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MICHAL BRANC*, JIŘÍ HORÁK*, TADEÁŠ OCHODEK*

FINE PARTICLE EMISSIONS FROM COMBUSTION OF WOOD AND LIGNITE IN SMALL FURNACES

Assessment of household combustion emission was carried out based on data on meteorological conditions in heating season (outdoor temperature) and the emission factors. Available emission factors, both for various fuels and for various combustion devices differ markedly. The results of experimental determination of particle matter emissions, including dividing total suspended particulate matter into various fractions (PM_{10} and $PM_{2.5}$) have been presented in the paper. Various combustion devices to burn wood and lignite were used in experiments. Samples were taken in a dilution tunnel with the help of an impactor. It was found that specific emissions differ significantly during the combustion cycle. Compared to the used emission factors, differences are evident. It was found that TSP specific emissions depend mainly on the type of construction not its age.

1. INTRODUCTION

Ambient particle matter belongs to significant pollutants threatening human health due to its size spectrum and chemical composition. The size of particles determines the respiratory tract deposition; particles exceeding 10 μm in size are captured in the upper respiratory tract (nose, nasopharynx, mouth). Smaller particles (PM_{10}) are called a thoracic fraction; they are farther separated in the lower respiratory tract (larynx, bronchia etc.) and a wider spectrum of particles penetrates into human lungs (predominantly particles smaller than 2.5 μm ($PM_{2.5}$) [1]). Chemical composition determines toxic influence of particles deposited on organism.

Assessment of household combustion emission in the Czech Republic is carried out based on meteorological conditions in heating season (subsequent determination of fuel consumption) and the emission factors. For lignite combustion, the emission factor is defined by the relation $1\times A^r$ in kg/t, where A^r is ash content in fuel (in %). Apportionment of PM_{10} and $PM_{2.5}$ in the total particle matter amount has been determined

*VŠB – Technical University of Ostrava, Energy Research Center, Innovation for Efficiency and Environment, 17. Listopadu 15/2172, 708 33 Ostrava-Poruba, Coresponding author J. Horák, e-mail: jirka.horak@vsb.cz

so far based on results of measurement performed in Poland [2] (PM_{10} proportion in total suspended particulate matter (TSP) is 75%, $PM_{2.5}$ – 25%). For wood combustion, the emission factor is expressed independently as ash content and it is 5.2 kg/t. Proportion of PM10 fraction is determined to 95% and PM2.5 proportion to 90% of TSP. The emission factor is applied regardless to age and composition of heating devices which results in a considerable inaccuracy when assessing emissions in this category of furnaces.

Table 1

Overview of emission factors

Emission factor source		Device category	Coal			Wood		
			Emission factor [g/GJ]					
			TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
GAINS[a]		boilers, output <50kW	350	315	280	250	240	233
		boilers, output <50kW, new	210	189	268	210	189	268
		stoves	600	540	480	750	672	651
		stoves adapted	420	378	336	259	249	241
		stoves new	300	270	240	140	134	130
		fireplaces	–	–	–	750	720	698
EIG	simplified calculation	household heating devices output <50 kW	444	404	398	730	695	695
	detailed calculation	fireplaces, open	350	330	330	900	860	60
		stoves	500	450	450	850	810	810
		stoves, modern	250	240	220	250	240	240
		boilers, output <50kW	400	380	360	500	475	475
		boilers, output <50kW, automatic	80	76	72	70	66	66
		pellet stoves	–	–	–	80	76	76
CEPMEIP		household heating devices	350	140	70	–	–	–
		household heating devices, low emission	–	–	–	150	143	135
		household heating devices, high emission	–	–	–	300	285	270
EF used in CR[b]		Household heating devices, output <50 kW	387	290	97	356	338	320

[a]http://gains.iiasa.ac.at/gains/EUR/index.login?logout=1

[b]For fuel with considered parameters: wood – lower heating value 14.6 MJ/kg, lignite –lower heating value 18.1 MJ/kg, lignite – ash content 7%.

Other three sets of emission factors (thereinafter EF) are applied in EU for determination of household solid fuel combustion emissions. These are EFs used in the GAINS emission model (developed by IIASA international research organization, used for projection of greenhouse gas and basic pollutant emissions in Europe) as well as EFs published by the European Environment Agency in the Emission Inventory Guidebook (EIG) [3] and an EF set prepared within the framework of the project *The Co-ordinated European Programme on Particle Matter Emission Inventories, Projections and Guidance* (CEPMEIP) [4]. All of the mentioned EFs were determined by reputable agencies and it is not possible to say which of them are more representative.

The Czech EF is converted for average values of lignite and wood used for household heating and it is shown in Table 1 together with the above mentioned EFs.

2. EXPERIMENTAL

Used combustion devices and fuel. TSP experimental determination was performed on 6 combustion devices representing fundamental concepts such devices used in Czech Republic for heating requirements. These are automatic boilers, over-fire boilers, under-fire boilers, gasification boilers and fireplace stoves (Fig. 1).

