COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

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: Emissions formation of single fuel particles combustion under FBC condition
STSM start and end date: 27/07/2018 to 31/08/2018
Grantee name: Ognyan Lyubchov Sandov

PURPOSE OF THE STSM

The purpose of this short-term scientific mission (STMS) was to experimentally investigate key parameters characterizing the burning of several types of solid biofuels, namely biomass pellets (sunflower seeds, rapeseed, straw and alfalfa), cherry stone and coffee residues that are currently available and used for house heating in regions where the population does not have access to the central heating services.

According to the working plan, the main gas phase products (CO2, SO2 and NO) were measured simultaneously with the PM content in the flue gas during the combustion of single particles of the above-noticed fuels (with a mass of about 0.2 g) in the Formation Rate Unit (FRU) . The analyzes were conducted using the appropriate laboratory appliances available at the Institute of Chemical, Environmental and Bioscience Engineering, Vienna University of Technology (TU-Wien).

This STSM has enabled to continue collaboration with the Research Group led by Prof. Franz Winter, who has considerable experience in this field of research.

In addition, during this mission there were also participants from Czechoslovakia and Italy, who also contributed to the implementation of the planned studies. The future prospect of this work is to further the investigations in the frame of the same international and interdisciplinary research environment.

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 controlled conditions (pressure, temperature range; mixture composition etc.) in the FRU reactor installed at TU-Wien.
The expected results can be generalised as follows:

1.) *Continuation of collaboration between the two research groups:* TU-Wien, Institute of Chemical, Environmental and Bioscience Engineering) and TU-Sofia, College of Energy and Electronics. It aims at initiating series of experiments for cleaner combustion and ambient air quality.

2.) *Measurement of flue gas emissions and chemical-kinetic parameters*, characterising the combustion process. 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
3.) *PM emission measurements*. During this STSM the methodology developed in my previous STSM mission was used to measure particulate matter (PM) emissions simultaneously with flue gas monitoring. This measures the particle number and the particle size distribution. The results obtained are still being analysed. In the following, some preliminary results are presented

Brief description of the implemented experimental setup (Figure 3):
<u>*Combustion device*</u>

The biofuels was burnt in the above-mentioned FRU, which has been presented in more detail in the report from a previous STSM mission [1] on the research topic. Prior to the onset of this STSM mission, the fuel supply system has been reconstruction (Fig.1). Two large valves were mounted at the top of the device, and the thermocouples were placed where the fuel had been fed. The principle of operation is shown in Figure 3 and a detailed description is available in [2,3,4].
According to the working plan, a single fuel sample is prepared and burnt in the fluidised bed device - FRU. The mass of the particles was about 0.2 g.

<u>*Gas phase products analysis*</u>
The concentrations of the main gas phase products (CO2, CO, NO and SO2) was measured In the flue gases. The measurement was carried out shortly after combustion of the fuel particle, following the procedure described in [6]. For this purpose, a gas analyser was used, which main features and principles have been described in [1].

<u>*PM analysis*</u>
One of the objectives of the last STSM was to combine the efforts of the representatives of both groups to demonstrate a FRU with a device for measuring PM in the exhaust gas simultaneously with the gas phase. During the implementation of the present studies, the same measuring devices were used and were connected in the same way as in the previous studies [1]. For this purpose a diluter was used (see Figure 3), to dilute the measured flue gas flow to reduce the particle number to the optimum number for the PM measurement device.

After calibration and synchronization of all measuring instruments the studies of biofuels (see Figure 2) under various conditions of combustion was conducted: temperature (700-900 ° C), partial pressure of the oxygen (5,13 and 21 kPa) and fuel sample mass (0.1 to 0.3 g). In this experiment PM analyses were performed with respect to the measurement range (0.2 μm - 10 μm).

Additionally, during this short-term scientific mission Florian Wesenauer prepared a software application for convenient and accurate processing of the obtained data.

