DEVELOPMENT OF NEWLY DESIGNED WOOD BURNING SYSTEMS WITH LOW EMISSIONS AND HIGH EFFICIENCY

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Abstract

In order to increase the thermal utilisation of wood fuels in Europe and to save fossil fuels with respect to the European CO_2 emission policy it is necessary to improve the combustion behaviour of small scale wood combustion systems. Therefore, the project entitled "Development of Newly Designed Wood Burning Systems with Low Emissions and High Efficiency" started in January 1996 under the JOULE III frame work programme of the European Commission. The research is focused on different firing systems such as mechanically fed stoves (0 - 15 kW_{th}), accumulating boilers (15 - 100 kW_{th}) and automatically fed combustion systems (50 - 1000 kW_{th}). The main objective of the project is to reduce the environmental impact of these small scale wood combustion systems, in particular, to reduce emissions of unburned carbon species as CO, volatile organic compounds (VOC) and particulate matter (PM) which could be emphasised in the last years to be the most problematic emissions. In detail it was planned

- to determine the combustion behaviour of different test firings by emission measurements as well as by detailed measurements in the reaction zones;
- to apply Computational-Fluid-Dynamic-(CFD) and equilibrium models;
- to set-up new concepts for stoves and boilers;
- to design and construct prototype of stoves, boilers and automatically fed systems and finally;
- to formulate scale-up criteria and design guidelines for industrial application.

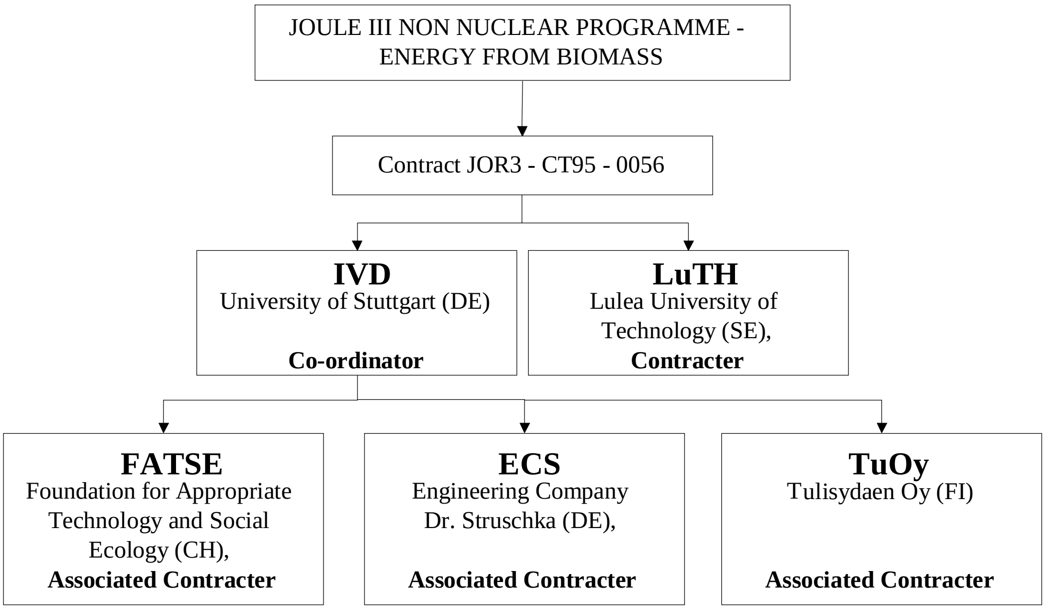
In a first step, tests to determine the combustion behaviour were carried out with various commercially available appliances in order to define the actual state of the art. For a further improvement of the combustion behaviour basic investigations were carried out determining gas concentrations of CO, O_2, CO_2 and VOC, temperatures as well as velocity and turbulence profiles in the reaction zones of most of the investigated test facilities. A new approach was

- the application of the Laser Doppler Velocimeter (LDV) towards the use in small scale combustion systems with unsteady combustion conditions controlled by the natural draught in order to characterise the flow field and mixing conditions;
- the use of suction probes to determine simultaneously temperatures and gas concentrations for a deeper understanding of formation and decomposition processes;
- the application of CFD codes for getting an insight into the complex inter-linked phenomena of chemical reactions and turbulent flow behaviours.

Based on the experimental and theoretical results several prototypes were designed and constructed which are in particular a fireplace insert, an accumulating masonry heater, four prototype boilers as well as a newly designed vortex burner system for the use of wood chips.
Measurements with the before mentioned prototypes showed that the emissions of products of incomplete combustion (PIC) were reduced in a further extent. With the developed vortex burner system a remarkable reduction of particulates have been achieved.
In order to supply the industry with the gained knowledge and tools to design and produce new products with low emissions, guidelines for newly designed wood burning systems were prepared. They give information about control elements for combustion air, dimensions of combustion chamber and load space as well as about optimal construction and operation with regard to a sufficient combustion during different firing conditions.

