Final report

1. Project details

Project title	MUPOS - Multi-pollutant-sensor
File no.	64016-0022
Name of the funding scheme	Biomass
Project managing company / institution	Technical University of Denmark, Department of Chemical and Bio-chemical Engineering (DTU, Chemical Engineering)
CVR number (central business registration no.)	30060946
Project partners	Hwam A/S Prevas DTU Fotonik
Submission date	29 June 2021

2. Summary

English version

This project is aimed to develop a new type of on-line multi-pollutant sensor system, which is inexpensive and can be used to small-scale biomass combustion appliances, such as wood stove, for monitoring the emission of pollutants including soot, tar and organic compounds. Ultimately it can be implemented to the digital control system in automatically controlled wood stoves, which will result in a significant reduction of these pollutant emissions.

The new optical sensor have been developed for measuring soot and tar. Two types of LED were applied as light sources to measure different pollutants. Blue LED was chosen to detect soot and deep UV LED with a pre-amplifier was used to measure tar. The two LEDs were integrated as a multiple pollutant sensor system. The sensor was tested in a wood stove produced by HWAM. In order to have reliable evaluation of the sensor, advanced measuring methods were developed, combining Scanning mobility particle sizer, Electric low pressure impactor and Fourier-transform infrared spectroscopy. The results show that the new sensor system can satisfactorily detect the soot and tar and the signals by the sensor are in good agreement with the advanced measuring methods. A long time stability of the sensor was tested and exhibited a good performance. The soot sensor was further improved to a more compact unit integrated with an O_2 sensor and a temperature sensor. The signal from the new unit were implemented to the existing HWAM control system with an additional

algorithm. The results show a satisfactory controllability of the new control system. In addition, experiments and CFD simulations were performed to provide knowledge for improving the combustion chamber design.

The new and cheap optic sensor system can be applied to wood stove and other small-scale combustion appliances for monitoring the particulate and other pollutant emissions and is ready for implementation to the existing control system to reduce the emissions.

Danish Version

Formålet med dette projekt er at udvikle en ny type af online multiforureningsdetekterende sensorsystem, som er billigt og kan bruges til overvågning af emissioner af forurenende stoffer inklusiv sod, tjære og organiske forbindelser fra små biomasseforbrændingsapparater, såsom brændeovne. Systemet kan i sidste ende implementeres i det digitale kontrolsystem i automatisk styrede brændeovne, hvilket vil resultere i en markant reduktion af disse forurenende forbindelser.

Den nye optiske sensor er udviklet til måling af sod og tjære. To typer LED blev anvendt som lyskilder til måling af de forskellige forurenende stoffer. Blå LED blev benyttet til at registrere sod og dyb UV-LED med en forforstærker blev brugt til at måle tjære. De to lysdioder blev integreret som et multiforureningsdetekterende sensorsystem. Sensoren blev testet i en brændeovn produceret af HWAM. Sensorsystemets pålidelighed blev evalueret ved sammen ligning med avancerede målemetoder, der blev udviklet ved kombination af Scanning Mobility Particle Sizer, Electrical Low Pressure Impactor og Fourier-transform Infrared Spectroscopy. Resultaterne viser, at det nye sensorsystem tilfredsstillende kan registrere sod og tjære, og signalerne fra sensoren er i god overensstemmelse med de avancerede målemetoder. Sensorens langtidsstabilitet blev testet og udviste en god ydeevne. Sodføleren blev yderligere forbedret til en mere kompakt enhed integreret med en O2-sensor og en temperatursensor. Signalet fra den nye enhed blev implementeret i det eksisterende HWAM-styresystem gennem en ekstra algoritme. Resultaterne viser en tilfredsstillende styrbarhed af det nye kontrolsystem. Herudover blev der udført eksperimenter og CFD-simuleringer for at opnå en forbedret viden til forbedring af designet af forbrændingskammeret.

Det nye og billige optiske sensorsystem kan anvendes på brændeovne og andre små forbrændingsapparater til overvågning af partikler samt andre forurenende emissioner. Sensorsystemet er klart til implementering i det eksisterende kontrolsystem i automatisk styrede brændeovne for at reducere emissioner.

