57	1.56
1.5 m/s	**7.10±1.34**	**6.17±1.23**	*13*	**40.8**	**41.4**	*0.5*	**1.57**	**1.55**
0.95 m/s	**6.29±1.18**	**5.80±1.06**	*8*	**41.6**	**42.4**	*0.7*	**1.57**	**1.55**
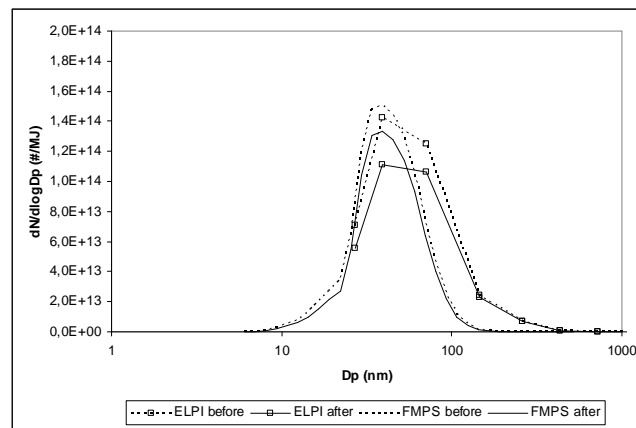
Figure 22. *Avergare size distributions and their changes in number emissions with the 1.5 m/s flow velocity, before and after the heat exchanger.*
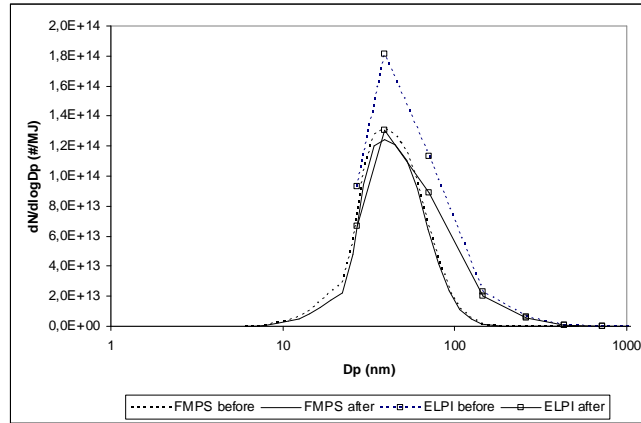
Figure 23. *Avergare size distributions and their changes in number emissions with the 0.95 m/s flow velocity, before and after the heat exchanger.*

Table 11. *The PM1- mass emission and the collection efficiency (η) of the heat exchanger with different flow velocities.*

v (m/s)	Sample #	Emission before (mg/MJ)	Emission after (mg/MJ)	η (%)
	1	18.7	17.1	8.8
	2	17.1	16.0	6.6
1.5	3	16.7	15.7	6.3
	4	16.2	14.8	8.5
	5	17.9	16.4	8.7
	$q_{e, average}$	**17.6**	**16.3**	**7.6**
	1	17.0	15.9	6.4
	2	16.3	14.7	9.5
0.95	3	17.4	16.4	5.3
	4	18.1	16.8	7.5
	5	16.3	14.9	8.7
	$q_{e, average}$	**17.0**	**15.8**	**7.4**

Figure 24. *The change in PM1- mass emission in the heat exchanger with different flow velocities.*

9.5 DISCUSSION

In the measurements we found fine particle deposition in both settings and in all samples. Because of the low humidity of the flue gas, the deposition obtained also was very modest. The heat exchanger did not change the shape of the size distributions. In this geometry, with the flow velocities used, the residence time did not seem to have 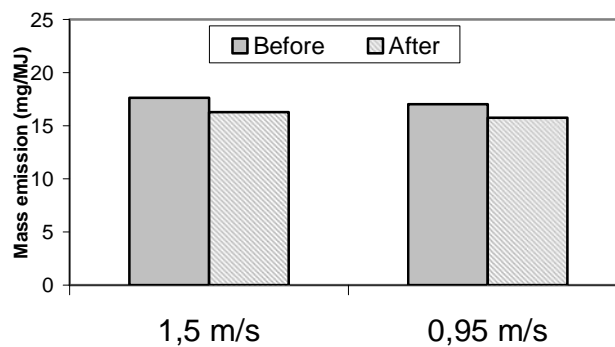effect on the collection efficiency. The differences between the two velocities fit in between the uncertainty limits of the measurements.

The use of diffusiophoretic and thermophoretic deposition in fine particle collection is possible, and the condensate helped to prevent fouling even with this relatively low flue gas humidity. In this geometry, the diffusiophoretic deposition was the main deposition mechanism. According to some preliminary CFD modelling, the temperature gradient was linear and efficient only in the very near vicinity of the heat exchanging surface. This lead to the fact, that the majority of the fine particles were not affected by the thermophoresis. Also according to preliminary modelling, even with this geometry the deposition can be elevated to even 30 - 50 per cent of the mass concentration by simply raising the water vapor content of the flue gas. This will be taken as the major variable under consideration in the following experiments.

As the collection efficiency depends on the geometry of the heat exchanger, the flue gas water vapor content and the temperature gradients in the heat exchanger, applications should be designed process-specific. In general, the heat exchangers are more applicable to continuous combustion than to batch combustion, where especially the optimization of particle deposition might not be possible due to problems with achieving steady condensation rates.

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10 PARTICLE REMOVAL BY FLUE GAS SCRUBBERS

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10.1 ABSTRACT

District heating plants are suitable application targets for flue gas scrubbing and condensing technologies. Tens of scrubbers have been taken into use since the end of 1980's in Finland, and the experiences on them have been positive. In most of the cases the main reason for purchase has been the economical profitability due to the efficient heat recovery, but the flue gas purification has effected on the purchase decisions. Economical profitability is based on savings in fuel consumption and improved efficiency, when heat content of the water formed in combustion process is utilized in scrubbing and condensing processes. Most of the scrubbers have been installed to heating boilers, the output of which exceeds 4 MW, which use moist fuels such as bark, sawdust, wood chips or peat. Purchase of scrubber often replaces the purchase of electrostatic precipitators, which increase the profitability significantly. Typical pay-back times usually vary between 3 -5 years. In Finland only few scrubbers have been installed to power plant scale boilers. At power plants the higher selling price of electric power compared to heat diminishes the economical profitability of the purchase of a scrubber.

