SHORT TERM SCIENTIFIC MISSION (STSM) – SCIENTIFIC REPORT

The STSM applicant submits this report for approval to the STSM coordinator

Action number: CM 1404 SMARTCATs
STSM title: Experimental investigation of key parameters, characterizing the combustion of solid biofuels
STSM start and end date: 31/03/2018 to 29/04/2018
Grantee name: Ognyan Lyubchov Sandov

PURPOSE OF THE STSM

The use of biofuels increases significantly during the cold period of the year, especially in settlements without centralized heating. As a result, emissions of environmentally harmful gases and particulate matter (PM) are significantly increased during this period.

Emissions of small-scale household stoves must comply with certain limits in the admission process [5]. These emissions do not only vary between different burning phases [4], but can also strongly depend on burning conditions [1]. Specifically, completeness of combustion is influenced by three factors [3]: Amount of (well-mixed) oxygen present in relation to the fuel, temperature, and residence time of the fuel/oxygen mixture in the combustion zone. While automated stoves (e.g., pellet stoves) normally operate under ideal conditions, manually fuelled wood stoves allow for much larger emission variability due to differences in user operation. This can potentially lead to drastically higher emissions than asserted in the approval procedure [2]. Despite the effort done in optimising the combustion process of the small scale devices, operating with solid biomass-based fuels that are widely used in Europe for residential heating there is still a great concern about the emissions and the ambient air quality in the settlements, where centralised heating or alternative energy sources are not available or inaccessible due to different socio-economic factors.

The purpose of this short-term scientific mission (STMS) was to experimentally investigate several key parameters, characterizing the combustion of solid biofuels, namely biomass pellets, currently produced and offered at the Bulgarian biomass market.

Thus, according to the work plan the main gas phase products (CO_2, , SO_2 and NO) were measured simultaneously with the PM content in the flue gas during single pellet combustion (weighing around 0.5g) in the Formation Rate Unit (FRU) reactor. The analyses were carried out using the appropriate laboratory appliances at the Institute of Chemical, Environmental and Bioscience Engineering, Vienna University of Technology (TU-Wien).

This STSM offered me the opportunity to collaborate with the Research Group, supervised by Prof. Franz Winter know to have vast experience in this research field.

Moreover, the mission aimed to establish long-term cooperation between both research institutions in the frame of the SMARTCATs COST Action CM 1404.

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

The present work was focused on the experimental investigation of several key combustion characteristics, during single particle combustion of biomass based pellets under well control conditions (pressure, temperature range; mixture composition etc.) in the FRU reactor installed at TU-Wien.

The expected results can be generalised as follows:

1.) *Establishing long term collaboration* between the two research groups: TU-Wien, Institute of Chemical, Environmental and Bioscience Engineering) and TU-Sofia, CEE. It aims at initiating series of experiments for cleaner combustion and ambient air quality.
2.) *Familiarization with safety and technical terms of conditions* at the laboratory together with implementation of the methodology required to perform the planned analyses.
3.) *Measurement of flue gas emissions and chemical-kinetic parameters*, characterising the combustion process. Thus the rate of fuel combustion and the time history of the flue gas emissions was studied in terms of the main gas phase (CO_2, CO, NO, SO_2) products
4.) *PM emission measurements*. During this STSM effort was done to implement an experimental setup allowing the measurement of the emissions of particulate matter (PM) simultaneously with the flue gas monitoring. Thus the particle number density and the particle size distribution were measured. The obtained results are still being analysed. Further in the text some preliminary results are presented.

Brief description of the implemented experimental setup (Figure 3):

Combustion device

The biofuel was burnet in the above mentioned FRU. It is made of stainless steel with diameter of 35 mm and 250 mm height. The FRU was heated electrically by heating shells. A fluidized bed was used to achieve constant conditions around the fuel particle, where no significant temperature gradients were observed. Detailed description of the FRU is available at [6, 7, 8, 9]. Photo of the utilised installation is shown in Figure1.

Figure 2 shows am example of the available Graphical user interface (GUI) that allows managing the combustion conditions.

According to the work plan a single fuel sample was prepared and burned-out in the fluidized bed device - FRU. The particle mass was about 0.5 g.

Gas phase products analysis

Thus the concentrations of the main gas phase products (CO_2, CO, NO, and SO_2) were measured in the flue gas, shortly after the burning of the fuel particle, following the procedure described in [6]. For that purpose gas analyser was used (model EL3020) to the flue gas outflows to determine the composition of the flue gases in volume percentages and ppm. The used measurement principle is ***non-dispersive infrared absorption***. Currently Photometer with 1 or 2 beam paths (gas paths) was used to measure up to 4 components. The detectable sample components and the relevant measurement range were as follow: O_2 - 0-25%, CO - 0-10000 ppm, SO_2 - 0-2000 ppm, CO_2 - 0-20%, NO- 0-2000 ppm.