3. Project objectives

The objective of this project is to design and develop a cheap online multi-pollutant sensor system that can be used to monitor, control and eventually minimize the harmful emissions including soot, tar and other organic compounds by using the sensor for wood stoves in the following aspects:

- Warning wood stove users when the high pollutant emission level is detected from the chimney
- Being used as a part of a digital wood stove control system

In this project, the new type of optic sensor system has been developed for small-scale biomass combustion units, e.g. wood stove. The use of wood stoves can be an efficient and CO_2 neutral method to provide residential heating. However, the use of old wood stove technologies and poor firing habits limit optimal utilization. Presently, combustion of wood in small-scale appliances is a major source of emission of particulate matter smaller than 2.5 µm ($PM_{2.5}$), contributing to more than 60% of the total Danish $PM_{2.5}$ emissions. About 40% of the woody biomass used for energy and heat in Denmark was burned in small-scale residential appliances (mainly wood stoves). There is a huge potential in improving energy efficiency and reducing emissions from the more than 750,000 small-scale combustion units in Denmark. Thus, it is obvious that new technical measures are needed to reduce stove emissions.

The cheap sensor for multiple pollutants would increase the competiveness for automatically controlled wood stoves and replace the manually controlled wood stoves to increase the energy efficiency and reduce the PM emissions. The project supports the strategies for using more biomass, an important renewable energy, and thereby decreasing the CO_2 emission

The project has been conducted in close collaboration between the stove manufacturer HWAM A/S, DTU Chemical Engineering, DTU Fotonik and Prevas. The main activities were focused on development of prototype of the new optical sensor system based on the specifications provided by HWAM. The results show a good performance with long time stability of the sensor system. The soot sensor has been implemented to the digital combustion control system, with satisfactory results.

4. Project implementation

In the execution of the project, the work is divided into four work packages (WPs) that form the basis for development of the new technology:

1) Development of the sensor, (WP1)

2) Measuring methods, (WP2)

3) Control of the combustion process, (WP3)

4) Combustion chamber design, (WP4)

The work package 1 (WP1) and work package 3 (WP3) are the core tasks for the project. WP2 is to support WP1 for evaluation of the new sensor and thereby to implement the sensor to digital control system. WP4 is for improving the knowledge of combustion chamber design of HWAM wood stove.

A PhD student participated in this project, conducting most of the experimental evaluation of the sensors developed using new measuring methods. In addition, fundamental studies of the mechanisms of the influence of alkali compounds, which are present in the bark of the wood logs, on the soot formation were investigated experimentally and theoretically. A bachelor project was connected in the project to setup a simple model of oxidation of CO in the combustion chamber. A postdoc (7 months) participated in the late stage of this project, carrying out the CFD modeling of the combustion chamber of the wood stove and the implementation of the soot sensor to the control system.

The development of the prototype of the new optical sensor (WP1) started soon after the launch of the project, based the input and specifications from HWAM. The design included optical and mechanical designs and corresponding electronics. The design has considered the requirement of a compact system and harsh operating conditions. Two types of LED were applied as light sources to measure different pollutants. Blue LED was chosen to detect soot, the major compound of the particulate matters (PM) from wood stoves. Deep UV LED with a pre-amplifier was used to measure tar. During construction of the prototype of the sensor system, the new measurement methods were developed using new ELPI (electric low pressure impactor) together with SMPS (Scanning mobility particle sizer) for online measurement of particulate concentrations in the flue gas. The two LEDs were integrated as a multiple pollutant sensor system and was tested in the HWAM testing wood stove. The soot and tar signals were well correlated to those measured by SMPS and ELIP, indicating good performance of the sensor system. A six-month test was done, showing a good long time stability of the sensor system. The soot sensor with a more compact unit was selected as a component to implement into the digital control system of the HWAM testing wood stove (WP3). The existing control algorithm in the automatically controlled wood stove was updated with implementation of the soot sensor signal as an additional control parameter, in addition to the temperature and oxygen sensors. The new control system was tested and showed satisfactory results. The improved combustion chamber design (WP4) was focused on the tertiary air injection location for a better mixing of the air and combustion gas by experimental study and CFD simulation.

The largest risk for the technology development in the execution of the project is that the sensor system needs to be installed in the chimney of a wood stove, where the conditions are harsh. For example, the temperature is high and varying in the combustion cycle; the sensor may experience accelerated aging, fouling by particulates, and alignment shift in these conditions. The long time tests did find the shift of the background signal and alignment shift of the sensor. The observed problem was solved by temperature compensation and by new design of replacing the receiver by a reflector. The risk for utilization of the technology is the price of the sensor. Too high price would prevent the product from commercialization.