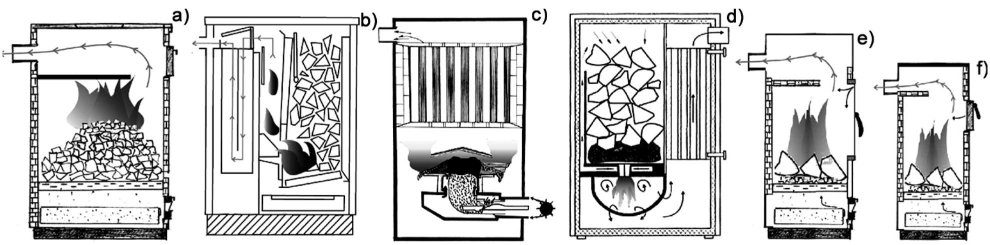

Fig. 1. Schemes of the over-fire (a), under-fire (b), automatic (c) and gasification (d) boilers, the fireplace stove (e) and classic stove (f)

An over-fire boiler is a hand fired device. Fuel batch is fire-penetrated all at once, whereas flue gas goes through the whole fuel bed. Flue way is formed by a single pass. An under-fire boiler represents a hand fired device. Fuel burning from the bottom is replenished with fuel which gradually slides down into the hearth from a reservoir. Flue gas does not pass through the stoked fuel bed. Flue way is formed by three passes. A gasification boiler represents a hand fired device of a modern design with two-phase combustion. In the first phase, fuel is gasified and in the second one, gas burns in a separate combustion chamber. Flue way is formed by "one-and-half pass". An automatic boiler represents a modern design device. Fuel is stoked automatically into a burner with the help of a screw conveyer and it burns subsequently in the under-fire way. Flue way is formed by a single pass only, though, the boiler is fitted with a deflector to capture particles. The conception of the used fireplace and classic stoves makes use of the over-fire combustion system therefore the conception corresponds to the over-fire boiler. During the tests, lignite and wood of parameters presented in Table 2 were used. In the table, w_t^r is the total water in raw fuel, percentages of ash (A), carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (*S*) refer to dry ash (superscript *d*) or raw fuel (superscript *r*), V^{daf} is the proportion of volatile combustible, Q_i^r – gross calorific power of raw fuel.

Table 2

Fuel parameters

Sample	w_t^r [%]	A^r [%]	A^d [%]	C^r [%]	H^r [%]	N^r [%]	O^r [%]	S^r [%]	V^{daf} [%]	Q_i^r [MJ/kg]
Lignite nut 1	27.5	4.18	5.77	46.9	3.83	0.650	16.4	0.620	51.1	19.1
Wood (beech)	9.58	0.83	0.92	41.1	5.11	0.09	43.08	0.22	85.58	15.68

Sampling principle. Before the measurement, the combustion devices were placed on a weigh bridge and fitted with instrumentation for determination of basic operation parameters and flue gas composition behind the boiler and in the dilution tunnel (DT). The schematic diagram of the combustion devices, connection to the DT and location of sampling points is shown in Fig. 2.

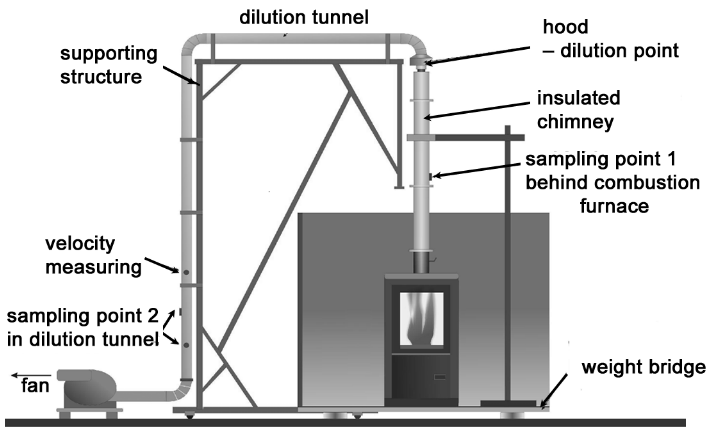

Fig. 2. Scheme of the dilution tunnel

Flue gas composition was measured in two sampling points (1 and 2). With the help of concentration of one component (O_2) in the sampling points, TSP concentrations determined in the DT can be converted to the condition before dilution or to the O_2 reference value. PM determination was performed by the gravimetric method. The principle of the measuring method is based on "isokinetic" aspiration of a gas sample from the DT (sampling point No. 2) and a capture of particular fractions. The impactor made by TCR TECORA (Fig. 3) serves for sampling of particle matter and their dividing to PM_{10} and $PM_{2.5}$ fractions. It is a probe with a retainer in which fractions are separated by centrifugal forces with the help of a jet system and subsequently they are captured on filters. The titan impactor including 2 dividing levels (for 10 μm and 2.5 μm) was made according to ISO 23210-2009 and it complies with EN13284-1.