Keywords: wood combustion, emission reduction, domestic heating appliances, wood fired boilers

Project Consortium



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Objectives

The investigations focused on the combustion and emission behaviour of small scale wood burning systems for untreated wood fuels with batch-wise and quasi-continuous mechanical feeding systems. The general objectives were to minimise the pollutant release of these combustion systems during the different operational phases and to reduce the specific CO_2 release by increasing the efficiency of the combustion process. For both objectives mentioned before the reduction of the products of incomplete combustion (PIC) is necessary. Therefore, the following technical objectives were provided in the project proposal:

- improvement of the mixing process of combustion air and combustible gases in the reaction zones (furnace, burnout zone);
- averaging the residence time spectrum in the burnout zone;
- reduction of emissions during initial phase in firings with batch-wise feeding;
- reduction of emissions under partial-load conditions in firings with quasi-continuous feeding;
- reduction of emissions of particulate matter (PM);
- enhancement of combustion stability even in case of changing fuel qualities;
- definition of guidelines for the design of stoves and boilers with low emissions and high efficiency.

These general objectives may be specified for the three different types of combustion units investigated during this project:

Small scale batch operated wood combustion systems:

To ascertain the emission behaviour of this special type of combustion unit usually used for room heating, emissions in the flue gas as well as velocity, temperature and concentration profiles in the reaction zones had to be measured. Based on this characterisation of the combustion cycle and the derived emissions the process had to be optimised by operational and constructive measures. The combustion temperatures had to be stabilised on a high level, in order to ensure a sufficient turn-over rate of combustible gases during the entire combustion cycle. Also, the ignition process had to be accelerated therefore. Last but not least the mixing conditions in the reaction zone and in the zone of the primary and secondary air injection had to be optimised to maximise the residence time of the co-reactants in zones of high temperatures and sufficient air ratios.

Medium scale batch operated wood combustion systems:

In general the objectives pursued within the R&D activities regarding this type of facilities were the same as the objectives for the small scale units mentioned above. But the work within this task focused on the reduction of the start-up emissions, whereas the research on the small scale units focused on the mean emissions during the entire burn cycle.

Medium to large scale continuous operated wood combustion systems:

The goal of this task was the development of a newly designed low emission biomass burner for boilers in the range of 50 - 1000 kW_{th} thermal output burning preferably wood chips. The combustion chamber creating a vortex to increase gas phase turbulence in order to maximise complete combustion is the main feature of the new burner design. The main emphasis of the burner design was to reduce the release of particulate matter. The combination of vortex and air staging techniques was supposed to reduce the NO_x emission level.

Technical description

Small scale batch operated wood combustion systems

In order to get an overview of the actual state of the emission behaviour of small scale wood heaters the state of the art was defined based on extensive emission measurements on different stove types such as sauna stoves, single room heaters, masonry heaters, cook stoves, etc.

For the characterisation of the combustion behaviour an experimental set-up designed for investigations on solid fuelled small scale firing systems for domestic heating purposes was built up. The flue gas analysis system, shown in Figure 1, is capable to determine the concentrations of CO, CO_2, O_2, H_2O and total hydrocarbons in the flue gas. Additionally the flue gas temperature, the chimney draught, the combustion air volume flow as well as the temperature of the preheated primary or secondary combustion air was measured continuously. The experimental results of these measurements were used to characterise the general combustion and emission behaviour as well as for obtaining information about the comparability of different burn cycles.

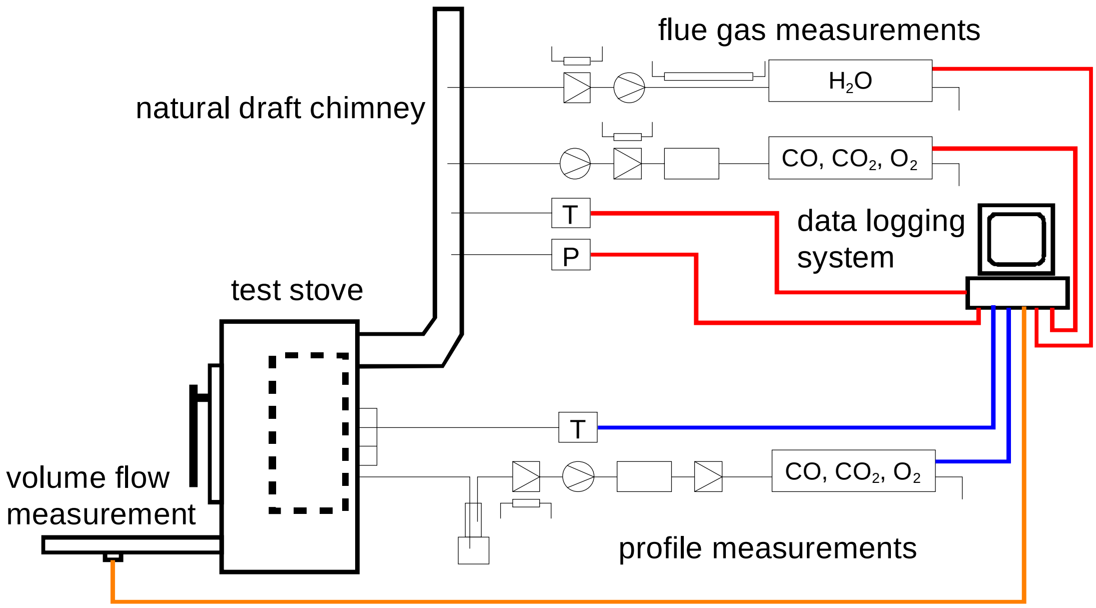


Figure 1: Experimental test field for gas and temperature measurements within reaction zones of small scale wood stoves for domestic heating purposes