The progress of the project went well until the last year. The last series of planned experiments were delayed due to the COVID-19. A task of computational fluid dynamic (CFD) simulations of the combustion chamber of the wood stove was added for optimizing the chamber design with a focus on the tertiary air injection. In the extension period, the main tasks and milestones planned for the project have been completed.

In the beginning of the project, it was planned to include the optically based CO_2 sensor in the multi-pollutant sensor system, which will later replace the zirconia based O_2 sensor. Unfortunately, the tests were not successful. It was found that the problem is due to the uneven temperature profile in the chimney, which cannot be solved by temperature compensation. Thus, this idea was abandoned and no further effort was made. The control system is still use the zirconia based O_2 sensor.

5. Project results

The objective of this project has been achieved, i.e. the new sensor for multi-pollutant measurement has been developed successfully, and the soot sensor has been improved and implemented to the control system of the HWAM wood stove.

5.1 Development of the sensor

The first sensor was designed using two LEDs, a blue LED at the wavelength of 400nm for measuring soot, and a UV LED at the wavelength of 280nm for measuring tar as illustrated in Figure 1.

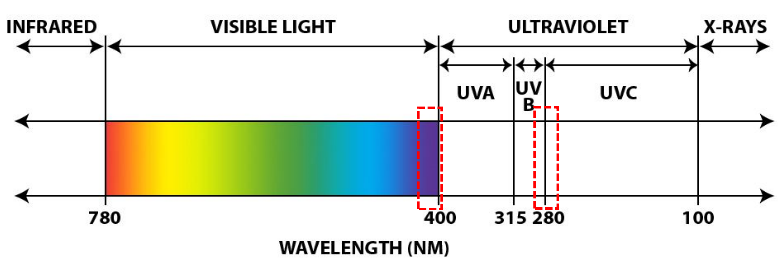

Figure 1 Illustration of the principle of design of the two LEDs for soot and tar measurement.

The two LEDs were installed and evaluated in the HWAM testing wood stove. Figure 2 shows the two LEDs and corresponding detectors mounted in the chimney of the wood stove.

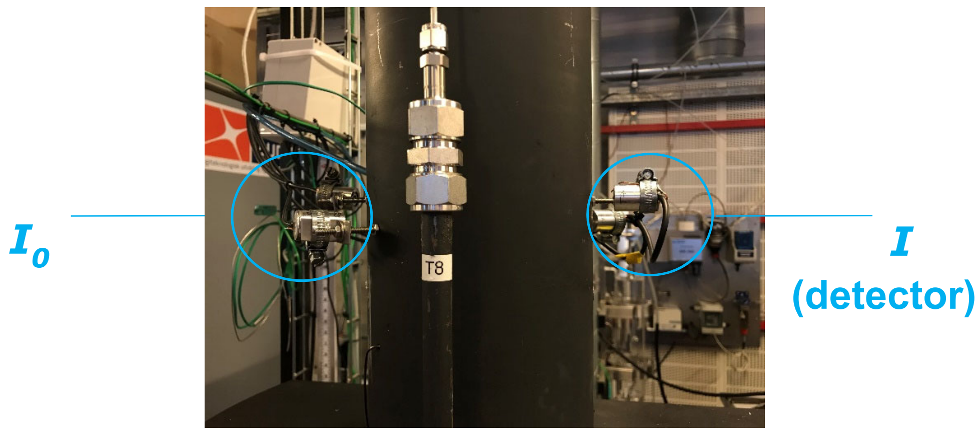

Figure 2 illustration of the two LEDs mounted in the chimney of the testing wood stove.

The online LED signals were compared to the particle concentrations in the flue gas measured by the advanced inline instrument for particulate matters (PM). A typical result of the comparison of the LED signals and PM concentrations in one combustion cycle is shown in Figure 3.