10.2 TECHNOLOGY

The main components of a flue gas scrubber are the spray scrubber and the condensing unit. Largest particles are removed in the spray scrubber and the condensing of the water starts from the wet bulb temperature. Multi-cyclones or cyclones are usually used as preliminary separators of particulates in the flue gases. Most of the residual heat content of the flue gases will be recovered in the condenser unit, usually in fixed-bed heat exchangers (packed tower). Many impurities of flue gases, such as sulphur dioxide and hydrogen chloride, and a part of the smaller particles, can be removed from flue gases in the tower. Traditional construction materials include acid-proof steel and reinforced plastic.

After the condensing the flue gases are led through a droplet separator into stack. The residual heat of the flue gases are often recovered by humification of the combustion air, which increases the heat recovery significantly. The condensate formed in the heat recovery is neutralized and the solid matter is separated in a clarifier before dumping into sewerage or in the water courses. Sodium hydroxide (NaOH) is usually used as a neutralizing chemical, which reacts with the washing fluid forming sodium salts. In wood combustion the consumption of neutralizing chemicals is low because the sulphur content of wood is low and the basic wood ash neutralizes the condensate.

10.3 OPERATING VALUES

Separation rates on the scrubbing of flue gases vary widely on the basis of fuel, combustion technology and the means of combustion. Some experimental estimates are given below:

Solid matter	80 – 99% (wood about 80%, peat over 90%)
Sulphur dioxide (SO_2)	60 – 99%
Chlorine	80 – 90%
Heavy metals	60 – 80%.

Heat recovery from flue gases is determined e.g. by moisture content of the fuel, temperature of the return water of the district heating network, combustion air coefficient and the degree of humifacation of the combustion air. The variation range corresponds to 10 – 45% of the boiler output.

Standard values for condensate include e.g. pH 6 – 11, maximum temperature 40 ºC, sulphide content less than 5.0 mg/l and the combined value for sulphates, thiosulphates and sulphites less than 400 mg/l.

10.4 APPLICABILITY FOR SMALL SCALE BOILERS

The scrubber removes effectively the coarse particles (diameter > 2.5 μm) and ultra-fine particles (diameter less than 0.1 μm), but removes poorly the particle fraction of the accumulation area (0.1 – 1.0 μm) (Figure 25). Main fraction of small particles, formed in combustion of wood fuels, belongs to this group. The scrubber removes sulphur dioxide and hydrogen chlorides from flue gases effectively.

For the efficiency of heat recovery, it is vitally important that the air ration is small which is often hard to reach in small-scale combustion. Processing of condensate requires the use of a clarifier and pH control, which increase the costs because of the equipment and space requirements.

Other problems observed include:
- The scrubber resists the gas flow and has low temperature, because of which the draft is poor so a flue gas fan is required
- Only a little condensing power can be obtained from dry fuels such as wood pellets
- Scrubbers can not be applied for batch combustion or heat-accumulating heating systems
- Scrubber and clarifier, used as a after-purification system, require a lot of space
- The use of expensive materials has to be used because of the corrosion risk.

10.5 CONCLUSIONS

In small-scale combustion the wet-scrubber could be applied technically for boilers (output over 100 kW), in which the technical level of the control system is high enough for sufficient control of the combustion process, and hence for obtaining of high rate of heat recovery. Wider use of scrubber technology in small-scale combustion requires the development of new type of boiler to meet the requirements of scrubbing technology.
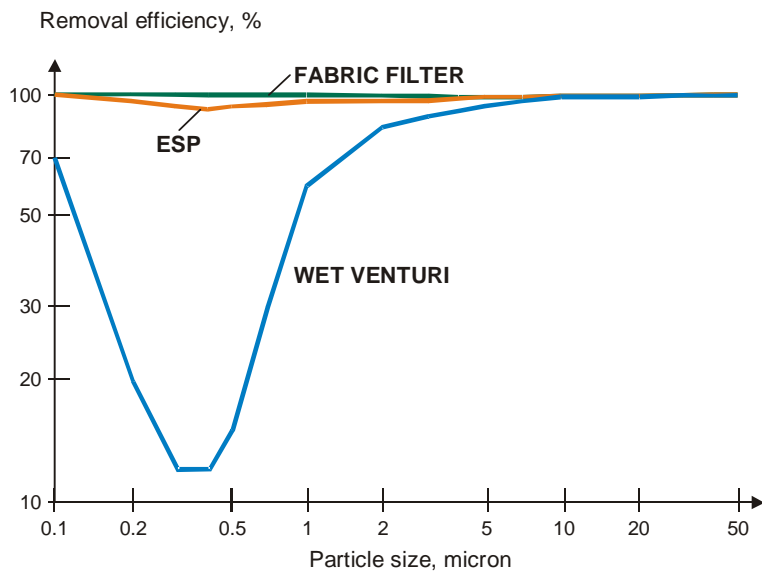
Figure 25. *Removal efficiencies of particle separators. ESP = electrostatic precipitator.*

11 ELECTROSTATIC PRECIPITATORS IN SMALL SCALE WOOD COMBUSTION

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Note to the reader: This presentation is intended for a reader not familiar to ESP technology. The writer has made some intentional simplifications to make the ideas presented more easily adapted. Writer hopes that ESP professional are not offended by this.

The use of electric forces to clean gases from small particles has a long history. The principle of electrostatic precipitation comes from the year 1600 and the first successful industrial applications are from 1908. Today ESP's are widely used in industrial gas cleaning as well as in cleaning of domestic air. However ESP's have not yet been used in the small scale combustion.

The large scale ESP applications that clean hundreds of cubic meters of flue gas in every second utilises the same physical principles as the small domestic air cleaning devices. Still these two extremes of operation have very different practical solutions. Large industrial precipitators have very large collecting area, sophisticated control systems and complicated on-line cleaning systems. This all makes large scale precipitators very effective and very expensive. Small ESP's are more optimised for low initial investment costs to be available for private households. They can be made simpler as the typical dust load is low, operation conditions like temperature and gas composition don't require special solutions and cleaning of the devise is done manually by the end user.

Main problem with the small scale combustion is that it should combine the sophisticated construction needed and the low price that's necessary.