PM analysis

One of the objectives of this STSM was to combine the effort of the representative of both groups to upgrade the FRU with a device for measuring the PM in the exhaust (flue) gases simultaneously with the gas-phase products. The goal was successfully implemented under the supervision of Professor Franz Winter and the instructions Professor Thomas Laminger, TU-Wien. For that purpose to the FRU a measurement device was attached that allowed determining the number and the size of the PMs in the FRU flue gases. Furthermore, the gas analyser located at the exhaust gas path was successfully reconnected to the FRU. Part of the exhaust gas was diverted to the gas analyser to determine the content of CO_2, CO, NO and SO_2. After the calibration and synchronization of all measurement instruments, the biofuel study started (see Fig. 3) under different combustion conditions such as: temperature (700 – 900 ^oC), partial oxygen pressure (10 -21 kPa), and fuel sample mass (0.14 to 0.6 g).

The PM measuring device was Welas® 2000 P, the pressure of the carrier gas was measured continuously during the test and the required operating flow rate was automatically set to 5 l/min. The PM measuring

device includes: mass flow controller for flow rate regulation, absolute pressure capsule and filter unit. Typically, the PM measurement range allows covering a wide range of mean particle diameter: from 0.2 to 100 µm. For that purpose 4 different measurement ranges are determined: 0,2 µm – 10 µm , 0,3 µm – 17 µm , 0,6 µm – 40 µm , 2 µm – 100 µm. *In the current experiment the analyses were carried out in terms of the first two measurement ranges*.

The measuring principle is optical light scattering. The measurement range of the particle number (number of PM) < $1 \cdot 10^6$ particles/cm^3.The time resolution is ≥ 10 ms. The thermodynamic conditions are as follow: operating temperature between 10 – 40 °C, at operating pressure ≤ 10 bar.

The device is connected to laptop, which is equipped with high quality data acquisition software (PDControl and FTControl) for recording and visualising the obtained results. The PDControl software is designed for measurement value acquisition and data analysis by all of the welas digital systems. It enables quick and easy particle size and concentration analysis with the welas digital opt. aerosol spectrometer. The PDControl enables quick and easy particle size and concentration analysis.

The FTControl software is used for reliable and economic performance of filter tests and fractional separation efficiency measurements with the welas digital optical aerosol spectrometer. The FTControl software provides the user with special advantages, including individually programmable sequences for fractional separation efficiency measurement etc.

The PM measurements were carried out simultaneously with the gas phase species measurements and continuously during the burning of a single pellet sample, taking place every second.