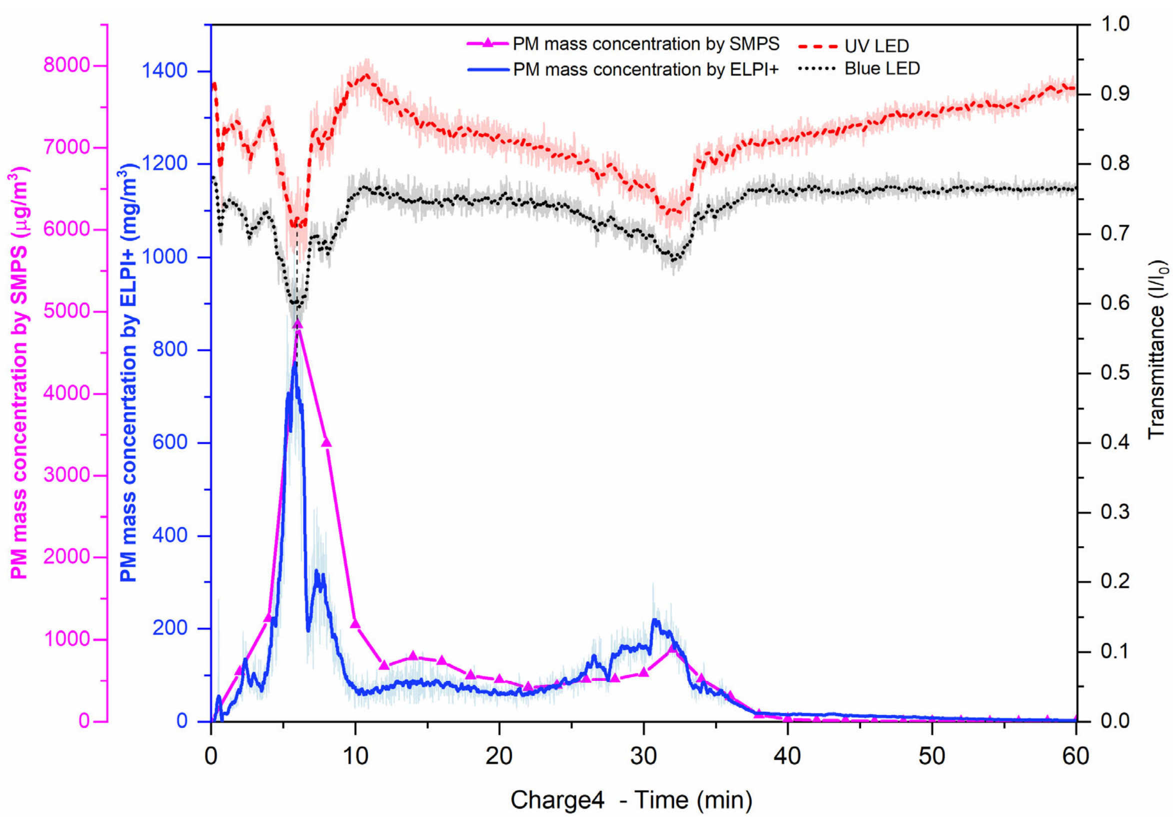

Figure 3 A comparison of the LEDs signals to the measured particle concentration by SMPS and ELPI

The results show that the LED sensor signals generally correlated well with the measuring results derived from other advanced instruments under both normal combustion and poor combustion conditions. Although, the UV LED for the tar measurement shows some degree of the background signal shift, overall, the low-cost LED sensors were able to monitor the transient change of organic and PM emission levels over the combustion cycle. The six month long time stability test indicate that the sensor is robust with good stability. Detailed results and discussion of this part are provided in Appendix 1 (the presentation at the 27th European Biomass Conference and Exhibition, 2019, Lisbon, Portugal) and Appendix 2 (the manuscript prepared for submission to Biomass and Bioenergy).

5.2 Measuring methods for pollutant emission measurements

Comprehensive experiments were performed in the testing wood stove using the developed measuring methods. The results show that the use of wood logs with separately attached bark (WBS) led to obviously higher combustion rates in the initial combustion stage, during which two equally notable emission peaks for both CO and organic compounds can be identified. Using bark in the combustion also resulted in the higher total PM emissions in the initial stage, and particularly the combustion of WBS caused both the higher number and mass emissions of particles with large sizes. In addition, according to UV measurements, higher concentrations of PAHs (Polycyclic Aromatic Hydrocarbons) with two to three aromatic rings and soot were found at the ignition phase of WBS compared with that of wood logs without bark. Therefore, at least for birch, the use of bark tended to cause vigorous combustion with high emissions of various pollutants. The mechanisms were studied on the effect of KCl on the PM emissions.