ESP operation can be divided in three parts:

    (i)   inserting an electrical charge to the particles (charging)
    (ii)   collecting the charged particles by an electrical field (collecting)
    (iii)   removing the collected particles from the esp (cleaning)

Particles are charged using a corona discharge (Figure 26). A thin wire (corona electrode) is set to a high electrical potential (tens on kV). Close to the wire surface the electrical field strength is high enough to ionise the surrounding gas. Ions produced in the ionising zone a pushed away from the corona electrode by the electric field. Part of the ions attach to particles and charge them. The charging process is sensitive to the changes in gas composition and especially in particle concentration. Rapid increase in the particle concentration may in worst case even stop the charging process if its effect is not compensated by the voltage source control system. An alternative to adaptive control is to use a "worst case design". In industrial

processes the particle concentration is typically stable and a particle surge usually happens only during the cleaning of heat exchangers or other boiler surfaces. As the cleaning cycle is controlled by the automation system they are easy to predict and compensate. In small scale combustion the particle load is not stable. Here major particle surges are related to the addition of burning material. If the feeding system is automatic like in pellet burners these particle surges can be predicted in some extend. In small scale combustion sophisticated automation becomes easily far too expensive solution and so the problem needs to be solved by carefully sizing the charger capacity for peak particle loads. This however increases the electrical power consumption (= running costs) and so decreases the total power efficiency of the heating installation.
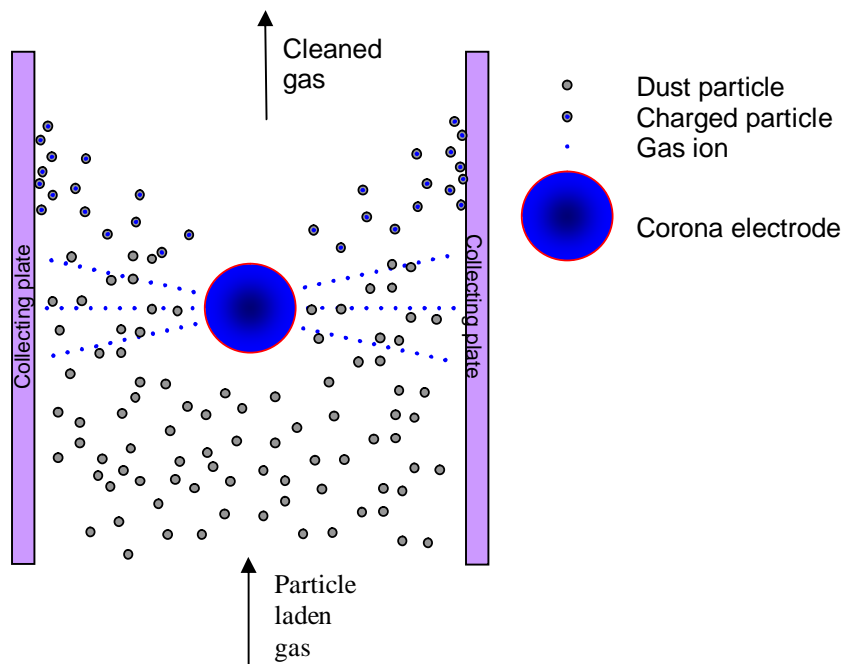

Figure 26. *Operation of ESP.*

After the charging particles can be collected by using electric field that forces the particles to collide with the collecting plates. Large scale precipitators are typically designed so that the charging electrodes are located in the middle of two collecting plates. This way the particles can be collected by the same electric field that is used to charge them. The total collecting plate area is directly related to the collection efficiency of the precipitator – the larger the collection area, the higher the particle removal efficiency (Figure 27). It should be noted that a certain amount of collection area always removes a same fraction of the total particle concentration. This means that if a precipitator with a collection area A has a 50% efficiency the area needed for a 75% efficiency is 2*A and for 99% 7*A. ESP's with high removal efficiency are very large. In domestic heating systems the available space for gas gleaning is limited. Heating with wood already requires much more space that for example electric or gas heating because of the storage needed for the fuel.
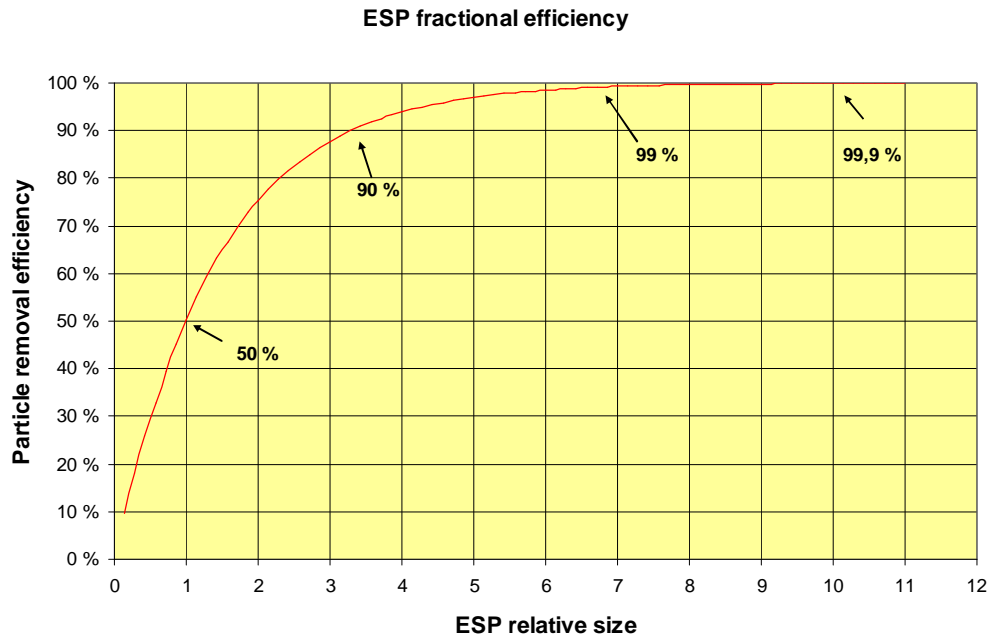
ESP fractional efficiency

Figure 27. ESP fractional efficiency.