For a detailed investigation of the formation and decomposition processes of different gas species and a characterisation of the combustion process gas concentration and temperature profile measurements using suction probes were carried out at different positions within the reaction zones of the selected test stoves. The profile gas analysis system was designed to measure the gas components CO, CO_2, O_2 and total hydrocarbons simultaneously to the flue gas measurements. Shielded suction probes were used facilitating the measurements of gas concentrations and temperatures at the same time. Due to the reduction of radiation effects by the shield between the surrounding walls, the flames and the thermocouple as well as depending on the surrounding temperature level deviations of up to 150 °C could be measured with the suction probes compared to unshielded thermocouples which is well known from previous measurements in gas and coal dust flames. Additionally, for completing the set of profile measurement data wall temperatures at different positions in the reaction zones were measured.

Figure 2: Application of LDV measurements on small scale wood heater

Besides information about the gas concentrations and temperatures inside the reaction zones of the investigated stoves data about the turbulent flow field behaviour and especially about the mixing conditions between combustible gases and burnout air were of special interest. For that, profile measurements of velocities and turbulence intensities, shown in Figure 2 were carried out using a 2D-Laser-Doppler Velocimeter (LDV). The Laser-Doppler Velocimetry is a non-intrusive, optical measurement technique for the determination of fluid velocity components with a high temporal and spatial resolution. The measurement principle is based on the Doppler effect describing that coherent light, scattered from particles suspended in the fluid shows a frequency shift which is proportional to the particle velocity.

The transmitting and receiving probe of the used LDV system was mounted on a 3D-traversing system which was controlled and actuated by the LDV data logging system. The traversing system enables to carry out velocity measurements on predefined grids, adapted to different measurements tasks, automatically which was an important feature with regard to the instationary combustion process. The tracer particles (magnesia), as a prerequisite for LDV measurements, were added to the combustion air after the flow sensor for the combustion air volume flow measurement.

The before mentioned detailed experimental investigations on the combustion process within small scale wood heaters were carried out on two commercially available test stoves representing the state of the art. The stoves differ in the combustion technique whereas the first test stove is designed for backdraft combustion in combination with a spatial division of the two reaction zones. The second selected stove, a fire-view stove is characterised by only one large combustion chamber where the wood logs are burnt by updraft combustion.

Following, characteristic results obtained during the investigations on the first test stove, a tile stove heating insert, are shown. The evaluation of the LDV profile measurements within the burnout zone of the heating insert are represented in Figure 3.

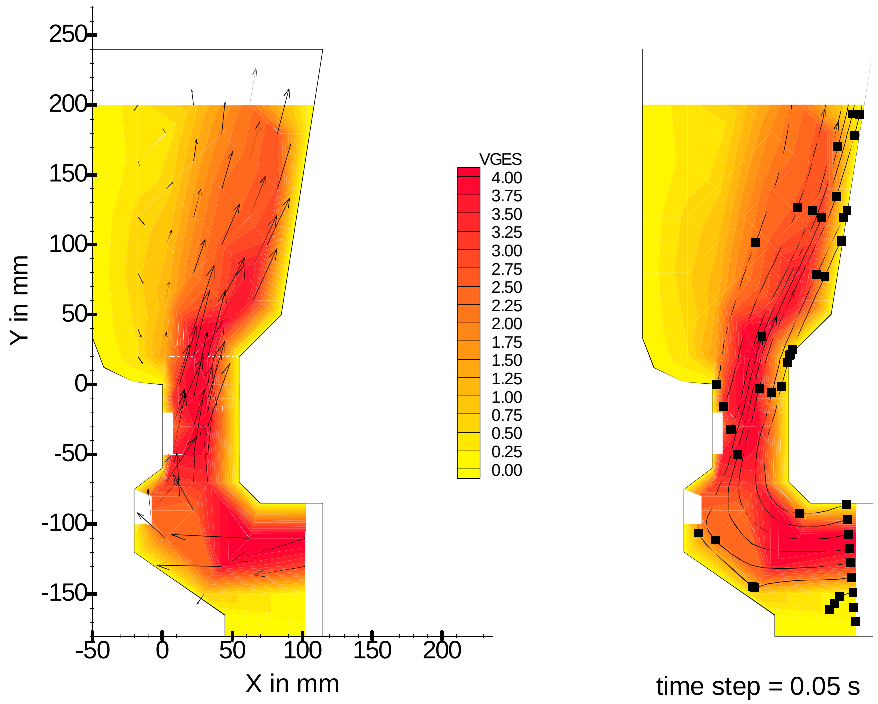


Figure 3: Flow field (right) and residence time distribution (left) measured by LDV in the burnout zone of a test stove

On the one hand the general flow field behaviour and the influence of (secondary) combustion air added to the main flow could be determined during a complete burn cycle. On the other hand important information about the residence time distribution of the reacting gases in the burnout zone could be obtained by the LDV measurements.