The investigation on different fueling temperatures show that the THC and PM concentrations of the cold-start combustion cycle were higher than those under the warm-start conditions. In comparison, the difference in emission levels of warm-combustion cycles that were refueled at different temperatures was less significant, with slightly higher PM and THC emissions being observed at a lower refueling temperature than the recommended temperature by the stove manufacturer. The detailed results are in the Appendix 3 (PhD thesis of Yifan Du, Chapter 3 and Chapter 5).

5.3 Control of the combustion process

After test and evaluation of the two LEDs, it was decided to use soot sensor with an improvement for implementation to the control system of the HWAM testing wood stove. The improvement of the soot sensor was focused on integration of the light source, amplifier and receiver into one piece. The working principle of the new sensor is shown in Figure 4

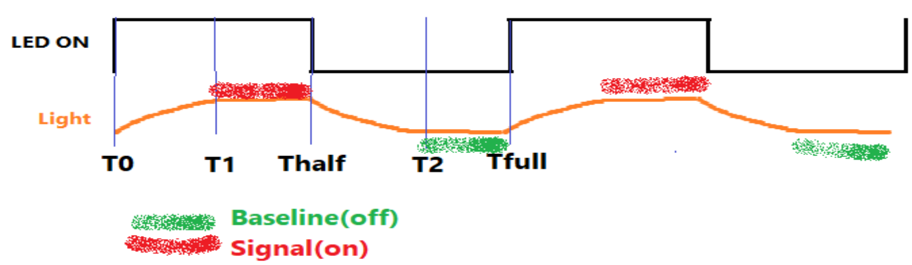

Figure 4 The measurement principle of the new soot sensor

The LED is modulated in On/Off cycle with a frequency of 10 Hz. When the LED is on, the transmitted light is measured as the signal. When the LED is off, it is defined as baseline. The difference between the signal and baseline is a measure of the transmission coefficient through the chimney with smoke (PM). Such differential measurement principle helps to suppress low frequency noise of the system. An illustration of the installation of the new soot sensor the chimney of the wood stove is shown in Figure 5.

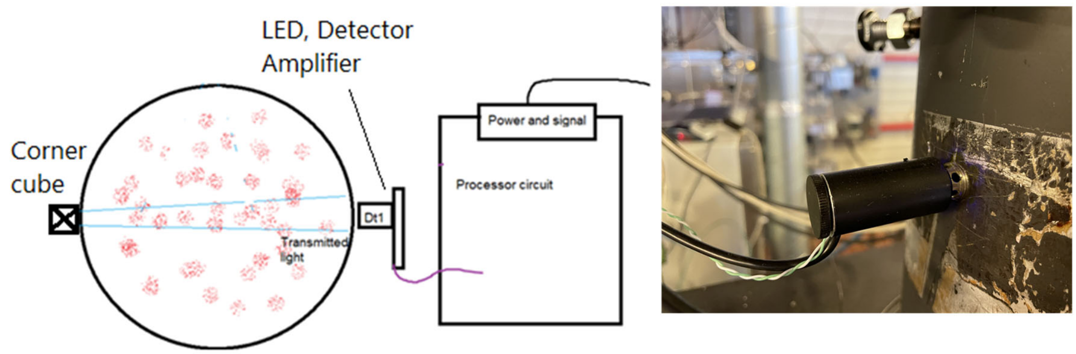

Figure 5 Illustration and a photo of installed soot sensor

After the new soot sensor was constructed, the sensor signal was implemented into the control algorithm as an additional parameter to regulate the operation of the wood stove. The basic idea is that when the soot signal is higher than a critic value, the amount of tertiary air will increase to eliminate the local oxygen depletion in the combustion chamber, thereby decreasing the soot formation. The diagram of the new control algorithm is in appendix 4. The new control system was evaluated by experiments in the testing wood stove. An example of the operation with the new control system is shown in Figure 6.