The collecting plates can not hold an infinite amount of dust and so they need cleaning. Care has to be taken that the collected dust is not released back to the gas flow during the cleaning. Best way to ensure this would be to do the cleaning when the boiler is not used and there is not gas flow. If the boiler runs continuously for long a period this may not be possible. In large scale precipitators this is a major problem. Large ESP's are separated in two or more blocks with separate power sources. If particles escape the firs block when it is cleaned by rapping (hitting the collecting plates by automated hammers) they are still collected by the next block. Of course particles that re-enter the gas flow from the last block still escape from the precipitator. The last block however has the lowest dust load and the particle emission during cleaning can be minimised. All the ESP blocks need power sources and cleaning devises. This means higher investment cost so this solution may not be available in small scale combustion.

How would a successful small scale electrostatic precipitator be made? We need a device that is small in size, inexpensive and simple to operate. It should also have good precipitation efficiency and it should be insensitive to changes in combustion. And it should do all this with moderate amount of maintenance. Sounds demanding and so it is no surprise that there are several research groups in many countries at this very moment trying to answer to the challenge.

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ESP for small scale combustion
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12 REDUCTION OF FLUE GAS EMISSIONS FROM SMALL HEATING APPLIANCES BY USING CATALYTIC CONVERTERS

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12.1 INTRODUCTION

There are over a million hand fired small scale heating appliances in Finland in which about six million cubic meters of wood fuel is used. Combustion in such heating appliances is a batch-type process. This kind of hand fired small scale heating appliances consists of kitchen ovens, baking ovens, open fireplaces, heating ovens and stoves.

In the early stages of combustion when the volatiles are being burned, the formation of carbon monoxide (CO) and other combustible gases are difficult to avoid especially when using fuels that have a high volatile matter content. Harmful emissions are formed mostly after each addition of fuel.

When the CO-content in flue gases is, say over 0.5%, also other harmful emissions will be formed. Methane (CH_4) and other hydrocarbons are released and the amount of polycyclic aromatic hydrocarbons (PAH) compounds can be high. Some PAH-compounds are very carcinogenic.

Fuel is added according to heat demand with as large amounts as possible being added at a time. In this way the time used for heating is minimized. The heat output being controlled by the amount of combustion air introduced and the draught in the flue. This type of control system works well with fuels having low amount of volatiles where the combustion is mainly heterogeneous combustion of solid carbon that is quite easy to control. Batch-type combustion of fuels having large amount of volatiles leads often to incomplete combustion and high emissions because the mixing of the combustion air and the combustible gases is not sufficient and the temperature is not high enough.

To illustrate batch-type combustion process of wood, CO_2- and CO -concentrations versus time are plotted in the Figure 28. In this example birch-wood having moisture content of 13% was used. Figure 28 shows that fuel was added several times and clearly illustrates that unsteady combustion is taking place.
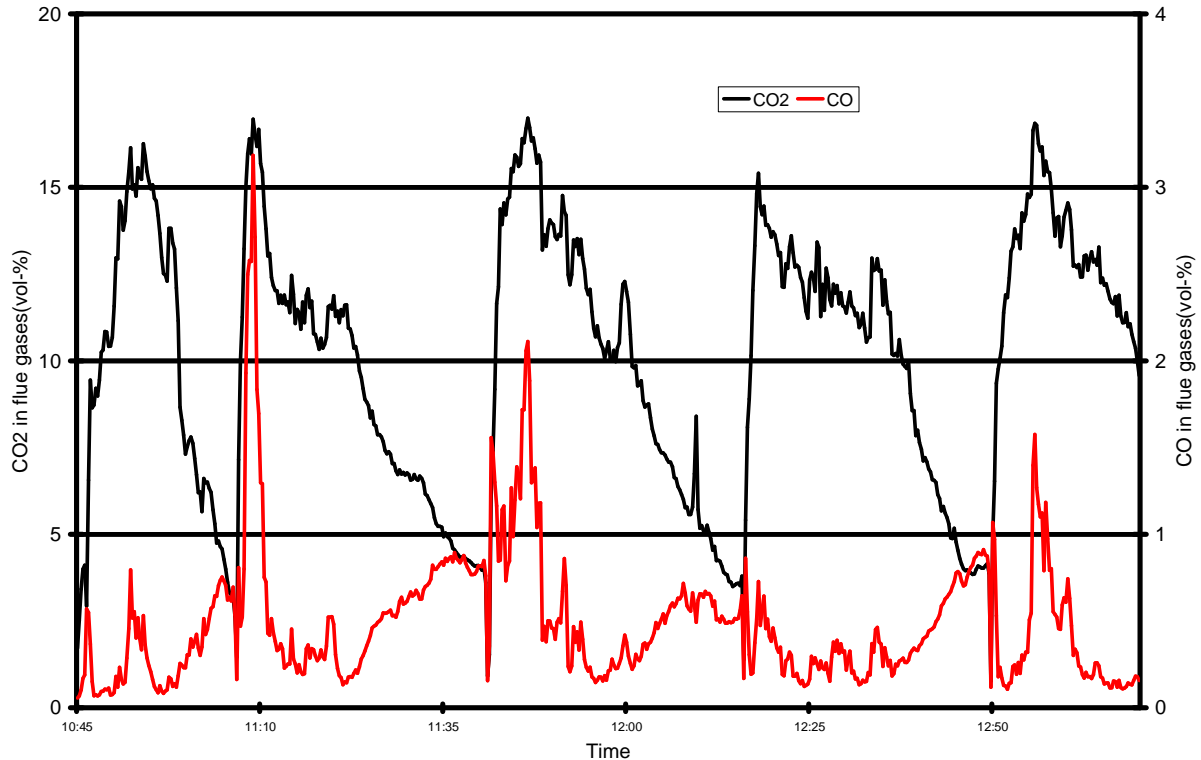
Figure 28. *A measurement graph illustrating a batch-type wood combustion.*

It is observed that higher CO-content appears after each addition of fuel. Because of difficulties in preventing smoke and harmful emissions in batch-type appliances, there are restrictions for their use on many densely populated regions. It is only permitted to use so called "smokeless fuels" like coke having very low volatile matter content.