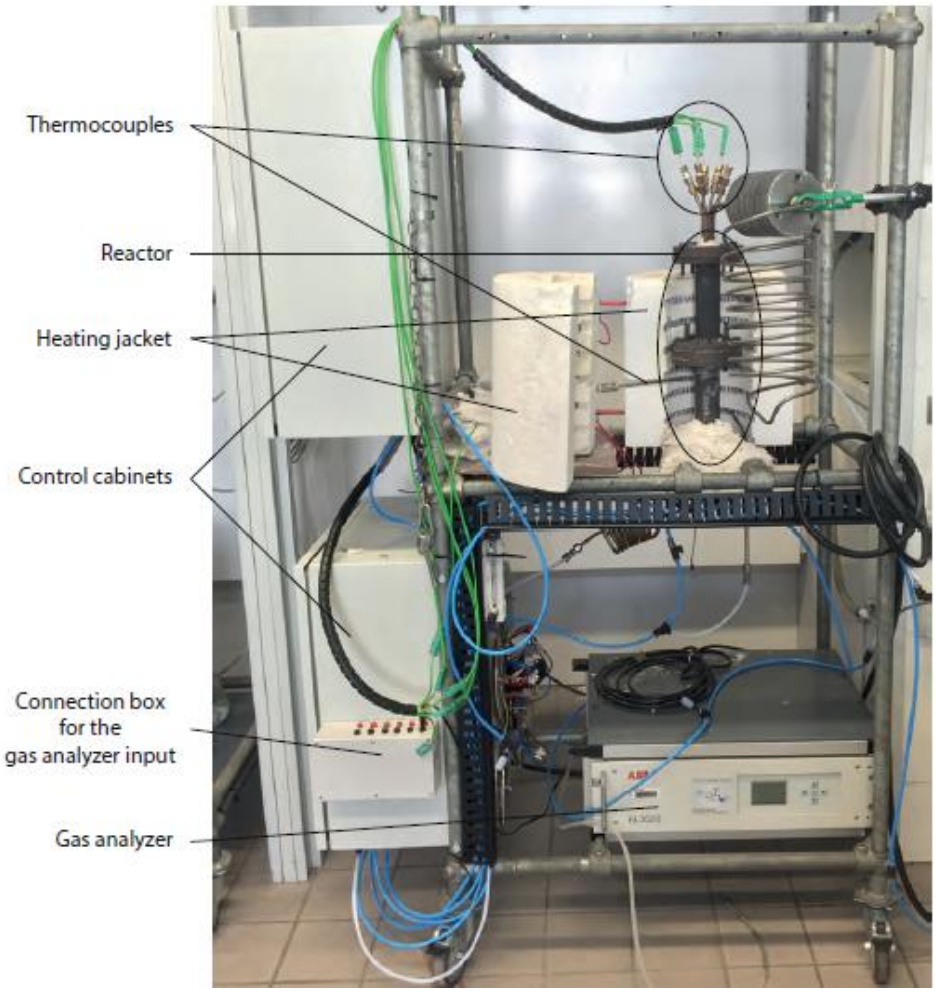

Figure 1. Picture of the Formation Rate Unit reactor [10]

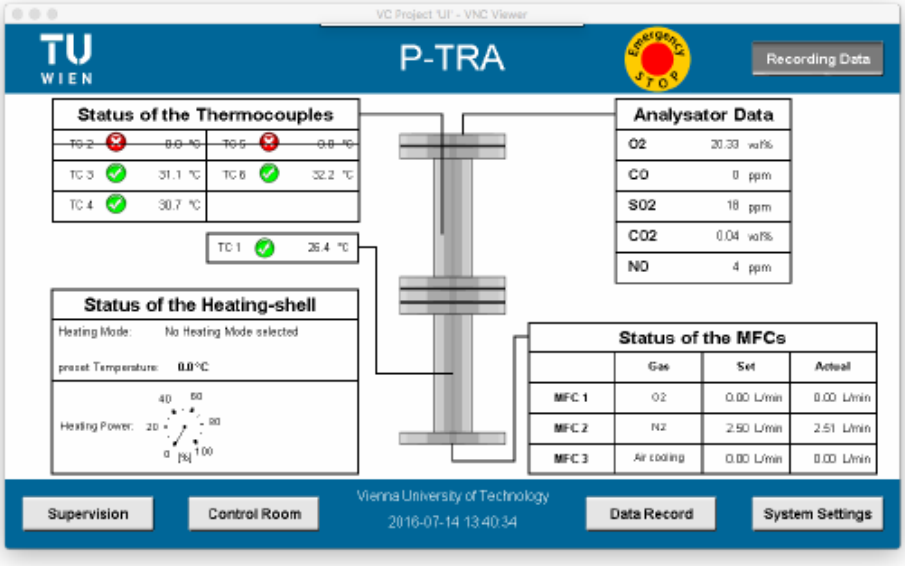

Figure 2. Interface of the Graphical User Interface (GUI)