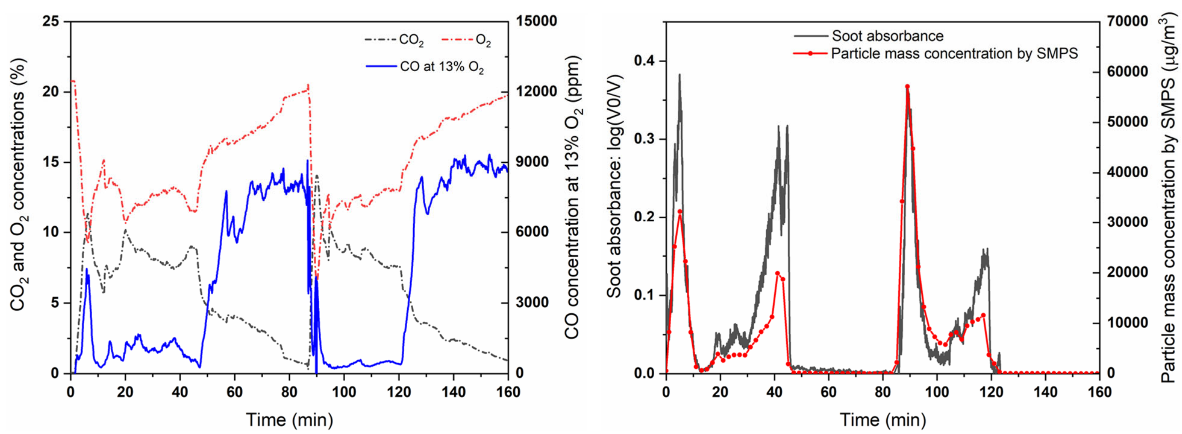

Figure 6 The testing results of the new control system

The results indicate that the new control system, with the soot sensor implemented, works satisfactorily. The absorbance by soot determined by the optical sensor shows good accordance with the particulate matter (PM) emissions measured by advanced instruments.

5.4 Combustion chamber design

This part focuses on the effect of design for the tertiary air injection on the PM and other pollutant emissions from the wood stove. Experiments were performed and CFD simulations were conducted. The details of the different designs of the tertiary air injection are described in Appendix 3 (chapter 4). The emission measurements at the ignition phases show that the no-hole design and the small-hole design had the similar CO, THC and PM emission profiles. In comparison, the involvement of large tertiary air injection holes led to slight variations of emission characteristics. Specifically, it was found that when using large-hole design, CO and THC emissions at the ignition phase decreased, whereas PM emissions increased.

The results of the CFD simulation were firstly compared with the experimental data. When the results show that the CFD model can give a reasonable prediction of volatiles combustion in the wood stove, the simulation continues. In this way, the simulation produces a reasonable trend of soot formation at different stages of wood logs combustion. The simulations indicate that the injection angle of the tertiary air would have impact on the PM emissions. The results may provide new inside for improving the combustion chamber design. The detail description of the CFD simulations is given in Appendix 5 (the manuscript prepared for submission to Energy and Fuel).

Based on the results with respect to technology development, the project has been successfully conducted.

The commercial investigation was focused on the price of the sensor, to validate that the product is cheap. The total cost of the sensor was investigated by Prevas (Appendix 6), which is approximately 320 DKK. This price is acceptable for application to wood stoves.

At this stage, there are two target groups that can use the sensor product and get benefit from the product. One group is the manufacturers of wood stoves and another group is the users of wood stoves. The Implementation of the new sensor system can provide more clean- burning and energy efficient wood stoves with low cost and improve the opportunities of wood stove manufacturers to increase the competiveness. For the wood stove users, improved automatically controlled wood stoves mean a higher comfort and reduced wood use. Also, the sensor may be installed in users wood stove chimneys and acting as an alarm by warning of high PM emission level and thereby avoiding smoke and local air pollution. Furthermore, the senor may be used by local environmental authorities to control and reduce air pollution from private wood stoves.

Some of the results from this project have been presented at the 27th European Biomass Conference and Exhibition, 2019, Lisbon, Portugal (Appendix 1), and at CEN/TC295/WG5 on-line meeting, July 2020 (Appendix 7). In addition, the work of this project has been presented in the CHEC annual day in 2018 and 2020 at DTU Chemical Engineering, with about 100 participants. A paper entitled ‘Particulate emissions from a modern wood stove - Influence of KCl’ has been published in Journal Renewable Energy (Appendix 8). A manuscript entitled ‘Influence of potassium on benzene and soot formation in fuel-rich oxidation of methane in a laminar flow reactor’ has been submitted for publication to Journal Combustion and Flame and in the second review (Appendix 9). Two manuscripts entitled ‘Demonstration of applicably optical measurement techniques and sensors for simultaneous real-time monitoring of OGC, PAH, and PM emissions from a wood stove’ (Appendix 2) and ‘CFD modelling of a wood stove with a focus on soot formation’ (Appendix 5) have been prepared for submission to Biomass and Bioenergy and Energy and Fuels. The extended abstracts of the progress of this project have been published in the PhD yearbook of DTU Chemical Engineering in 2018, 2019 and 2020.