It has been estimated that in Finland two-thirds of carbon monoxide emissions and even more than 90% of hydrocarbon and PAH emissions in stationary combustion processes (transportation excluded) are due to small scale wood combustion. This is why small scale solid fuel combustion has a net contribution to the green house gas effect. It is of the same order as if CO_2 released from combustion could not be recycled to natural circulation (Hupa et al., 1988). Over six million cubic meters of wood are used in domestic heating in small heating appliances annually in Finland.
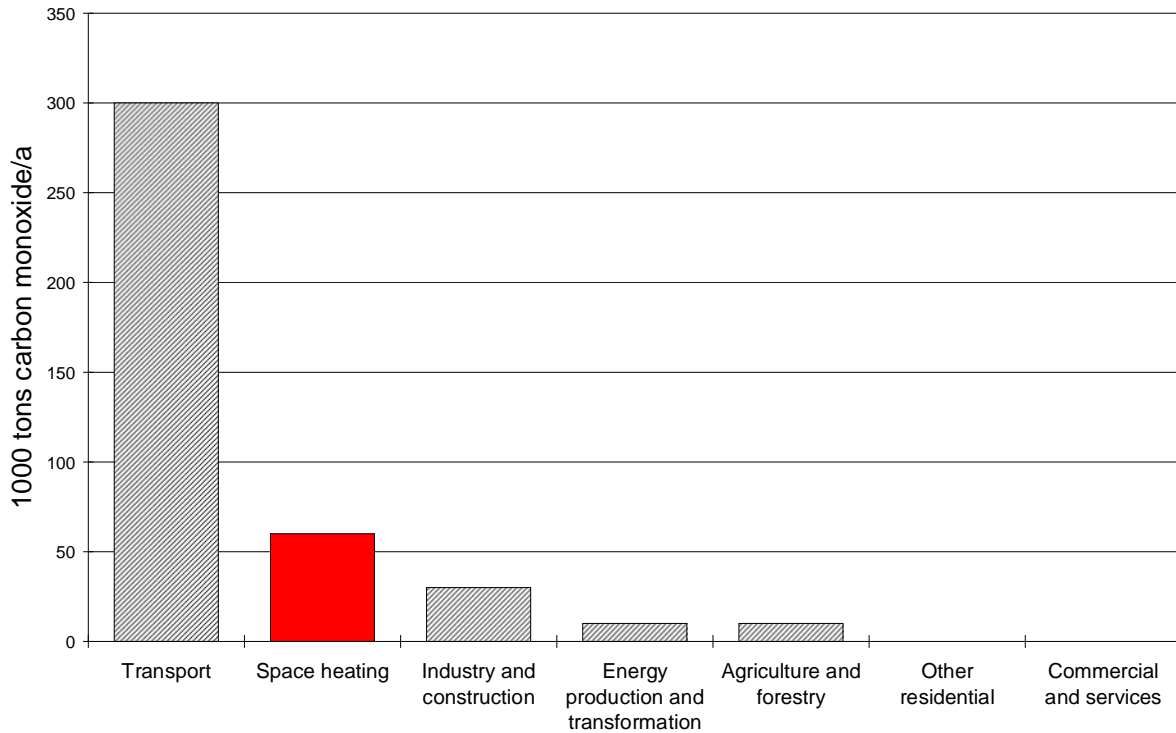
Figure 29. *Carbon monoxide emissions in Finland.*

An idea of the amounts of carbon monoxide and methane emissions from small heating appliances is given in Figures 29 and 30 respectively where the amounts are compared with emissions from other sources. In Figure 29 it is seen that CO emissions from transportation are clearly the highest with the next highest being space heating where the emissions are about two fold compared with those of energy production. In Figure 30 it is seen that methane emissions from space heating are almost equal with the emissions from transportation and seven fold compared with that of energy production (Boström, 1992).

Figure 30. *Methane emissions in Finland.*

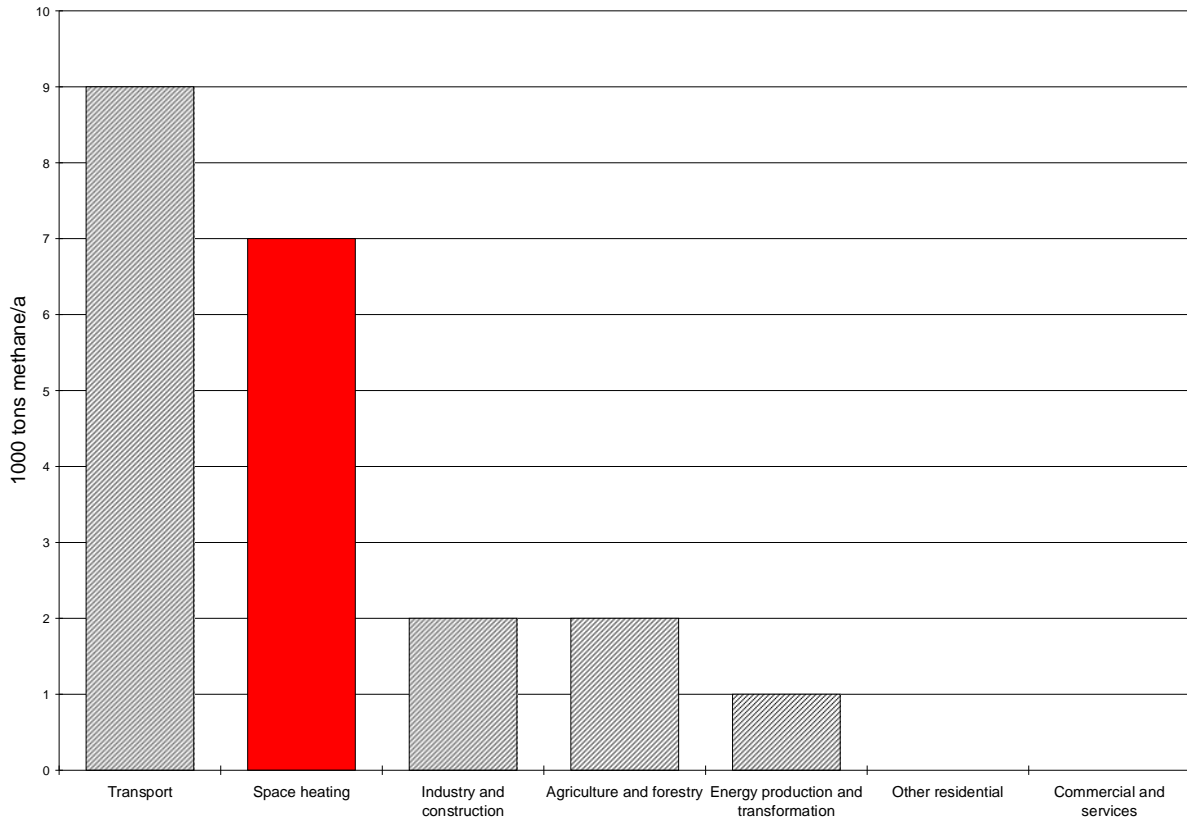Emissions from small heating appliances can be reduced by developing the combustion techniques, but also by using other means, for example catalytic converters. When installed into a suitable place inside a heating appliance, a catalytic converter can oxidise unburned gases in the flue gas into compounds that are not harmful to the environment.