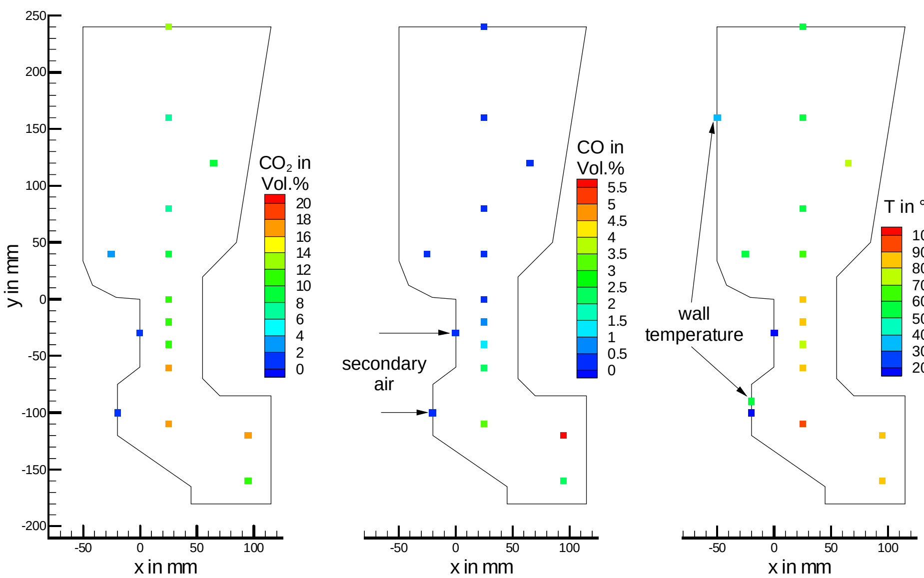


Figure 4: Measured gas concentration and temperature profiles in the secondary reaction zone of the heating insert

The data set for the description of the combustion process was completed by the before mentioned gas concentration and temperature profile measurements. Results measured during the main combustion phase are shown in Figure 4.

Besides the direct evaluation and interpretation of the experimental measurements the temperature, gas concentration and velocity data were used as boundary conditions for mathematical modelling studies. The objectives of the modelling studies were to use them for basic investigations of the mixing and combustion processes as well as an engineering tool for parameter studies where variations of different firing parameters such as furnace geometry, wall temperature, ratio of primary air to secondary air, pre-heating of combustion air, etc. can be carried out effectively.

Results obtained by the numerical modelling studies of the combustion process within the burnout chamber of the test stove are shown by distributions of the gas components CO, CO_2 and O_2 in Figure 5. The modelling studies, carried out in close co-operation between IVD and his minor subcontractor Tampere University of Technology (TUT), describing the conditions during the main burning phase were carried out on the basis of the before mentioned boundary conditions.

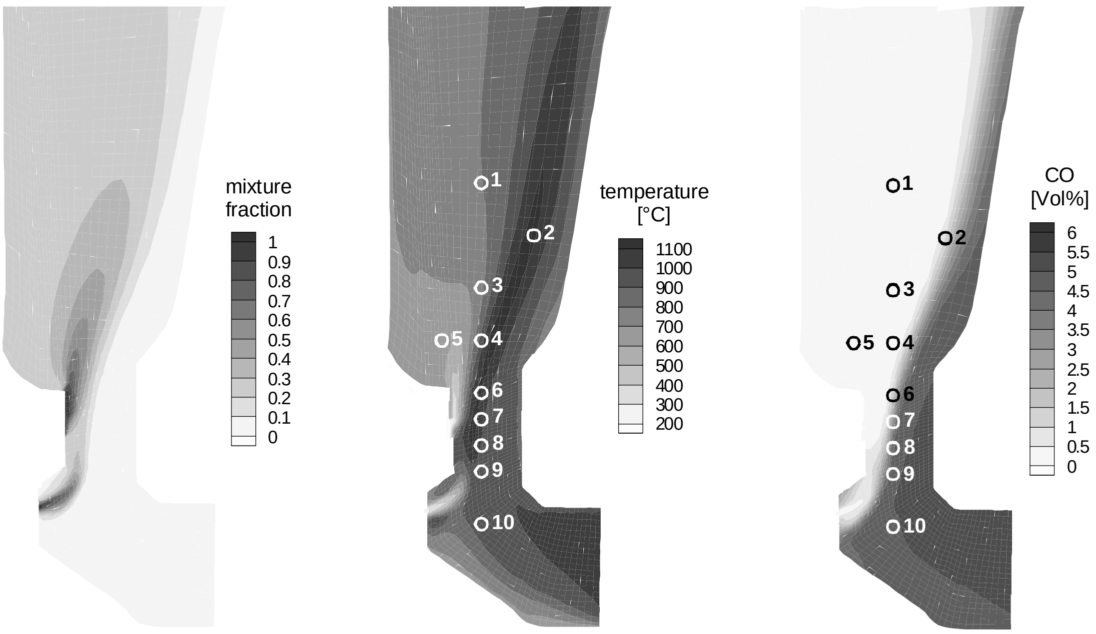


Figure 5 Modelling studies of homogenous gas phase reactions within the burnout zone of the tile stove insert during the main combustion phase

These studies, assuming stationary conditions, facilitated a detailed investigation of the combustion process during one burn phase, i.e. main burning phase. The distribution of the CO-concentration within the burnout zone shows a considerable reduction of CO in the zone of secondary air injection by the three nozzles and the slot. However, the non-symmetric furnace design and the injection of secondary air by the slot with low exit velocity leads in a low penetration depth of the secondary air and therefore in an incomplete mixing between combustible gases (CO) and burnout air. As a result of the prevailing conditions a gas streak with a CO-content of about 2 Vol.% remains at the left side of the burnout chamber. Before entering the flue gas channel the high CO-content of the streak can not be reduced.