Figure 1. Picture of the reconstructed Formation Rate Unit reactor

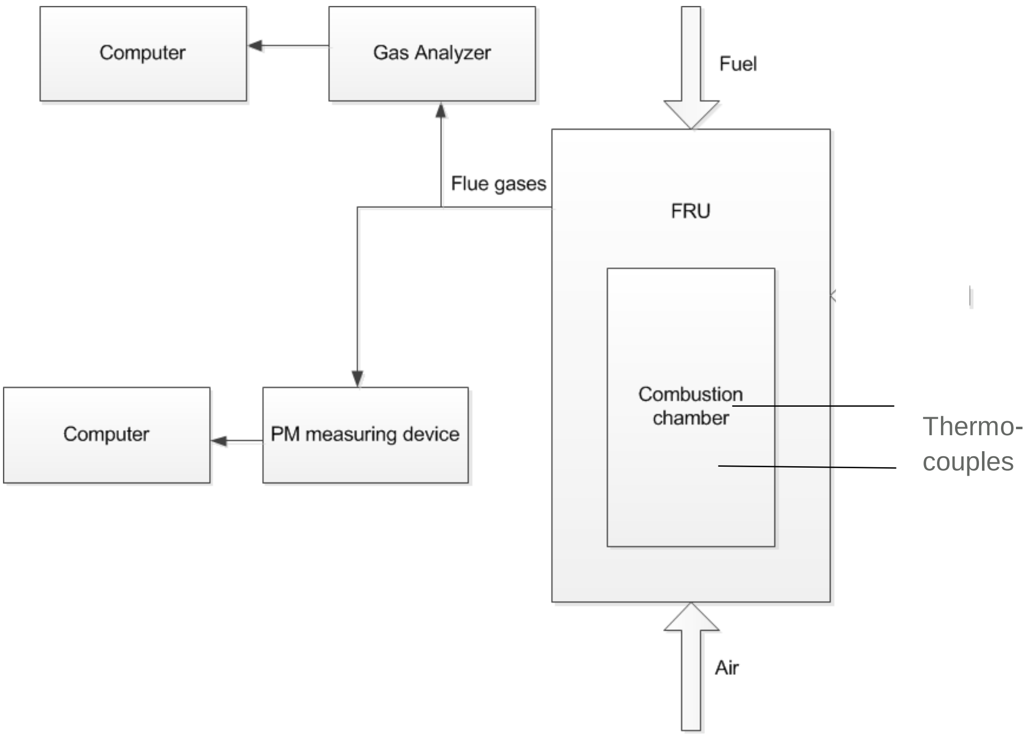


Figure 2. Schematic installation of the experimental equipment utilized to implement the analytical procedure

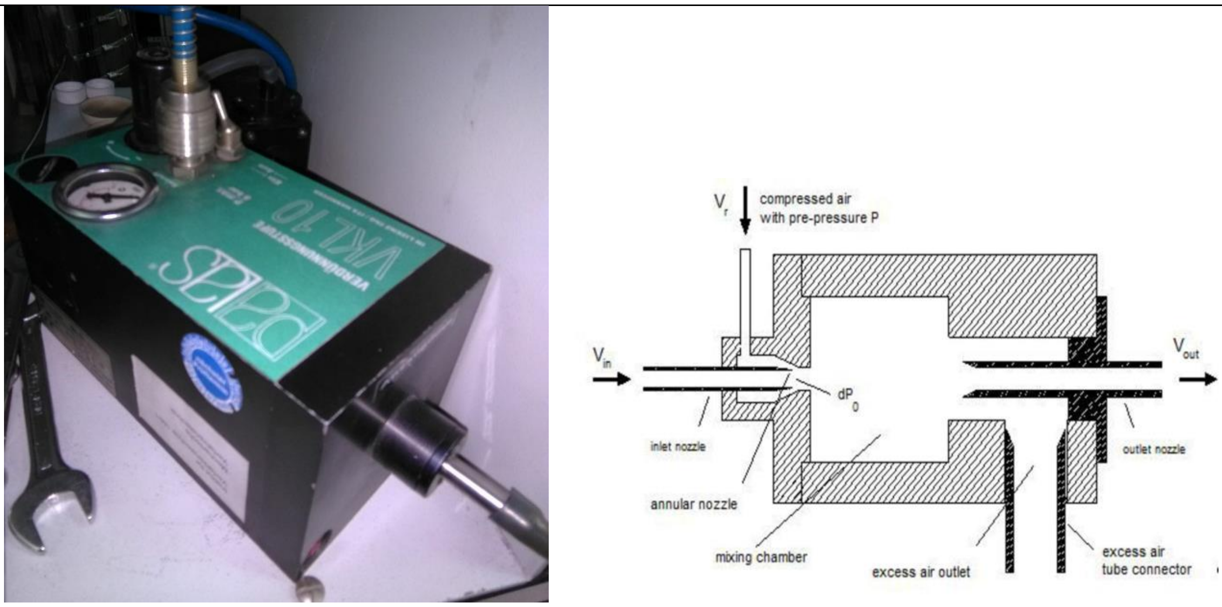


Figure 3. Picture of a diluter and a diagram showing the principle of operation

DESCRIPTION OF THE MAIN RESULTS OBTAINED

The choice of the biofuels was based on the concept, prescribed in the relevant legislation for resource utilization. Therefore, besides the softwood pellets, presented here mainly for comparison reason, merely fuels that are produced partially or entirely from biomass residue were considered.

Prior to this STSM, series of analyses were initiated, aiming to characterize the investigated biofuels. The proximate analysis was carried out at CEE, TU-Sofia, whereas the ultimate and ash analyses, and the calorific value are being carried out at external laboratories. Finalised data from the proximate, ultimate and the ash analysis (major element) were summarized in Table 1. Because it is still work in progress, the table is expected to be completed in the coming weeks.