12.2 CATALYTIC OXIDATION OF UNBURNT FLUE GASES

A catalyst augments the rate of chemical reactions without itself being consumed. It helps chemical reactions to go through other path where the activation energy of the reactions is lower. If the frequency factor (A), that describes the rate of reaction in the Arrhenius equation can be assumed to be constant, the activation energy determines essentially the reaction rate. With the aid of a catalyst, reactions go through another way were the activation energy is lower.

Activation energy is lower because an intermediate compound is formed which has lower activation energy than the reaction without a catalyst. When the intermediate compound is decomposed, a catalyst is recovered unaltered. Besides chemical composition the quality of the catalyst surface has an important meaning. The whole surface is not chemically active, only certain parts of it, called active sites (Tommila, 1969).

In a batch-type combustion part of the reactions are endothermic and absorb energy. It can happen that inside the combustion chamber there may not be enough temperature, or enough mixing and/or enough time for oxidation reactions of pyrolysis products. Better designing of the

combustion chamber and the combustion air inlet in different stages can reduce emissions. However, in heating appliances that use natural draught, optimal combustion air inlet is quite difficult to achieve. The need for varying amounts of primary and secondary air changes all the time when a batch of fuel is burning.

There are basically two types of catalytic converters which are used in wood stoves. The structures of the catalytic converters are shown in Figure 31. On the left a honey comb structure is shown. On the right a metallic foil is shown, which some manufacturers use to make catalytic converters. The width of a band determines the length of a catalyst. Metal foil is coated with aluminium oxide coating which acts as a washcoat for precious metals, normally platinum (Pt), rhodium (Rh) and palladium (Pd).

Figure 31. *Honeycomb catalytic converter and metal foil used to make catalytic converters.*

12.3 SOME RESULTS

Birch wood having moisture content of 13% and 18% and peat briquettes having moisture content of 13% were burned. Fuel consumption was measured. Fuel was added when the CO_2 concentration of the flue gas fell to below 4%. This simulates the Swedish SP Method 1071 that is used for measuring tar emission of stoves. The stove heat output was high, about 15 kW.

12.3.1 Oxidation of carbon monoxide

Conversion of carbon monoxide into carbon dioxide is presented in Table 12.

Table 12. *Mean values of the CO-content.*

Fuel	Moisture content	CO-concentration before the catalyst	CO-concentration after the catalyst	Conversion
	%	ppm	ppm	%
birch	13	2400	177	93
birch	18.5	1834	242	87
peat briquette	13	1397	420	70

12.3.2 Oxidation of hydrocarbons

Oxidation of some hydrocarbons into carbon dioxide and water is presented in Table 13. Measurements were done with an FTIR measuring device.

Table 13. Oxidation of hydrocarbons.

Experiment	Concentration before the catalyst	Concentration after the catalyst	Conversion
	ppm	ppm	%
Birch			
w = 13%			
methane, CH_4	214	59	72
acetylene, C_2H_2	56	0	100
ethene, C_2H_4	94	0	100
ethane, C_2H_6	32	0	100
Birch			
w = 18,5%			
methane, CH_4	89	63	29
acetylene, C_2H_2	15	1	93
ethene, C_2H_4	20	4	80
ethane, C_2H_6	6	0	100
Peat briquette			
w = 13%			
methane, CH_4	241	55	77
acetylene, C_2H_2	80	0	100
ethene, C_2H_4	69	10	86
ethane, C_2H_6	58	3	95

12.3.3 Effect of the catalyst on PAH-emissions

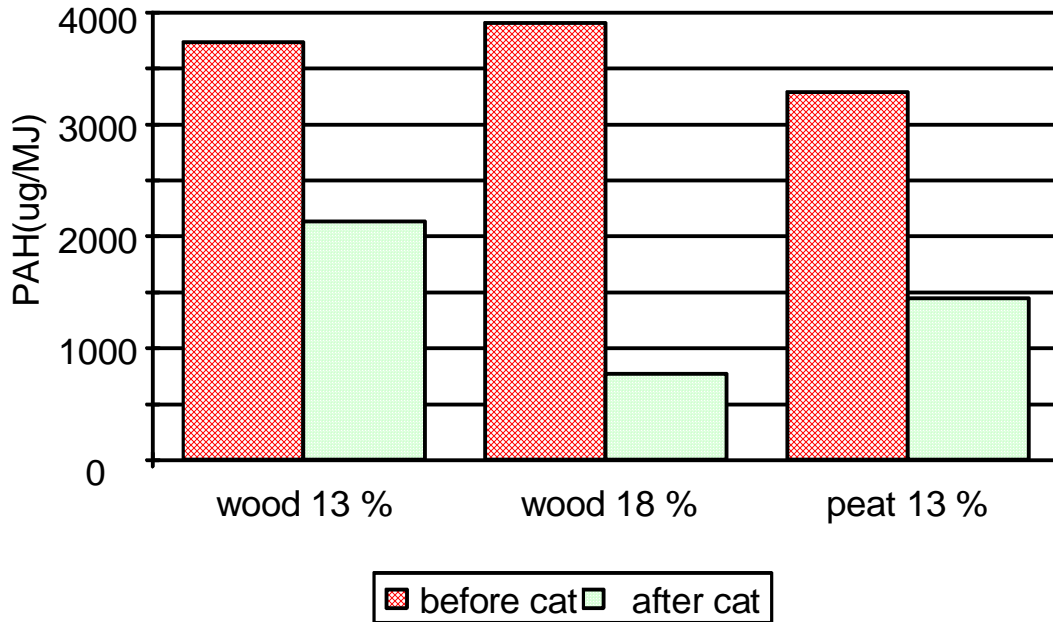Effect of the catalyst on PAH-emissions is presented in Figure 32.