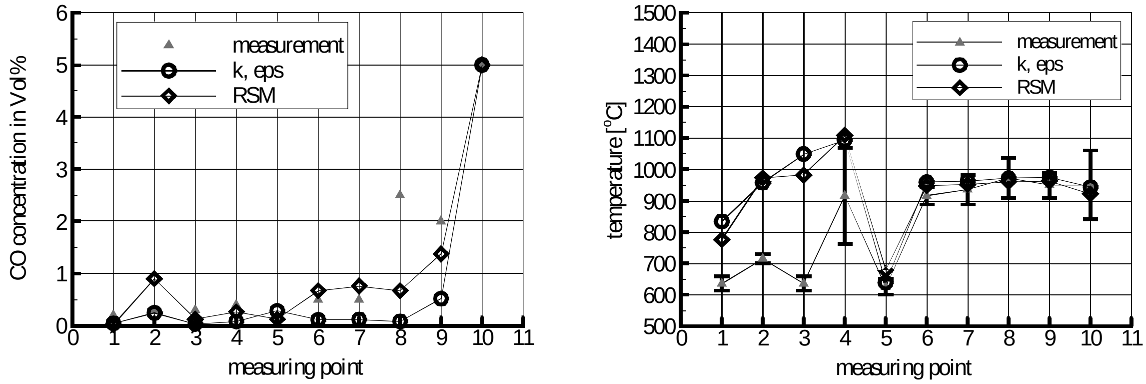


Figure 6 Detailed comparison of computed values using different turbulence models (k,eps, RSM) with experimental data

The comparison of the numerical simulations using two different turbulence models, namely the k,ε-model and the Reynolds Stress Model (RSM), with measurement data shows that the characteristics of the computed gas concentration and temperature fields are in good accordance with the measurement data (Figure 6). The fluctuations of measured temperatures at the different measuring positions are due to changes in the flow field and combustion conditions in the burnout zone depending on the burn course and on different boundary conditions.

The results and experience obtained by the detailed experimental and theoretical investigations on the selected test stove were used:

- as a basis for the definition of guidelines for the design and construction of new small scale wood heaters with low emissions and high efficiency,
- for the development of new firing concepts for a fireplace insert and an accumulating masonry heater. For both concepts prototypes were built within the project. For the fireplace insert prototype extensive test using the same measurement techniques as for the commercially available stoves were carried out in order to verify the improvements and the defined guidelines.

Medium scale batch operated wood combustion systems

The work focused on the minimisation of start-up phase emissions originating from wood boilers for domestic central heating systems. During the practical work carried out to optimise downdraft batch operated wood boilers three prototype boilers were developed. Based on the experience gained during the project scale-up criteria for the enhancement of the developed down draft boiler concept for burning 1 m wood logs instead of 0,5 m wood logs were defined.

In order to obtain detailed data for a further reduction of start-up emissions from wood boilers various experimental investigations were carried out. The size of the wood logs and the moisture content were supposed to have a strong influence on the start-up combustion conditions. Additionally, two different kinds of wood, namely birch and beech were investigated during the project. The prototype boilers used for the investigations were improved in different stages concerning the air distribution, air preheating technique as well as concerning the furnace geometry and refractory lining of the combustion chamber.

In the experiments investigating the emission behaviour of the boiler prototypes the primary air was supplied by a mass flow regulator and the primary air was heated. In the start-up experiments the secondary air was controlled by a mass flow controller while for the rest of the experiments the secondary air was supplied with a fan and measured with a Prandtl-tube, which has been calibrated against the mass flow regulator. The boiler was connected to an insulated chimney of 4.5 meters height and a diameter of 160 mm.

The different gas components measured in the raw exhaust were total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), nitrogen monoxide (NO) and oxygen (O_2). Nitrogen dioxide is calculated as the difference between NO_x and NO.
Non-water soluble hydrocarbons up to hexane were sampled in black Tedlar-bags after removal of water by water-coolers with the help of a small pump and a heated valve system controlled by the GC. Sampling was done through 8 minutes, which means that each sample comprise an average during that time. Water soluble and higher hydrocarbons were grab-sampled. Sampling and analyses of pyrolysis/gasification gases have been performed for several tests on birch with varying moisture content and different wood size. In addition the gases have been measured in a few runs with the reference fuel beech.

For temperature measurements thermocouples of K-type were utilised. The temperature of the preheated primary air during the start-up phase was measured after the electric heater. The flue gas temperatures were measured at two positions in the fireplace. One position was in the centre of the flue gas pipe and the other one at a distance of 10 mm from the wall. The flue gas temperature used in the efficiency calculations were the average with a heavier weight on the fluegas in the centre. The temperature of the preheated secondary air was measured by sucking this air past a thermocouple, which had been embedded in Kaowool (a heat resistant insulator) to decrease the influence of radiation. The temperature was measured in the secondary combustion zone by inserting a thermocouple in a stainless steel tube pointing towards the back of the boiler in the centre of the secondary zone. To decrease the influence of heat radiation the tip of the tube was filled with Kaowool and also insulated.