6. Utilisation of project results

The new type of multi-pollutant sensor has been developed. The performance of the sensor prototype has been tested in a wood stove. The immediate utilization of the sensor would be the wood stove. The wood stove manufacturers are the user of the sensor, who applies the sensor the stoves for warning of the improper operation of the stove and for the control system in advanced stoves.

The soot sensor can be used in diesel engines for monitoring the soot emissions, which is also an indicator for the combustion performance of the engine. The diesel engine producers are the user of the technology.

As a participant of the one of the main wood stove producers, HWAM has a strong interest in use the new technology to improve stoves and maintain its market position as selling stoves with the lowest pollution class on the market. Although no immediate timetable is setup due to the current pandemic situation, HWAM has long term interest for use the results of this project in the future, which is also a part of partnership with French SEGUIN Group.

This new sensor is capable to deliver the online pollutant emission level as an input to the control system. Its low price will increase the competitiveness of the product.

The cheap sensor for multiple pollutants would increase the competiveness for automatically controlled wood stoves and replace the manually controlled wood stoves to increase the energy efficiency and reduce the PM emissions. Improvement of use of biomass for domestic heating would promote the CO_2 reduction.

A PhD student, Yifan Du has been involved in this project. A presentation was made in an international conference. Three manuscripts were prepared, one has been published in Journal Renewable Energy. The extended abstracts of the progress of this project have been published in the PhD yearbook of DTU Chemical Engineering in 2018, 2019 and 2020. In the CHEC annual day in 2018 and 2020 at DTU Chemical Engineering, with about 100 participants, presentations were given on the project.

7. Project conclusion and perspectives

A new type of cheap, online optic sensor has been developed, which is able to measure multiple pollutant emissions, such as soot, tar and organic compounds, from small-scale combustion appliances. The sensor has been evaluated in a testing wood stove from HWAM by using advanced measuring instrument, such as SMPS, ELPI and FTIR. The results show that the LED sensor signals generally correlated well with the measuring results derived from other advanced instruments under both normal combustion and poor combustion conditions. The low-cost sensor is able to monitor the transient change of organic and PM emission levels over the combustion cycle. The results also show a good long time stability of the sensor.

The soot sensor was improved with a more compact construction, which has been used to the control system of automatic controlled wood stove from HWAM. The signal of the sensor has ben implemented to the control system with additional algorithm. The improved sensor has a good performance and the new control system works satisfactorily.

The analysis for commercialization with a focus on pricing indicates that the new sensor is cheap. All the results from this project suggest that the new sensor is not only feasible form technology point of view, but also competitive from economic point of view.

Currently, the sensor implemented control system works satisfactorily, but yet to be optimized for further reducing the PM emissions, as well as increasing the efficiency. This could be the next step. In addition, the study with the influence of KCl indicates that the inorganic aerosol may be detected by the sensor. This may also be examined in next step. If this is confirmed, it would provide opportunities for the sensor to be used in the other combustion appliances where the inorganic aerosol emission is the main PM source.

The soot sensor may be used to applied to diesel engines, where the soot emission is a concern, to monitor the emission level. The results from this project provide a competitive hardware for detecting the pollutants in small-scale appliances. It may help to develop the control system by using AI technology in these appliances.

8. Annexes

Appendix 1: The Application of Optical Sensor Systems to a Wood Stove, Presentation

Appendix 2: Demonstration of applicably optical measurement techniques and sensors

Appendix 3: PhD Thesis Pollutant formation and control in wood stoves

Appendix 4: Control algorithm

Appendix 5: CFD modeling of wood stove

Appendix 6: Commercial investigation Report

Appendix 7: WG5-meeting_on-line, Presentation

Appendix 8: Renewable Energy-Particulate emissions from a modern wood stove

Appendix 9: Combustion and Fame manuscript