Figure 32. *Effect of the catalyst on PAH-emissions.*

12.3.4 Effect of the catalyst on tar emissions

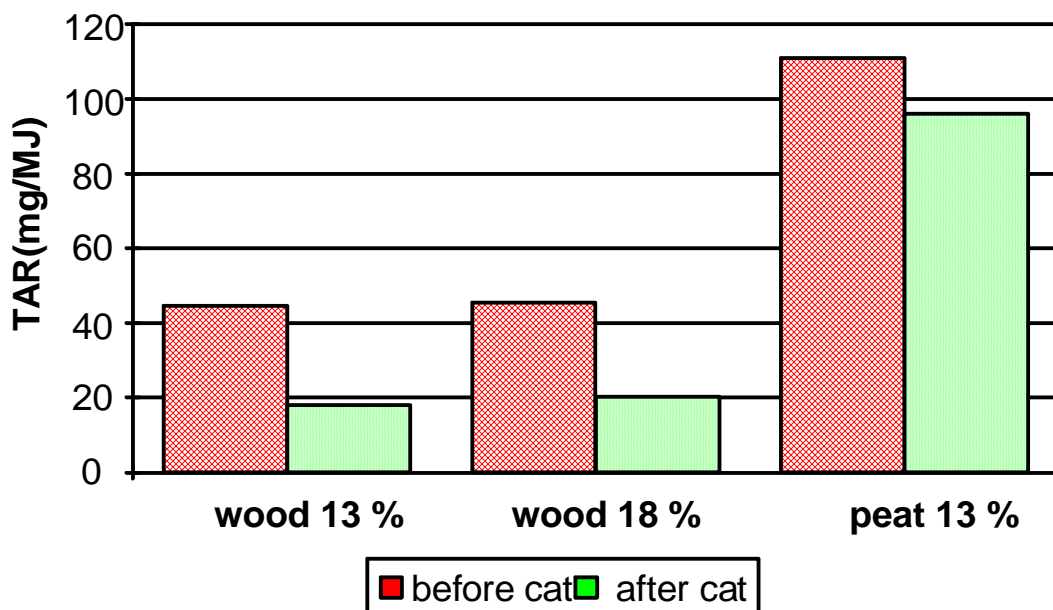Effect of the catalyst on tar emissions is presented in Figure 33.

Figure 33. *The effect of the catalyst on tar emissions.*

12.4 AGEING AND DIRTYING OF THE CATALYST

Ageing and dirtying of the catalysts was not studied. For commercial stove catalysts sold in the USA, the lifetime of 10,000 hours is guaranteed. It is worth mentioning that the catalyst as such does not wear out due to catalytic reactions. The ageing is due to catalyst poisons such as sulphur that reacts with the precious metals used in a catalytic converter.

12.5 CONCLUSIONS

Prototype catalysts made by EcoCat Oy (Kemira Metalkat Oy) promoted well the oxidation of carbon monoxide and hydrocarbons if the surface area per volume in the catalyst was of the right order. If the surface are is too small, conversion is small or oxidation does not happen at all.

In the first experiments the conversion of carbon monoxide was between 70% and 93%, with methane being between 29% and 77% and other measured hydrocarbons being between 80% and 100%. It was worth noticing that carbon monoxide conversion was quite stable in spite of great variations in the flue gas CO-content coming to the catalyst. The catalytic reactions started at the temperature of about 250 $^{\circ}$C.

The catalyst lowered PAH-emission by between 43% and 80% and tar emission between 56% and 60% in wood combustion but by only 14% in peat briquette combustion. This can be due to different type of tar forming in peat combustion. Tar compounds that are high molecular weight hydrocarbons were not qualitatively analysed. Forced draught was used because of high pressure drop over the catalyst.

Combustion tests have showed that catalytic converters can reduce emissions from hand fired heating appliances quite remarkably provided that a catalyst has enough surface area for catalytic reactions. In practise a compromise must be made between the surface area and cleaning efficiency if natural draught is set as a demand. Tighter catalysts can be used in stoves and a CO-conversion roughly of around 90% is easily achieved. Methane and other lighter hydrocarbons oxides also convert well due to a catalyst and the catalyst can also reduce PAH and tar emissions very effectively. The leaning of catalysts placed in conventional stoves is quite easy to achieve. The use of catalytic converters in heat storing heating appliances is more difficult. The pressure drop over a catalyst must be very low which is why the surface area cannot be very large and cleaning efficiency is not very good. In practise between 50% and 70% reduction in CO-concentration can be achieved. Cleaning of the catalysts is more complicated to arrange in heat storing appliances.

A small, simple, inexpensive catalyst can be the easiest solution to lower emissions of hand fired heating appliance that use batch-type combustion process.

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13 SUMMARY

13.1 THE REDUCTION OF FINE PARTICLE EMISSION BY COMBUSTION TECHNOLOGY AND OPERATION

Sippula: When combustion is mainly good, which means that incomplete combustion conditions exist only rarely, main fraction of the particle emission is ash i.e. inorganic fine particles. Fuel ash content has been found to correlate with PM1.0 emission. Also the composition of ash, oxidizing/reducing circumstances and temperature in the firebox affect ash particle formation. Chlorine in fuel tends to increase formation of fly ash particles, while silicon and aluminium based sorbent minerals and sufficient amount of sulphur decrease the formation. In larger scale combustion, the decrease of the release of alkali metal vapours and thus reduced ash particle emissions has been observed in the co-combustion of coal and potassium rich straw, as well as peat and wood fuel. The knowledge of optimal chemical composition of fuel gives an option to create fuel mixtures with decreased particle emissions also for residential combustion.

Pietilä: In the air staging, primary air is used to gasify the wood fuel, and secondary air is used to burn the pyrolysis gases. CO/CO_2 –ratio of the emission was used for control criteria in order to optimize the supply of primary and secondary air feed in a batch burning appliance. Good controllability was observed. Enough combustion air as well as good mixing of air and pyrolysis gases is needed to obtain clean burning. For good mixing, intensive burning and staged air feed is needed. If burning is too intensive, air feed might not be sufficient, which causes emissions. Moisture in the fuel decreases the intensity of the burning, whereas small log size increases it. Emissions of the RWC can be controlled by optimizing air feed as long as the conditions in the fire chamber favour clean burning.