The probe for sucking pyrolysis/gasification gases and measuring the temperature of those gases and the probe for measuring the temperature in the secondary combustion zone were fixed together and could be moved along the slot in the primary zone. The distance was measured from the back of the slot.

Both, birch wood and beech wood were utilised in the experiments. Birch was used in the systematic experiments while beech was used as a reference fuel. The varying moisture content of the startwood for birch was obtained by storing the wood in humidity controlled chambers a sufficient time. The delivered birch wood varied considerably in moisture content. To decrease this variation we had to store the birch in the humidity chamber for a month. The reference fuel beech was stored under shelter outdoors from time of delivery. The moisture content of the fuel beech was 9.4 % at time of delivery. The moisture content were determined by cutting slices with a maximum thickness of 20 mm drying at 103 C (+- 1 C) until constant weight was achieved.
Four factors were evaluated in the start-up experiments:

- Three different burnout combustion chambers causing different degree of preheating of the secondary air - [1, 2, 3]. The burnout combustion chamber 3 was designed for highest preheating of the burnout combustion air, while chamber 1 was designed for the lowest preheating effect.
- Electric preheating of the primary air during start-up tests. Setpoint of the electric preheater - [25, 145, 275 °C]
- Wood size of the start wood - [3 – 7 cm]
- Moisture of the start wood - [10, 15, 20 %]

The experiments were designed as a fractional factorial according to Figure 7. If one of the factors has a very low importance the design turns into a full factorial as can be seen in the Figure.

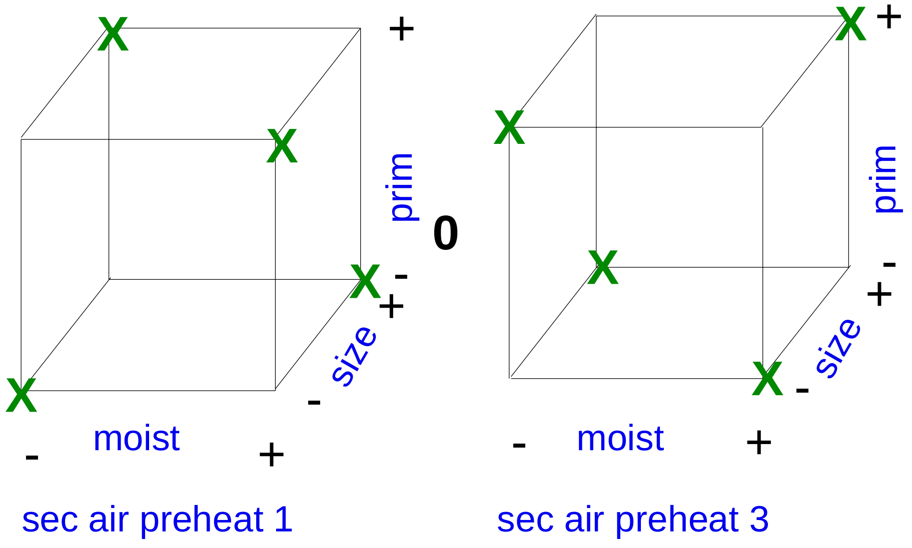


Figure 7: Design of start-up experiments.

To evaluate the influence of bark on the start-up emissions the centre points with normal amount of bark (50 grams) were paired with extra amount of bark (200 grams) distributed among the startwood.

Two factors were evaluated in the burnout experiments:

- degree of secondary air preheating - [1,2,3],
- temperature of the surrounding water in the heat storage - [50 – 100 °C].

Medium to large scale continuous operated wood combustion systems

The process demonstration unit of the automatically fed wood chips combustion systems (Figure 8) was designed to meet the following requirements:

- Complete combustion with low emissions of products of incomplete combustion (PIC) such as volatile organic compounds (VOC) and carbon monoxide (CO)
- Low particulate emissions
- Low nitrogen emissions (NOx)