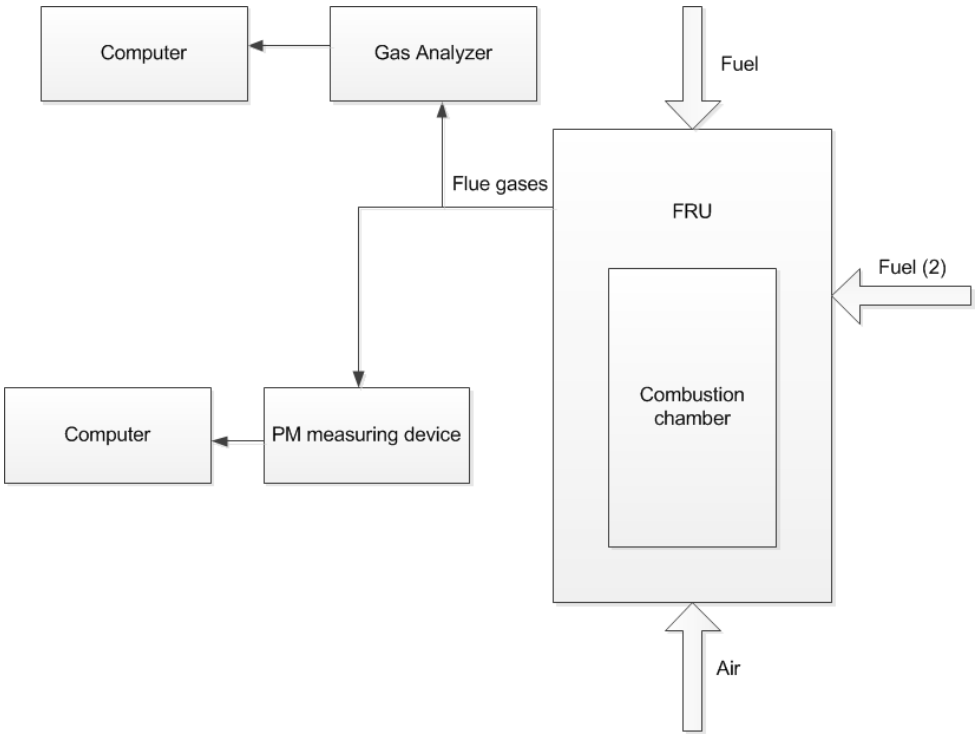

Figure 3. Schematic installation of the experimental equipment utilized to implement the analytical procedure

DESCRIPTION OF THE MAIN RESULTS OBTAINED

Prior to the STSM the fuel was characterized in terms of the main fuel specific parameters. Thus the fuel specific net calorific value and the proximate analyses were obtained at TU-Sofia, whereas the ultimate analysis was carried out at TU-Vienna (using "EA 1108 CHNS-O"). The general results are summarized in Table 1.

Table 1: Proximate and ultimate analyses of the investigated biofuel

Proximate analysis *a – as analyzed*	**Soft Pellets (wood + bark)**	**SD ±**
Moisture (W^a), %	6.89	0.74
Ashes (A^a), %	0.65	0.13
Volatile organic compounds (V^a), %	78.77	0.10
Fixed carbon (FC^a), %	13.64	(by diff.)
Ultimate analyses *daf - water, ash free*		
Carbon (C^{daf}) %	47.77	0.03
Hydrogen (H^{daf}) %	6.48	0.11
Sulfur (S^{daf}) %	0.02	0.01
Nitrogen (N^{daf}) %	0.14	0.03
Oxygen (O^{daf}) %, (by diff.)	45.59	(by diff.)
Net calorific value Q_i^d (d - dry mass), MJ/kg	***19.00***	***0.06***

The formation of the main gas phase products (CO_2, CO, NO and SO_2), and the PM was measured simultaneously in the above described FRU under conditions relevant to fluidized-bed combustor. It is believed that under this conditions N_2O was also formed but it is rapidly destroyed (e.g. in reaction of type: $N_2O + H = N_2 + OH$). The experimentally measured results for SO_2 were close to or below the detection limit, thus currently not included in the results analyses.

During the implementation of the current work plan more than 100 single samples (single pellets with mass between 0.2 and 0.6 g) were burned-out at atmospheric pressure, temperatures: 700, 750, 800, 850 and 900 °C; concentration of the oxygen inflow O_2 = 21 vol%, 16.5 vol% и 10 vol%. Some of the preliminary results are summarized in Figures 4 to 8. At least 13 series of experiments were considered as successful. Each of the series was repeated generally between four to ten times.

Table 2. Series of the performed experiments

Series No.	**Inflow O_2, vol. %**	**Fuel pellets**	**Char pellets**	**Temperature, °C**
		Mass, g		
1	21	0.15 - 0.64		700
2	21	0.15 - 0.64		750
3	21	0.15 - 0.64		800
4	21	0.15 - 0.64		850
5	21	0.15 - 0.64		900
6	16.5	0.50 - 0.60		700

7	16.5	0.50 - 0.60		750
8	16.5	0.37 - 0.55	0.12 - 0.45	800
9	16.5	0.15 - 0.64		850
10	10	0.15 - 0.40		700
11	10	0.15 - 0.40		750
12	10	0.15 - 0.40		800
13	10	0.15 - 0.40		850

The effect of oxygen inflow concentration is shown in Figures 4 and 5. After the fuel particle was fed into the hot fluidized bed of sand it undergoes drying, devolatilization and char combustion [6]. Figure 4 denotes the effect of oxygen on the main gas phase products (CO_2, CO and excess O_2) obtained during biomass pellets combustion at 850 °C, atmospheric pressure and O_2 inflow concentration of 16.5 vol. and 21 vol. %. Because NO was measured in relatively small amount in the exhaust gases its concentration is not presented here.