Ruusunen: The potential advantages of automatic control in RWC are, among all, the adaptation to changes in combustion conditions (fuel, environment, device and user) and the continuous optimisation of the air/fuel ratio. With modern control technology it is also possible to monitor combustion conditions and optimise the energy consumption on higher level with system integration.

Kilpinen: There exists modelling tools with which it is possible to optimise burning appliances in order to reduce emissions of pollutants and improve heat transfer. Modelling of the batch-wise burning is challenging due to constantly changing circumstances.

Tissari: The old appliances cause considerably higher emissions than modern appliances. Use of heat storage tank for the wood boilers usually decreases emissions. In the case of the modern pellet boiler, typically the partial load increases emissions, as does the burner with pilot flame compared to one with electrical ignition. Moist wood fuel causes higher emissions than dry wood, as do large wood batches compared to small wood batches. Bark pellets have higher ash content than pure wood pellets, and thus they also cause higher particle emission. High combustion rate induce low emissions from the light metal stoves and open fireplaces (open air intake or small logs used) but high emissions from the storing masonry heaters. The use of big logs decreases emissions from masonry heaters. Public awareness about good operation practise in wood burning should be promoted.

Taskinen: CO-emissions were reduced by more than 65 % from the original level by developing a new and optimised air delivery system into a small-scale batch-type combustion furnace. The knowledge of secondary air jets mixing into other gases was gathered from visualisation tests, where the mixture of visualisation smoke and combustion air was fed to the secondary combustion zone of the furnace. In these tests, number and size of holes were varied in order to obtain penetration large enough for the secondary jets. In the real combustion tests, the minimum CO-emission was reached with the primary/secondary air ratio of about 0.5.

13.2 THE REDUCTION OF FINE PARTICLE EMISSION WITH FLUE GAS CLEANING DEVICES

Laitinen: In general electrostatic precipitators can be very effective flue gas cleaning devices. However, RWC is a challenging environment for ESP's, e.g. because particle concentration is changing during the batch combustion process. Because sophisticated automation is easily too expensive, the changing particle emission has to be managed by sizing the charger capacity for peak emissions of particles. ESP's particle removal efficiency is related to its size, so compromises have to be accepted. Also the cleaning of the ESP needs to be taken into consideration.

Suonmaa: By optimising a heat exchanger for fine particle deposition and applying it into small scale combustion process, it is possible to obtain both waste heat recovery and reduction in the fine particle emissions. Collection efficiency depends on the geometry of the heat exchanger, the flue gas water vapor content and the temperature gradients in the heat exchanger. In batch burning the temperature and water vapour concentration of flue gas vary as a function of time; thus the heat exchangers are more applicable to continuous combustion. The deposition of fine particles emitted from an 8 kW pellet burner to a glass heat exchanger was, on average, 8-24% of the total number emission and 8% of the mass emission. By raising the water vapor content of the flue gas, the deposition of 30 - 50% of the mass emission could have been gained. The condensate helped to prevent fouling which, at some point, starts to reduce the performance of the heat exchanger.

Oravainen: Catalytic converters can reduce emissions of methane, lighter hydrocarbons, PAHs, tar and CO from hand fired heating appliances quite remarkably, presuming that the surface area of a catalyst is large enough for catalytic reactions. In practice, a compromise must be made between the surface area and cleaning efficiency if natural draught is the only possible option. In stoves tighter catalysts can be used, and a CO-conversion roughly of 90% is easily achieved. The use of catalytic converters in heat storing heating appliances has more difficulties; the pressure drop must be very low which is why the surface area cannot be very large and cleaning efficiency is lower. In practice reduction in CO-concentration of 50%-70% can be achieved. Cleaning of the catalysts is more complicated to arrange in heat storing appliances. The reduction in particle emissions due to the use of the catalytic converter was not studied as weren't the ageing and the fouling of the catalysts, either. Catalytic converter can have a lifetime of 10,000 hours. A solution for cleaning the flue gases of RWC could be after treatment unit, which could include for example an exhaust gas fan, a device for particle removal and a catalytic converter.

Linna: The scrubber removes poorly fine particle fraction (PM2.5). In particle emission of RWC, the fine particle mode is very significant. For the efficiency of heat recovery, air ration

should be small; this is rarely the case in small-scale combustion. Processing of condensate requires space and expensive equipment. The scrubber resists the gas flow and has low temperature, thus the draft is poor and flue gas fan is required. Scrubbers can't be applied for batch combustion or heat-accumulating heating systems. In small-scale combustion the wet-scrubber could be applied technically for boilers of over 100 kW outputs and which would have a control system for the combustion process.

Ohlström and Makkonen: Fabric filters have very high collection efficiencies (99.9%) both for coarse and fine particles. Collected material is dry for subsequent processing and disposal, operation is relatively simple and there exists no corrosion problems. Disadvantages include pressure drop and rather high maintenance requirements and operation costs. The problem considering small-scale wood combustion is that fabric filters are nowadays too expensive to use for fine particles removal for boilers below 10 or 5 MW size classes. In addition, due to fire hazard, fabric filters must be protected against sparks if used in biomass burning.

The separation chambers and cyclones have only moderate efficiency compared to ESPs or fabric filtration, and cannot remove the finest particles from flue gas.

14 CONCLUSIONS

Primarily, the fine particle emissions from batch burning devices should be reduced by promoting good operation and in the long run by improving the combustion technology. Modern combustion technology has been applied to heat-storing fireplaces with success, for example air staging reduces emissions. Combustion technology of sauna stoves should also be improved. Especially in continuous combustion of pellets, optimal fuel mixtures and fuel additives seem to be promising solutions for the reduction of fine particle emissions. Automatic control in RWC is important also in the future.

Flue gas cleaning device used in RWC should have good particle removal efficiency; in addition it should be inexpensive, small and easy to use and maintenance. Great variation of the amount and composition of the emissions sets high requirements to the cleaning device; for this reason, developing the flue gas cleaning devices at first for continuous combustion could be reasonable. Cleaning of the devices can be difficult due to tar-like components in the emission. The most potential flue gas cleaning devices for RWC could be electrostatic precipitators, heat exchangers and catalytic converters in contrast to scrubbers, separation chambers and cyclones, which don't seem to be feasible for the reduction of fine particle emissions from RWC.