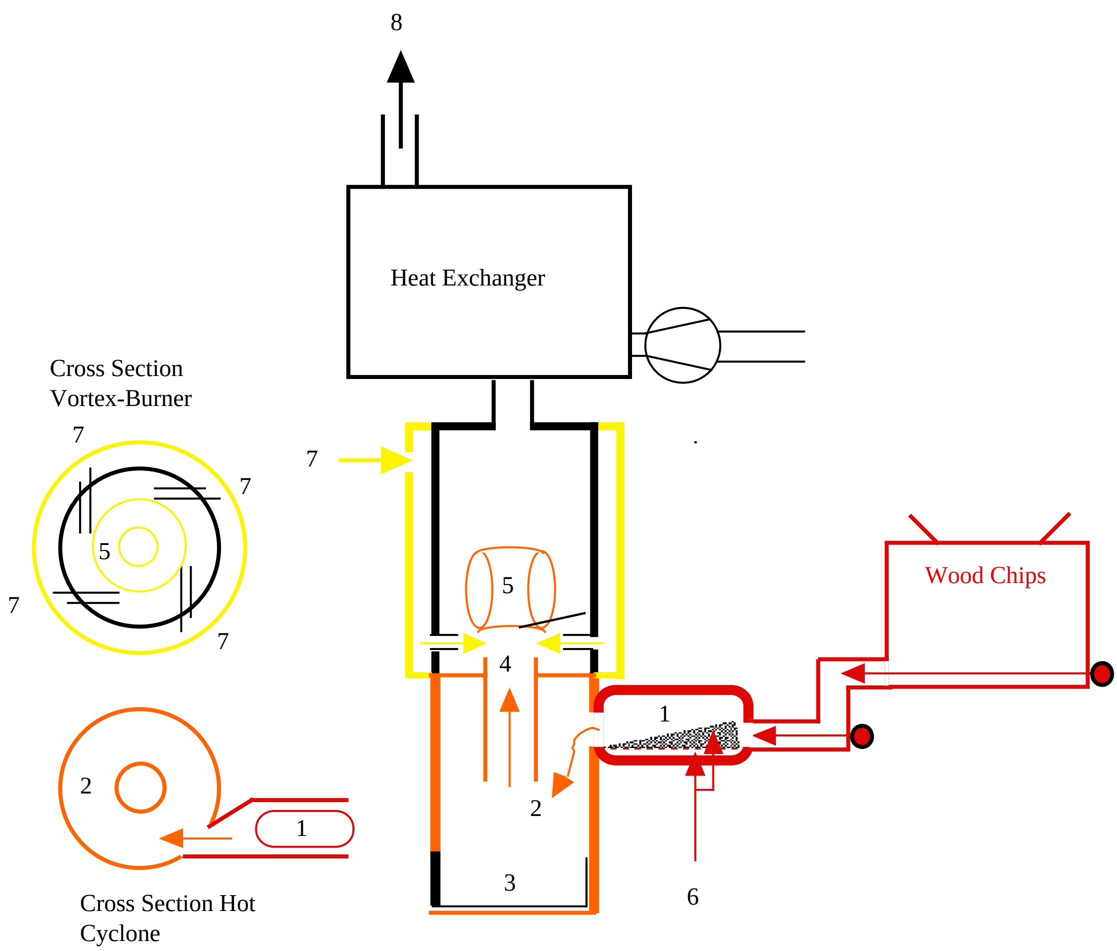
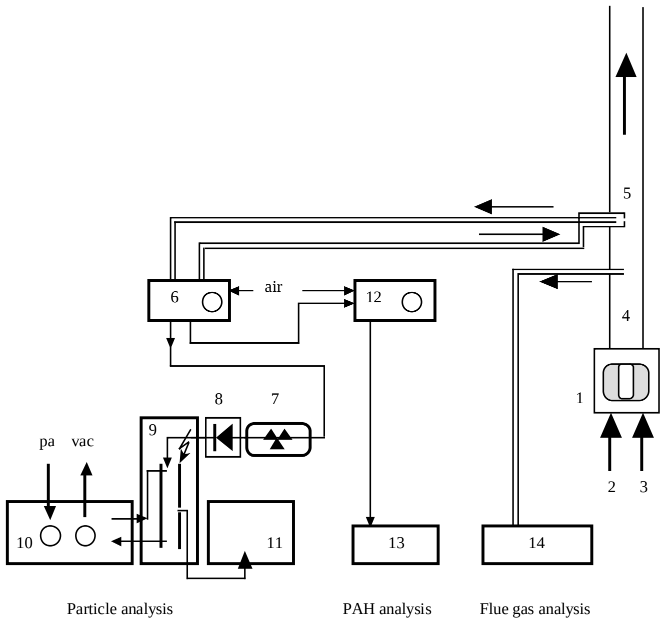


Figure 8: Newly designed process demonstration unit for combustion of wood chips, **1** primary combustion chamber, **2** hot gas cyclone, **3** ash disposal, **4** primary vortex, **5** secondary vortex in secondary combustion chamber, **6** primary air, **7** secondary air, **8** flue gas

To meet these requirements, the PDU combines a primary thermal conversion chamber with hot cyclone and the secondary combustion chamber.

- Primary thermal conversion chamber comprising a stoker (auger), a pre-drying zone to remove fuel water, a primary combustion chamber to produce the required energy for the pyrolysis/gasification process as well as a pyrolysis and gasification zone to convert solid fuel into gaseous ones
- High temperature cyclone with fuel rich atmosphere (mainly carbon monoxide, CO) and no oxygen for denitrification of nitrogen compounds (NOx)

- Secondary combustion chamber with vortex created by secondary combustion air to establish strong mixing of gas components to facilitate chemical reaction; temperature level to achieve complete combustion with low carbon particulate content and consequently low formation of PCDF and PCDD.



1 Vortex burner
2 Wood gas
3 Combustion air
4 Flue duct
5 Probe/ Dilution , 1. stage
6 Dilution control unit
7 Radioactive ionisation
8 Impactor 1µm
9 Differential mobility analyser
10 Flow controller
11 Condensed particle analyser
12 Dilution 2. stage
13 Photoelectric aerosol sensor (Hg)
14 O_2, CO, CO_2, NO_x analysis

Figure 9: Experimental test field for vortex burner system at FATSE

For the measurement of particles and gaseous emissions of the PDU the same equipment and methods, shown in Figure 9, were applied as for the commercial wood chip boilers and the bench scale burner tested earlier in the project.