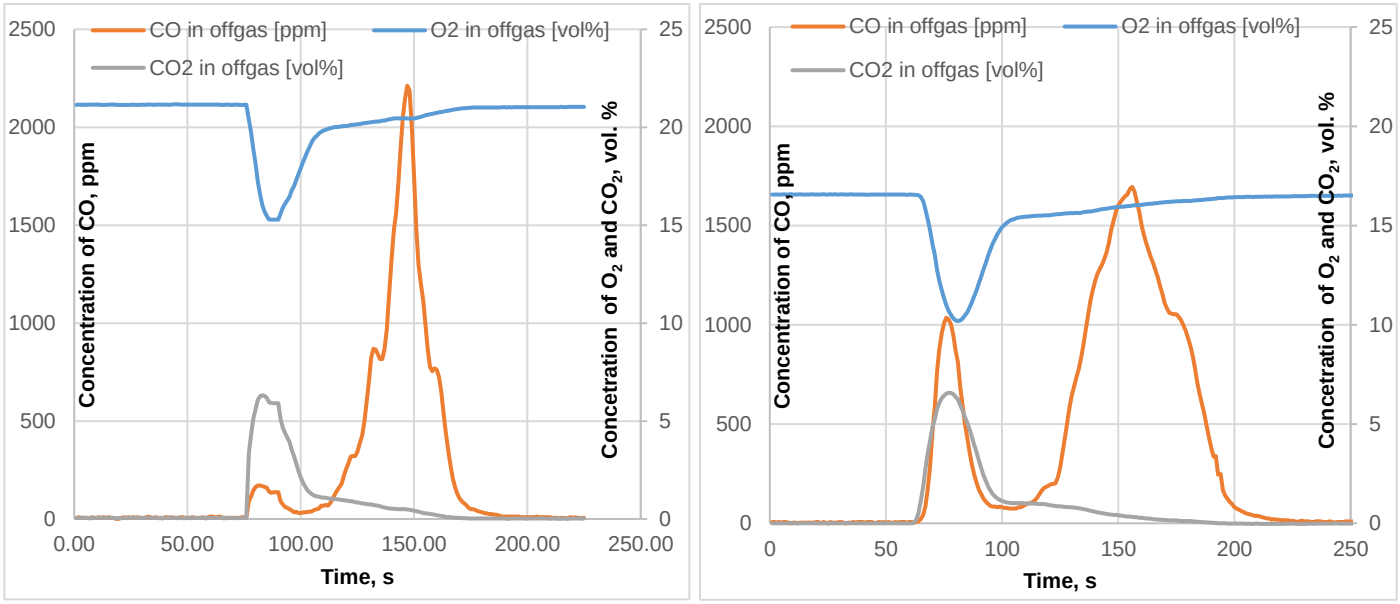

Figure 4. The effect of oxygen on the main gas phase products (CO_2, CO and the excess O_2) obtained during biofuel combustion at 850 °C, atmospheric pressure and O_2 inflow concentration of 21 vol.% (left hand side) 16.5 vol.% (right hand side).