Table 1. Chemical characterisation of solid biofuels

Parameter measured	Softwood including bark	pellets softwood	Sunflower husk pellets	Rape (colza) pellets	Lucerne pellets	Wheat straw pelets	Cherry stones	Coffee residue
NCV (MJ/kg) - dry basis		19.00±0.06		14.91±0.04				
Proximate analysis - w %. as analyzed								
Moisture		6.89	7.52	9.86	8.58	9.62	9.98	7.78
Ash		0.65	2.88	4.59	15.62	9.80	1.13	1.52
Volatiles		78.77	76.93	78.53	73.01	72.53	81.12	83.98
Fixed carbon (by diff.)		13.69	12.67	4.59	2.79	8.02	7.76	7.66
Ultimate analysis - w %. dry basis								
C		47.77						
H		6.48						
S		0.02						
N		0.14						
O		45.59						
Cl		<0.01						
Ash analysis (major elements) - w %. dry basis								
SiO_2		19.45	1.01		28.86	57.79	3.58	
Al_2O_3		7.93	0.15		5.78	3.93	0.43	
Fe_2O_3		2.56	0.92		1.45	1.37	0.43	
MnO		1.01	0.02		0.06	0.17	0.05	
CaO		31.28	20.44		12.06	8.12	13.00	
MgO		7.49	11.95		3.56	2.82	10.57	
BaO			0.01		0.04	0.01	0.01	
Na_2O		0.11	0.57		1.31	0.93	0.8	
K_2O		4.46	28.78		19.72	12.11	24.16	
Cr_2O_3		<0.5	0.07		0.01	0.01	<0.01	
TiO_2		0.12	0.14		0.20	0.20	0.14	
ZnO		15	0.06		0.06	0.07	0.08	
CuO		4.2	0.03		0.01	0.04	0.07	
SrO			0.02		0.03	0.04	0.03	
P_2O_5		1.62	5.88		4.78	2.57	26.65	

The formation of the main gas phase products (CO2, CO, NO and SO2) and PM is measured simultaneously in the above-described FRU under conditions relevant to fluidized-bed combustor.

During the implementation of this work plan more than 600 individual samples (with a mass of about 0.2g) were burnt at atmospheric pressure, temperatures: 700, 750, 800, 850 and 900 ° C; oxygen inflow concentration O2 = 21 vol.%, 13 vol.% and 5 vol.%. Some of the preliminary results are summarized in Figures 4 - 12. Each of the series is usually repeated between four and ten times.

Table 2. Series of the performed experiments

Series No.	Inflow O2, vol. %	Fuel type Mass, g	Temperature, oC
1	21	0.07 - 0.2	700
2	21	0.07 - 0.2	750
3	21	0.07 - 0.2	800
4	21	0.07 - 0.2	850
5	21	0.15 - 0.2	900
6	13	0.15 - 0.2	700
7	13	0.15 - 0.3	750
8	13	0.15 - 0.3	800
9	13	0.15 - 0.3	850
10	13	0.15 - 0.3	900
11	5	0.15 - 0.2	700
12	5	0.15 - 0.2	750
13	5	0.15 - 0.2	800
14	5	0.15 - 0.2	850
15	5	0.15 - 0.2	900

The formation of the main gas phase products (CO2, CO, NO and SO2) and PM was measured simultaneously in the above-described FRU under conditions relevant to fluidized-bed combustor.

The effect of oxygen inflow concentration on the major products was studied. Figure 4 presents the CO2 profiles, obtained for two different types of biofuels: dark colored softwood pellets and sunflower pellets. Figures 5 to 12 express the influence of the oxygen content on the mass normalized PM number density versus the particle diameter for five different biofuels. The obtained results follow unexpected trends. However, it should be noted that the data analyses procedure is still in progress and the results are not yet validated.

The final data is expected to be presented at the „1st International Conference on Smart Energy Carrier, in the frame of COST Action CM 1404 (SMARTCATs), Napoli, Italy, 21-23 of January, 2019“ and possibly in a journal publication.

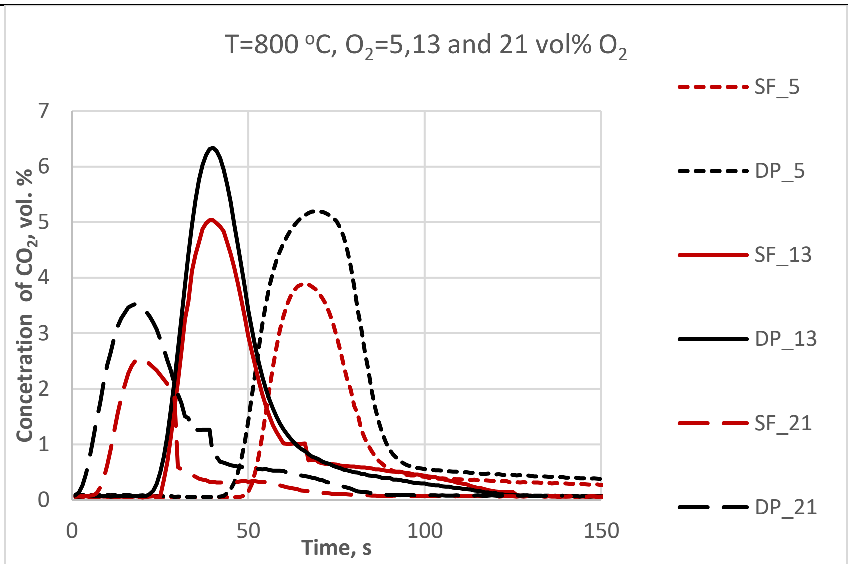


Figure 4. The effect of oxygen on the main gas phase products CO_2 obtained during biofuel combustion at 800 °C, atmospheric pressure and O_2 inflow concentration of 5, 13 and 21 vol.%.