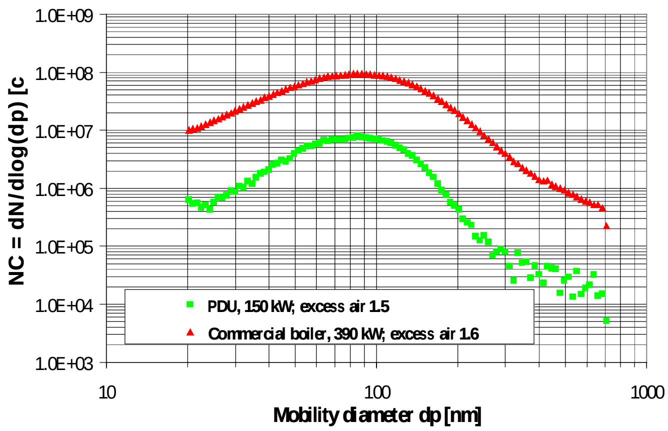


Figure 10: Particle size distribution of a commercial boiler and the newly designed PDU

The patterns of particle size distribution (Figure 10) of the PDU showed similar characteristics as the commercial boilers do. The PDU mode diameter (MD) are at sizes between 80 nm and 100 nm. The particle number concentration of the PDU is of an order of magnitude smaller than the one of the commercial burners.

Assuming spherical particles volume and surface of flue gas particles were calculated from the number concentration. Particle surface attracts polycyclic aromatic hydrocarbons (PAH). Any increase of surface is a potential of health risks. Any decrease in particle surface reduces transport of carcinogens compounds in to the lungs.

Results and conclusions

Small scale batch operated wood combustion systems

The basic investigations done by TuOy were summarised in close co-operation with ECS in the definition of the state of the art. [**TuOy** (ECS, IVD)]
Detailed profile measurements of gas concentrations, temperatures and velocities (LDV) were carried out for two commercially available test stoves (tile stove heating insert, fire-view stove) as well as for a newly developed fireplace insert. Results of these investigations are on the one hand the experience and know-how of the application and use of different measurement techniques on small scale wood heaters with regard to the specific requirements. [**IVD** (ECS)].
On the other hand the results consist of the measurement data including all measured values [**IVD** (ECS, TuOy)].
Based on the detailed determination of boundary conditions, numerical simulation studies for the tile stove heating insert as well as for the fireplace insert prototype were carried out. The results supplied important information for the definition of the construction and design guidelines as well as for the development of new firing concepts and their further optimisation [**IVD** (ECS, TuOy)].
In close co-operation of ECS and TuOy a fireplace insert prototype and an accumulation masonry heater prototype were designed, built up and tested. [**TuOy** (ECS)].
Summarising all experimental and theoretical investigations done during the project as well as taking into account the experience gained during the development of the prototypes general guidelines for the design and construction of new small scale wood heaters and stoves were developed. [**ECS** (IVD, TuOy)].

Medium scale batch operated wood combustion systems

Within the project duration four newly designed prototype boilers with different furnace geometry and air distribution and preheating techniques were designed and constructed. Experimental investigations on the reduction of the characteristic start-up emissions from such firing systems were carried out using different gas analysing systems and techniques. Results of this experimental work are a considerable reduction of the start-up emissions and scale-up criteria for the combustion geometry of such stoves. [**LuTH**].

Medium to large scale continuous operated wood combustion systems

The objective of this project part was the development and construction of a new firing system including a vortex burner for the use of wood chips. Based on investigations on a laboratory scale vortex burner a process demonstration unit (PDU) with a thermal capacity of about 100 kW was built up. An analysing system for particulate matter emissions was set-up and applied to the PDU. Various measurement series with different loading conditions and different wood fuels were carried out in order to determine the combustion and emission behaviour. [**FATSE**].
For the verification of the flow field as well as for a further improvement of the mixing conditions and combustion stability detailed LDV profile measurements in the secondary burnout zone were carried out. [**IVD** (FATSE)].

Exploitation plans and anticipated benefits

For a further exploitation of wood combustion units for local heating purposes it is necessary to improve their combustion behaviour in particular to reduce CO, hydrocarbons, soot particles and NO_x. To achieve this major objective experimental, theoretical and modelling studies have been carried out to provide the following deliverable items:

- detailed knowledge about the relevant combustion conditions responsible for low emissions and a high efficiency of wood firings;
- suitable models for simulating and improving the combustion behaviour of new combustion units before building them;
- general rules and guidelines for the design and the construction of high efficient wood firings with low emissions;
- prototype stoves, boilers and wood burners.

To exploit and disseminate these main items one possible way is to present the results on European and international conferences as well as to provide scientific-technical reports.

Furthermore, the results will mainly be used by the industry companies and manufacturers within this project. The first developed prototype fireplace insert developed and constructed by the two industry partners TuOy and ECS will be built by the industrial subcontractor UPO Oy for the European market. The results achieved with the process development unit for the use of wood chips gives the basic technology for a new boiler design. There are activities planed to use the knowledge in a new wood chip boiler concept. The team is going to apply for a grant in a Swiss innovation fund for applied research and development to build a prototype wood chip boiler. The development is carried on in an ongoing project (JOR3-CT98-0278). The scientific partners are ready for co-operation with other industrial partners in order to exploit the obtained knowledge and tools for further developments.

The developed tools and guidelines for the design and construction of small scale wood combustion systems with low emissions will demonstrate the feasibility of this units to operate with very low emissions and a high efficiency and offers to the industry the opportunity to market these systems in Europe successfully.