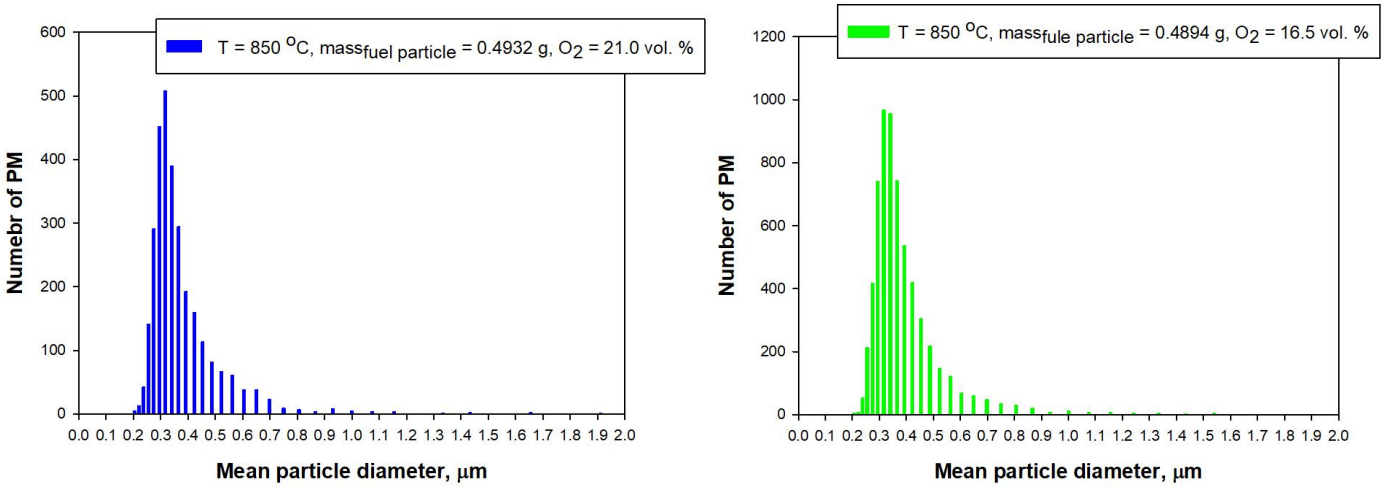

Figure 5. The effect of oxygen on the PM distribution obtained during the combustion of biofuel at 850 °C, atmospheric pressure and O_2 concentration of 21 vol.% (left hand side) 16.5 vol.% (right hand side).

Figure 5 expresses the effect of oxygen inflow concentration on the particle number density and the particle size distribution. The experiment was carried out in the conditions relevant for series 4 and 9, Table 1. Decreasing the amount of O_2 in the combustion mixture practically doubled the amount of PM in the exhaust. Interestingly, mainly ultrafine particles were detected in these initial experiments (0.25-0.4 μm), although the equipment was adjusted to measure in the range 0.2 – 10 and 0.2 – 17 μm.

As expected, significant temperature dependence was observed for the mass normalized mean values of the results, obtained for the measured PM characteristics (see Figure 6).

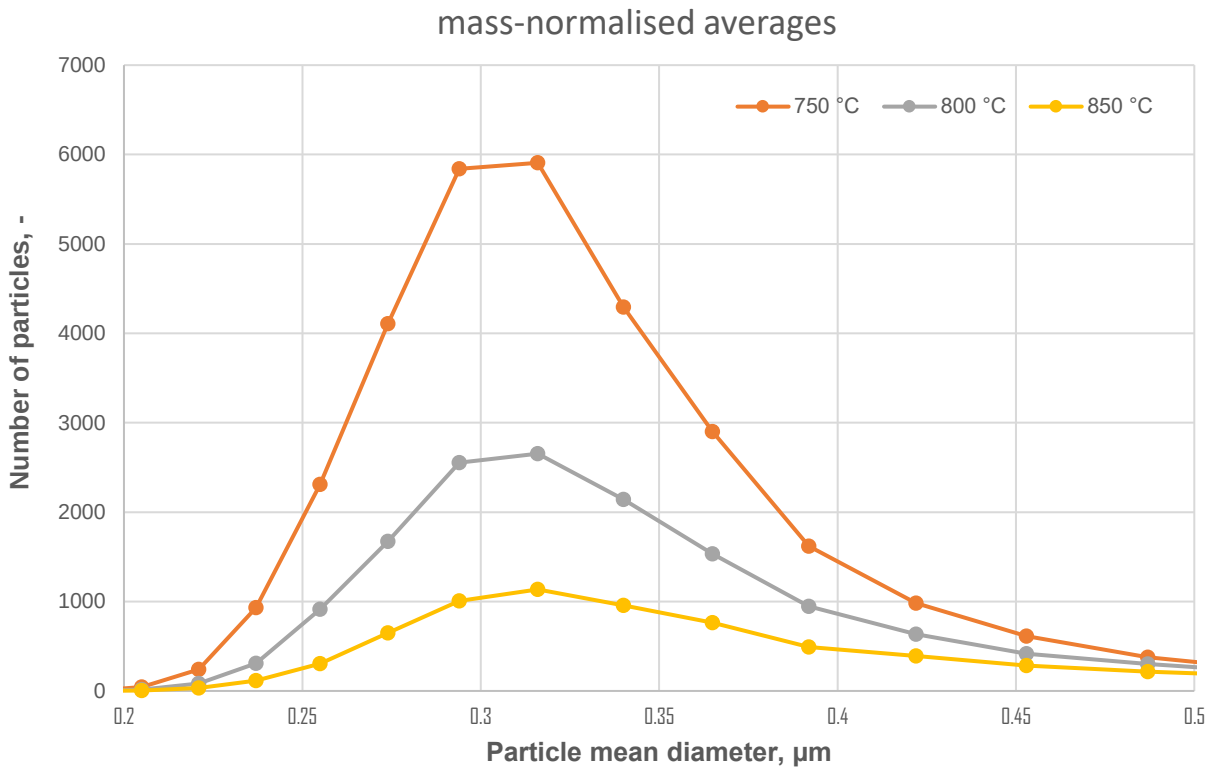

Figure 6. Mass normalized average results for the particle number density and the mean particle diameter, obtained at T = 750, 800 and 850 °C, atmospheric pressure and inflow O_2 concentration of 21 vol. %.