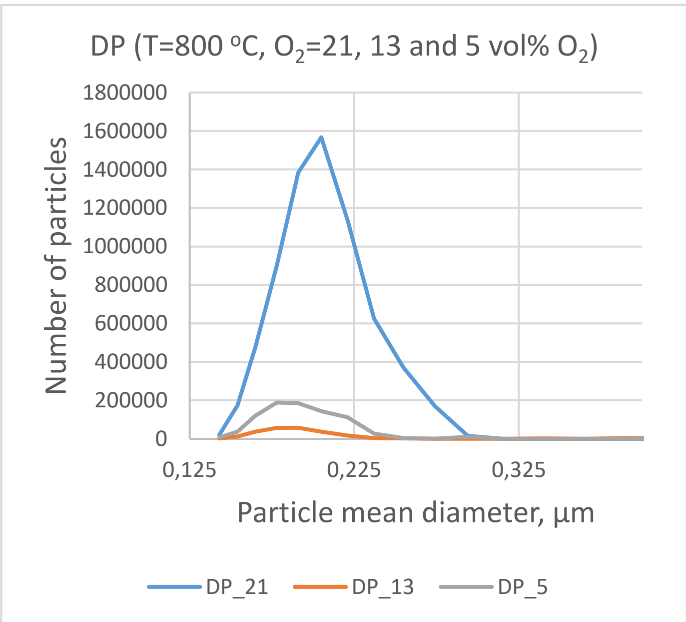


Figure 5. PM distribution obtained during the combustion of dark pellets at 800 °C, atmospheric pressure and O_2 concentration of 21, 13 and 5 vol.%.

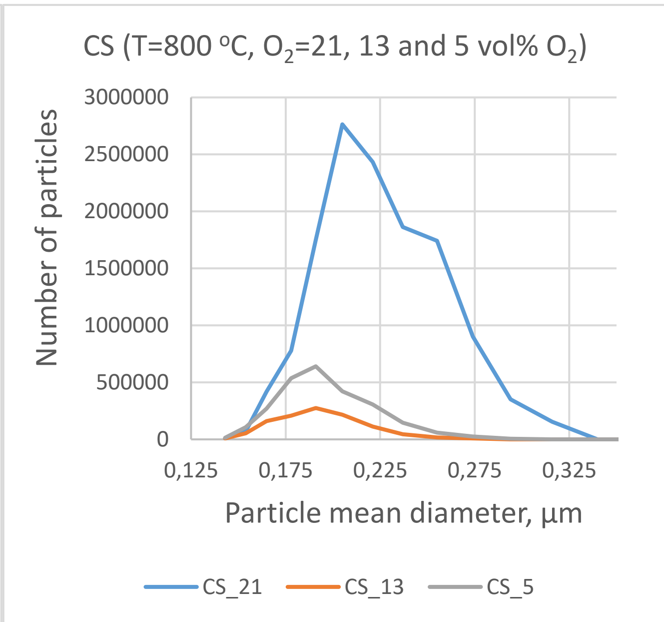
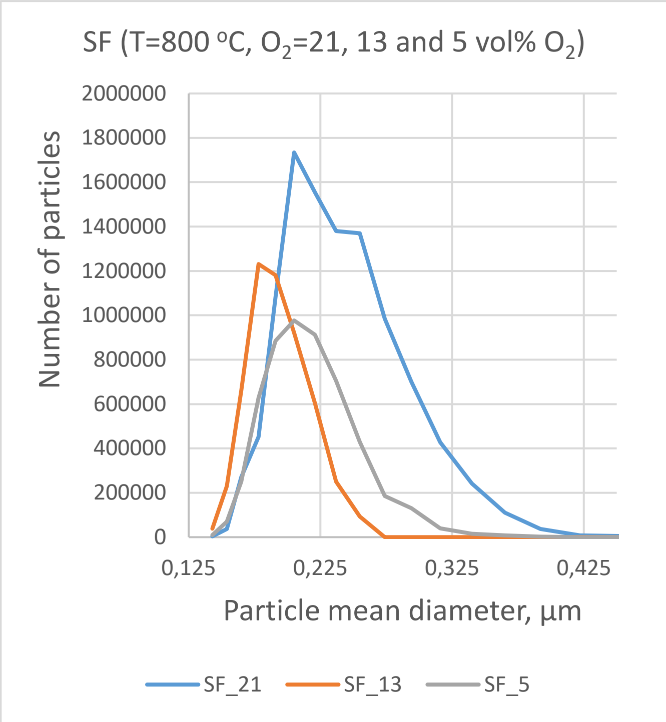


Figure 6. PM distribution obtained during the combustion of cherry stones at 800 °C, atmospheric pressure and O_2 concentration of 21, 13 and 5 vol.%.