The next experiment (Figures 7 and 8) has confirmed the hypothesis that some gas phase products and PM concentration strongly depend on the availability of volatile organic compounds (VOC) in the investigated fuels. Currently, the same type of experiment was carried out for the biofuel pellets (as received) and for pellets of carbonized fuel (char). Figure 7 expresses the comparison results for the CO_2 (in vol. % - *left hand side*) and the CO (in ppm – *right hand side*) from two samples of that kind with similar mass, whereas Figure 8, denotes the results for the NO (in ppm – *left hand side*) and PM concentration (number of PM - *right hand side*) respectively. The NO concentration is almost unaffected by the VOC. Nevertheless, the CO_2 peak is almost 2,5 times reduced in the char combustion, whereas the CO peak shows slight increase and is considerably shifted in the later time interval (150 - 250 s). Generally such shift was observed (up to a certain range) for all measured characteristics. During char combustion, the particle number was close to zero under the examined conditions.

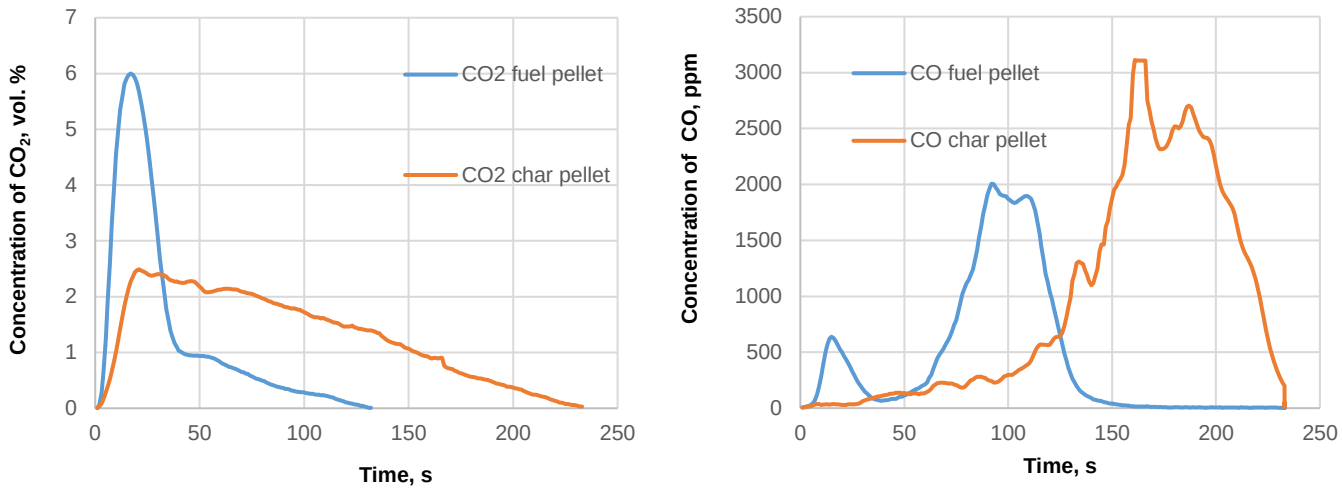

Figure 7. Time distribution of the CO_2 (left hand side) and CO right hand side) concentrations, obtained during the combustion of biofuel and char pellets at 800 °C, atmospheric pressure and O_2 inflow concentration of 16.5 vol.%.