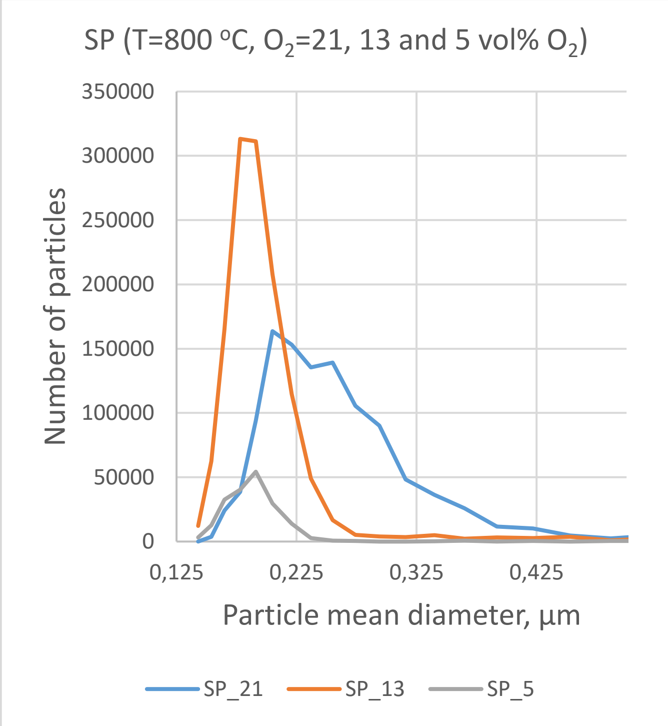


Figure 7. PM distribution obtained during the combustion of sunflower husk pellets at 800 °C, atmospheric pressure and O_2 concentration of 21, 13 and 5 vol.%.

Figure 8. PM distribution obtained during the combustion of wheat straw pellets at 800 °C, atmospheric pressure and O_2 concentration of 21, 13 and 5 vol.%.

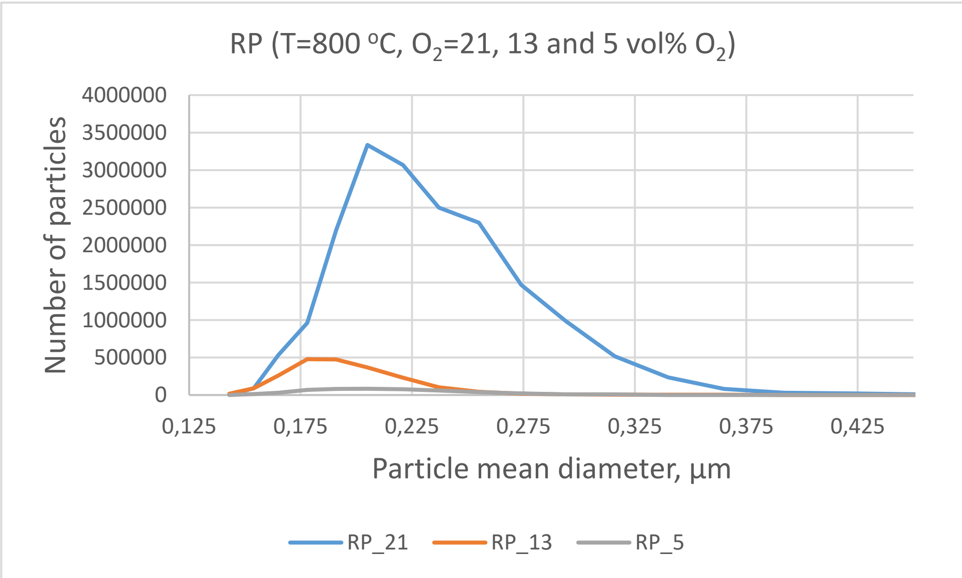
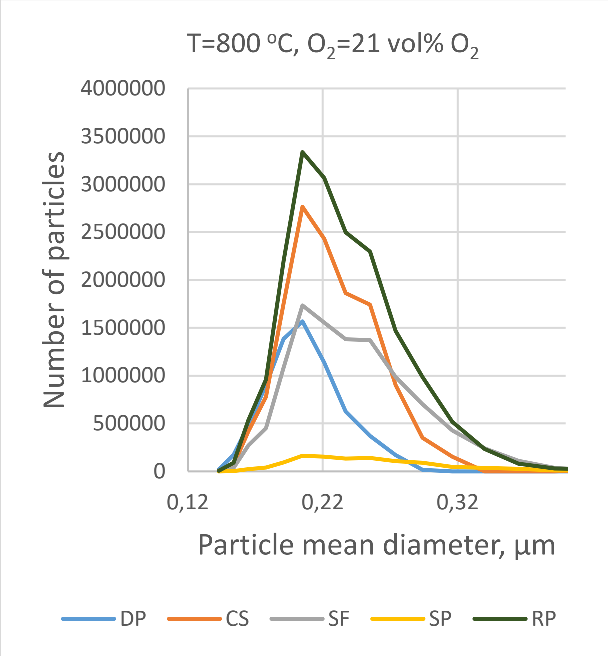


Figure 9. PM distribution obtained during the combustion of rape pellets at 800 °C, atmospheric pressure and O_2 concentration of 21, 13 and 5 vol.%.