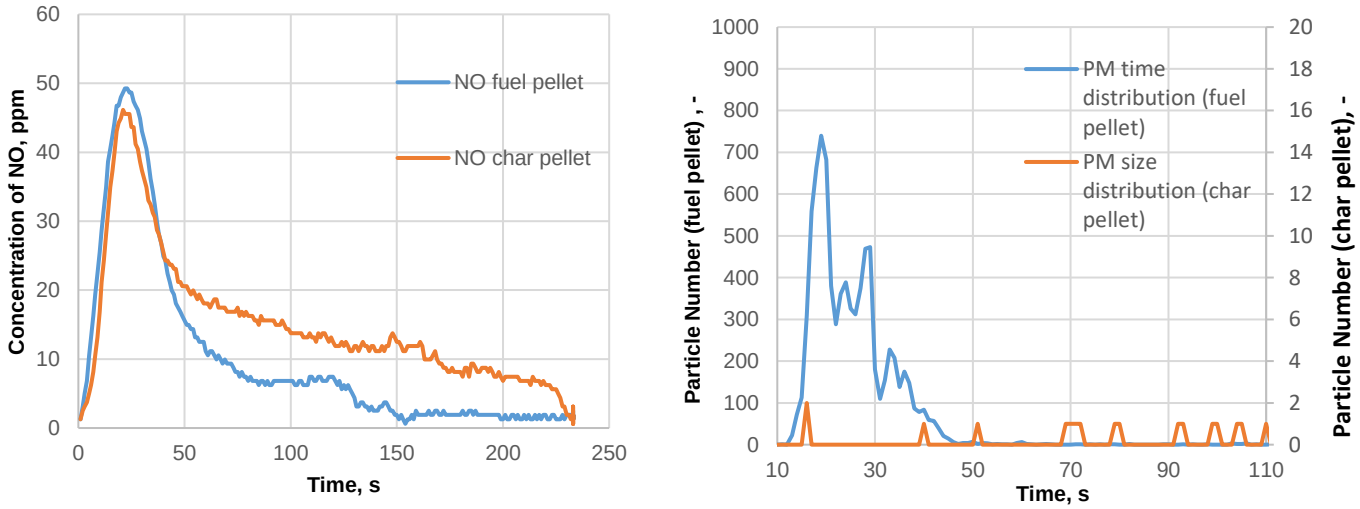

Figure 8. Time distribution of the NO (left hand side) and PM right hand side) concentrations, obtained during the combustion of biofuel and char pellets at 800 °C, atmospheric pressure and O_2 inflow concentration of 16.5 vol.%.

Table 3 presents summary of the currently analyzed data. Additional data analyses are in process. Future investigation is planned for obtaining key kinetic parameters, especially in terms of the PM formation.

Table 3. Summarized results

Residense time, h	Temperature, °C	Max sample mass, g	Average sample mass, g	O_2 inflow, vol. %	Minimum O_2 out-flow, vol. %	O_2 out average, vol. %	Average				Max		
							In the exhaust						
							CO_2 vol. %	CO ppm_v	NO ppm_v	PM	CO_2 vol. %	CO ppm_v	NO ppm_v
03:45	700	0.4897	0.4188	21.0	16.647	20.66	0.411	280	7.58	4578	4.5	2137	38.63
03:40	750	0.4997	0.4895		16.16	20.55	0.5115	295	9.48	5908	5.083	2190	45.53
03:30	800	0.5715	0.43715		15.11	20.69	0.4157	164	10.72	2654	6.13	1972	60.5
03:00	850	0.6352	0.5277		14.07	20.62	0.5128	137	14.68	1136	7.427	2212	68.55
05:00	700	0.5882	0.5302	16.5	10	16	0.91	638.4	10.6	2377	6.6	1910	62.31
04:20	750	0.6071	0.543		9.99	16	1.02	620	11.26	2665	6.7	2608	56.76
04:10	800	0.5499	0.48		9.76	16	0.96	507	10.77	2917	6.69	2505	52.4
04:00	850	0.5646	0.5142		9.06	16	1.26	458	10.5	2267	7.64	2328	60
03:40	750	0.4377	0.2229	10	6.936	10	0.46	315	6.57	860	4.578	1000	23.7
03:30	850	0.226	0.2031		6.61	10	0.518	270	6.83	715	3.46	1097	28.69
02:30	900	0.5523	0.5095	21.0	14.176	10	1.56	276	19.66	299	7.06	1386	62.93

FUTURE COLLABORATIONS

This work aimed to lay the foundations for long-term cooperation between the two institutions - the Technical University of Sofia and the Institute of Chemical, Environmental and Bioscience Engineering, Vienna University of Technology (TU-Wien) in the field of the intelligent energy carriers for cleaner combustion. The accent is on the combustion of currently favored biomass fuels. Based on the results obtained, further investigations were planned using different types of biomass, mainly agricultural residues (e.g. coffee husk, sunflower pellets and cherry pits). Such and other similar food waste matter is continuously produced in large quantities and has great energy potential. This study is considered to be in line with the objectives of WG2 - Chemicals for the control of by-products in the transformation of Smart Energy Carrier and others.

Acknowledgment

I would like to greatly appreciate the assistance of my colleagues at TU-Wien Prof. Franz Winter, Prof. Thomas Laminger, Boleslav Zach and Florian Wesenauer for the fruitful discussions and their research and technical assistance that facilitated the adequate maintenance and operation of the applied equipment and the implementation of the intense work plan.

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