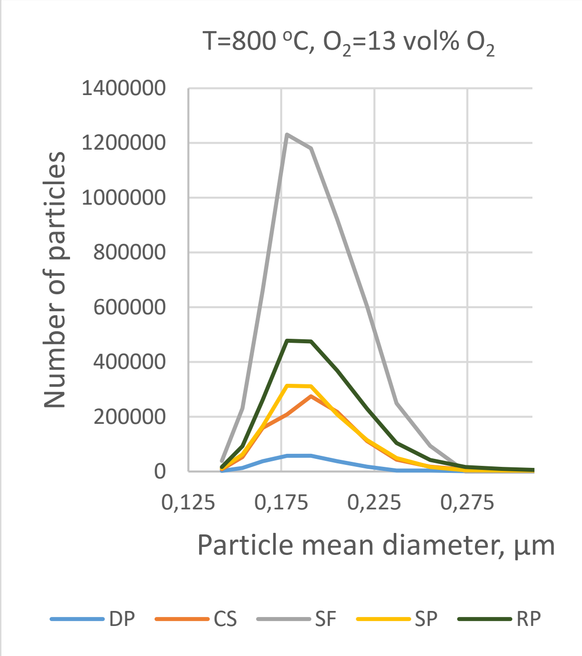


Figure 10. PM distribution obtained during the combustion of dark pellets, cherry stones, sunflower husk pellets, wheat straw pellets and rape pellets at 800 °C, atmospheric pressure and O_2 concentration of 21 vol.%.

Figure 11. PM distribution obtained during the combustion of dark pellets, cherry stones, sunflower husk pellets, wheat straw pellets and rape pellets at 800 °C, atmospheric pressure and O_2 concentration of 13 vol.%.

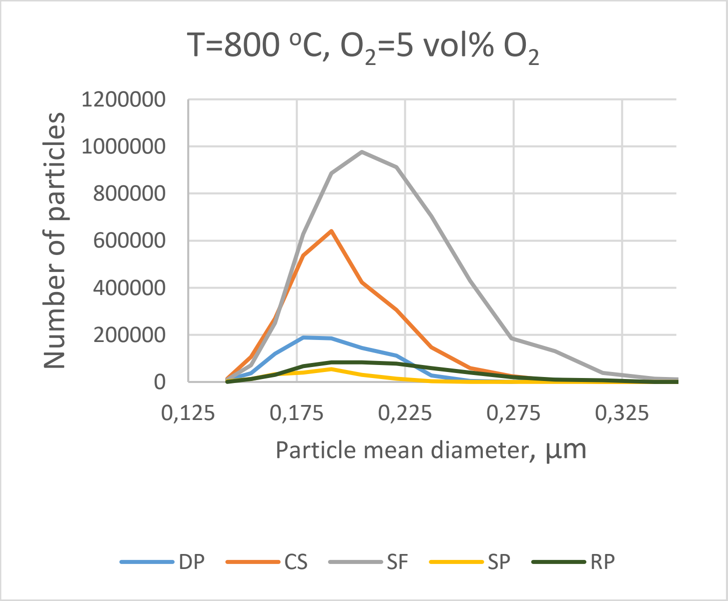


Figure 12. PM distribution obtained during the combustion of dark pellets, cherry stones, sunflower husk pellets, wheat straw pellets and rape pellets at 800 °C, atmospheric pressure and O_2 concentration of 5 vol.%.

Table 4 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.

Nomenclature:

SF ………Sunflower husk pellets

RP ………Rape (colza) pellets

LP ……..…Lucerne pellets

SP ………Wheat straw pellets

CS ………Cherry stones

CF ………..Coffee residues

AS ……....Apricot stones

PS ……….Peaches stones-

DP ……….Dark pellets

Table 4. Summarized results

biofuel	Minimum sample mass, g	Maximum sample mass, g	Temperature, ºC	Residense time, min	O2 inflow, vol. %	Minimum O2 outflow, vol. %	Average			Max			
							In the exhaust						
							CO_2 vol. %	CO ppm_v	NO ppm_v	CO_2 vol. %	CO ppm_v	NO ppm_v	PM
SF	0,1706	0,2712	700	04:00	21	18.82	2,65	4105	74,54	2,91	4315,32	76,66	1675
RP	0,2187	0,329		03:10		19,12	2,44	3750	73,44	2,64	4234,44	81,67	710173
LP	0,184	0,2227		02:05		15,71	5,4	7280	545	5,57	7901	600	
SP	0,1668	0,2957		03:15		19,46	2,08	1070	82	2,15	1230,506	91,062	
CS	0,2061	0,2663		03:30		18,4	2,43	2015,7	97,64	3,46	3047,27	118,41	454003
CF	0,195	0,2453		03:00		15,52	4,8	3804	293	5,76	5898	400	
AS	0,1462	0,2159		04:00		7,9	8,1	7000	300	10,98	10000	400	
PS	0,1775	0,2257		02:10		11,16	7,4	7082	146	10:38	10000	265	
SF	0,1994	0,259	750	03:00		18,78	2,35	4715	69	2,68	5536	81,7	
RP	0,1903	0,2683		02:20		18,45	2,6	4500	74	3,18	5000	90,4	1955725
LP	0,1816	0,2185		02:30		17,7	3,34	1598	178	3,85	1754	208,8	
SP	0,2199	0,2973		03:10		18,7	2,75	975	92	3,05	1532	143	
CS	0,2096	0,3188		02:00		18	3,25	2840	129	3,9	3549	140	7361051
CF	0,1942	0,2214		02:30		15,7	4,3	915	210	5,5	1439	246	
AS	0,1518	0,2138		02:30		13,8	5,9	2412	147	7,6	2799	179	
PS	0,1836	0,2204		02:20		16,4	4,6	2140	83	5,41	3057	128	
DP	0,1873	0,2956		03:00		18	2,85	2200	28	3,37	2414	34	
SF	0,0932	0,3049	800	02:05		18,86	2,6	3910	73	2,9	4533	80	4027266
RP	0,2126	0,2822		02:00		18,7	2,8	2000	80	3,23	3240	88,5	3241240
LP	0,1846	0,2958		02:10		16,93	3,65	947	123	4,45	1047	133	
SP	0,2128	0,2561		02:15		18,75	2,6	130	90	3,1	171	102	
CS	0,2415	0,2742		02:00		17,9	3,3	3185	122	4,15	3252	138	16076361
CF	0,2028	0,2353		02:00		14,6	5,6	761	234	6,5	1193	245	
AS	0,1566	0,2056		02:10		14,23	6,1	1125	152	6,98	1555	241,2	
PS	0,1726	0,204		02:20		17,3	4	962	59	4,6	1259	63,6	
SF	0,186	0,29	850	02:00		17,8	3,7	425	100	3,94	1000	112,8	1600553
RP	0,2147	0,2512		02:20		18,24	2,96	396	103	3,86	1867	126	
LP	0,2165	0,2215		01:50		15,18	5,47	3965	491	5,88	4873	524,8	
SP	0,2286	0,2935		02:30		18,1	3,5	900	96	3,9	2159	135,9	
CS	0,2345	0,2706		02:10		17	4	2632	151	4,65	3234	178	2956770
CF	0,1843	0,2155		02:15		14,88	5,8	812	365	6,42	1143	400	
AS	0,1693	0,2165		02:40		11,43	7,7	4155	223	9,67	7051	339,7	
PS	0,1854	0,2268		03:10		9,84	8,1	5150	266	9,78	6000	600	
DP	0,2617	0,2806		02:00		17,78	3,5	1000	42	3,84	1296	48,64	
SF	0,2423	0,2904	900	03:00		17,58	3,75	140	115	4,37	536	155	1804141
RP	0,2123	0,2886		02:30		17,84	3,46	55	101	4,1	87	147	
LP	0,1821	0,2078		03:00		16,9	4,56	1500	282	4,62	1589	305	
SP	0,2398	0,2716		02:15		18,37	2,82	17	81	3,55	28	123	
CS	0,238	0,2602		04:00		17,34	4,3	2450	206	4,5	2948	247	610011

CF	0,1962	0,2215		03:00		13,8	4,1	615	181	7,1	770	274	
AS	0,1856	0,2526		02:00		13,47	7,5	312	141	8,6	352	169,5	
PS	0,2	0,3112		02:20		14,2	6,2	1180	105	8,1	2433	135	
DP	0,2405	0,2937		03:30		17,3	4,15	300	64	4,68	442	75	
SF	0,2117	0,2946	700	03:30	13	10,87	2,41	2420	72	2,58	2635	80,4	428486
RP	0,2403	0,299		03:30		11,25	2,1	2200	62,5	2,2	2324	64,2	125957
SP	0,226	0,2932		04:00		11,3	1,99	892	67,8	2,1	944	77,3	
DP	0,268	0,2799		03:30		10,67	2,62	912	26,15	2,66	1062	26,85	
CS	0,1932	0,2643		03:10		10,08	2,93	1030	90	3,54	1205,8	120,3	2133759
SF	0,2083	0,2584	750	03:10		10,7	2,6	3000	74	2,83	3390	82	860437
RP	0,1905	0,2537		03:30		10,75	2,37	3106	66	2,85	3430	76	595675
SP	0,2199	0,2973		03:40		11,26	2,15	855	82	2,4	1093	107	
DP	0,1979	0,2228		02:50		11	2,4	900	23	2,5	1000	25	
CS	0,1601	0,2768		03:30		10,51	3,12	1259	102	3,38	1577	132	6426681
SF	0,2011	0,2306	800	02:20		8,17	4,95	4690	206	5,52	5259	230	12872771
RP	0,1954	0,2488		02:30		7,9	4,9	4990	214	5,92	5210	240	431231,1
SP	0,1931	0,243		02:40		8,57	4,6	2016	293	5,09	4209	393	
CS	0,2208	0,2403		03:00		7,52	5,6	2800	490	5,83	3097	500	541412
DP	0,187	0,2388		02:20		7,39	5,58	1570	60	6,31	1750	66	
SF	0,1846	0,2298	850	03:05		7,9	5,64	4800	225	6,22	5072	276	1473788
RP	0,2044	0,2271		03:55		3,94	8,7	3025	233	10	4914	284	
SP	0,2018	0,2182		03:30		2,32	10,6	3100	276	11,47	10000	403	
CS	0,214	0,2345		02:10		5,57	6,5	4090	425	8,08	10000	495	8158709
SF	0,2	0,2262	900	04:00		8,34	5	3752	181	5,25	4303	200	189168
RP	0,2115	0,2268		02:50		8,2	5,42	3765	183	5,68	4044	221,26	
SP	0,2148	0,2268		03:20		8,5	4,7	1600	275	5,19	3505	415	
DP	0,2167	0,2516		02:30		1,8	7,1	4100	75,5	11,5	10000	100	
CS	0,2019	0,2099		04:00		7,73	5,21	2515	310	5,79	3090	370,25	336098
SF	0,2136	0,2499	700	09:00	5	3,17	1,3	8050	41	2,13	9050	62,32	2258
RP	0,2079	0,257		10:00		4,5	0,59	6500	20	0,59	6702	20	186619
SP	0,2209	0,2901		10:00		4,37	0,65	5765	33	0,69	6521	34	
DP	0,1962	0,2896		05:30		3,27	1,16	9950	13	1,92	10000	16,23	
CS	0,1685	0,2454		05:00		2,8	1,7	10000^	78	1,9	10000^	87	3534
SF	0,2517	0,2929	750	08:00		3,35	1,6	2000	53	1,72	2240	57	385804
RP	0,2119	0,2746		06:30		3,53	1,53	1105	49	1,6	1268	52	2127338
SP	0,2354	0,2943		12:00		3,65	1,39	700	56,5	1,6	835	73,5	
DP	0,2424	0,2452		07:00		3,4	1,64	1550	16,6	1,67	1664	16,8	
CS	0,2376	0,2554		06:00		2,86	2,2	3595	104	2,4	4437	112	15252572
SF	0,1862	0,2248	800	07:00		2,29	2,93	3650	141	3,23	3920	147	234771,8
SP	0,2183	0,2282		08:00		1,6	3,42	2700	170	3,67	4231	186	
DP	0,179	0,2243		06:30		0,28	4,64	10000^	33	4,69	10000^	37	
CS	0,1584	0,2121		03:30		1,81	3,06	10000^	394	3,4	10000^	492	10345573
SF	0,2035	0,2243	850	07:00		2,31	2,95	3633	143	3,23	3919	146	2496267
RP	0,1985	0,2231		05:00		1,35	3,65	3400	150	3,96	4443	170	
SP	0,2183	0,2282		08:00		1,71	3,67	630	217	3,69	695	267	

CS	0,1868	0,2243		05:00		2,43	3,2	4185	159	3,5	4287	164	1509078
SF	0,2056	0,2294	900	04:00		1,1	4	7000	195	4,19	7534	220	100382
RP	0,2196	0,2253		05:00		0,86	3,98	4850	170	4,24	7425	200	
SP	0,2226	0,2654		06:50		1,34	3,9	5225	153	4	7191	166	
CS	0,2124	0,2225		03:30		1	3,65	10000^	382	3,76	10000^	463	1230650

FUTURE COLLABORATIONS

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The two STSMs provided the opportunity to initiate the basis of long term collaboration between both groups: the College of Energy and Electronics at the Technical University of Sofia (TU-Sofia) and the Institute of Chemical, Environmental and Bioscience Engineering, Vienna University of Technology (TU-Wien).
A project proposal is planned to be prepared involving this international and interdisciplinary work team. The focus is on the identification of key kinetic parameters, characterizing the formation of PM in biomass combustion involving chemical kinetic modeling.
This study is in line with the objectives of WG2 - Chemicals for the control of by-products in the transformation of Smart Energy Carrier and others.

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References

[1] Ognyan Sandov, Experimental investigation of key parameters, characterizing the combustion of solid biofuels, Scientific Report for STSM 40468 COST Action CM 1404, (2018), 31.03.2018-29.04.2018COST Action CM 1404, (2018),

[2] Winter, Franz & Wartha, Christian & Hofbauer, Hermann. (1999). NO and N_2O Formation during the Combustion of Wood, Straw, Malt Waste and Peat, Bioresource Technology, 70, 1999, 39-49

[3] Wartha CC, Winter FF, Hofbauer HH. The Trade-Off Between N_2, NO, and N_2O Under Fluidized Bed Combustor Conditions. ASME. J. Energy Resour. Technol, 122(2), 2000, 94-100, doi:10.1115/1.483169

[4] Wartha CC, Winter FF, Hofbauer HH. The Trade-Off Between N_2, NO, and N_2O Under Fluidized Bed Combustor Conditions. ASME. J. Energy Resour. Technol. 2000;122(2):94-100. doi:10.1115/1.483169

[5] Löffler G, Andahazy D, Wartha C, Winter F, Hofbauer H. NOx and N_2O Formation Mechanisms - A Detailed Chemical Kinetic Modeling Study on a Single Fuel Particle in a Laboratory-Scale Fluidized Bed, ASME. J. Energy Resour. Technol, 123 (3), 2001, 228-235, doi:10.1115/1.1383973