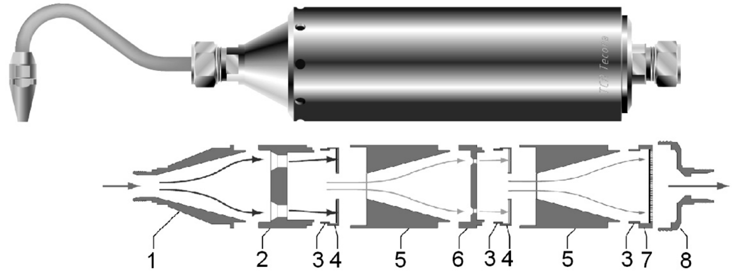

Fig. 3. Scheme of the impactor: 1 – connection cone to sampling nozzle, 2 – I PM10 cut stage, 3 – filter locking ring, 4 – I or II stage filter cassette, 5 – expansion cone, 6 – II PM2.5 cut stage, 7 – backup filter cassette, 8 – filter holder and connection cone to sample probe

The fractions over 10 μm and 10–2.5 μm fractions get stuck on the filter with the help of centrifugal forces, the fractions below 2.5 μm get captured on the filter by sieving of the sample. For capture, filters made of microfiber glass, 47 mm in diameter, MGG type, manufactured by Munktell, were used.

Sampling was carried out in the DT of 150 mm in diameter in which, thanks to dilution, concentration of solids was lower, and constant flue gas velocity *c* equalled 5–6 m/s. Flue gas sample was taken with the help of a sampling track which enabled maintenance of a required flow rate and, at the same time, it provided data on sampled amount of dry flue gas under normal conditions. The main parts of the apparatus were the Bronkhorst IN-FLOW Select flowmeter and the BUSCH SV 1025C frequency controlled pump. During the experiments, temperature in the DT was ca. 60 °C. The impactor was heated to this temperature as well, with the help of electrical heating strips with regulation. The sampled amount of flue gas was always calculated for the given temperature with the help of a software delivered by TCR TECORA; the sampled amount of flue gas had to be adhered to so that sorting of particle matter was ensured for characteristic 10 and 2.5 μm diameters. Sampling velocity corresponded to the flow rate value about 2.14 m_N^3/h. Isokinetics of sampling was provided by the choice of a nozzle with a proper diameter (12 or 14 mm).

Sampling was performed after stoking and then during a stable combustion process (the developed burning). Duration of samplings was given by the filter capacity and TSP concentration in flue gas. In most of the cases, the filter got blocked after ca. 10 min, however, at the gasification boiler, the sampling took 58 min. At stable modes, the TSP concentration was generally lower, therefore sampling periods were longer, they lasted about 30 min. In terms of burning, one sort of fuel in one combustion device, two samplings were always performed; for the automatic boiler, only one longtime sampling was performed.

After sampling, the filters (Fig. 4) were carefully removed and separated components of the impactor were rinsed with acetone into weighing bottles which were weighed beforehand. After evaporation of acetone in free air, the weighing bottles as well as filters were dried in a drier at 105 °C and subsequently cooled down in a desiccator. After cooling, the weighing bottles as well as filters were weighed on laboratory balances with 0.1 mg scale. Corresponding fractions on the filter and in the weighing bottles were summarized.

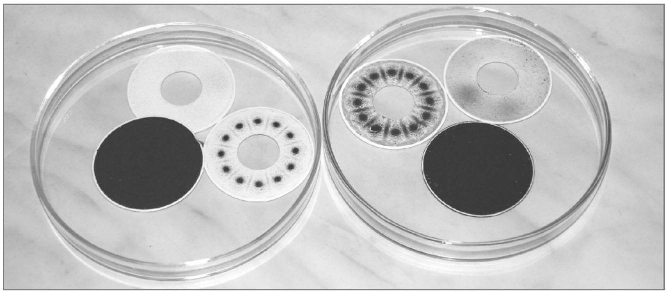

Fig. 4. Particular dust fractions on filters

Based on flue gas velocity, it was possible to determine its flow rate in the DT and mass flow of TSP and particular fractions. Based on the known fuel consumption and calorific power, specific emissions of TSP and particular fractions in mg/kg or in g/GJ were determined subsequently.

For all the devices, sampling was performed during a stable mode which was not operator intervened (door opening, fire poking, stoking-up, ash grate moving, etc). The devices were operated on nominal heat output and under the manufacturer recommended conditions. For the hand fired devices, sampling after servicing (stoking up and ash grate moving) which is necessary at a real operation, was performed as well.

3. RESULTS OF EXPERIMENTS

In Figure 5, the results of determination of particle matter emission factors related to fuel weight are presented. Within stable modes without servicing by an operator, the highest values of specific emissions were reached when burning lignite in the stove and the over fire boiler (135 and 117 g/GJ). On the contrary, the lowest value of 10.5 g/GJ was obtained when burning lignite in the under-fire boiler. For this boiler, the influence of the combustion method and of three passes of the flue way, in which there are convenient conditions for capture of emitted particles from the under-fired lignite bed, became evident. For wood, the highest specific emissions were determined when burning in the under-fire boiler (112 g/GJ). This fact bears evidence of different characteristics of particles emitted when burning wood and lignite and also of different properties of under-fired wood and lignite beds. Other emission factors during wood burning in the stable modes were very similar and they ranged from 39.4 to 42.6 g/GJ.

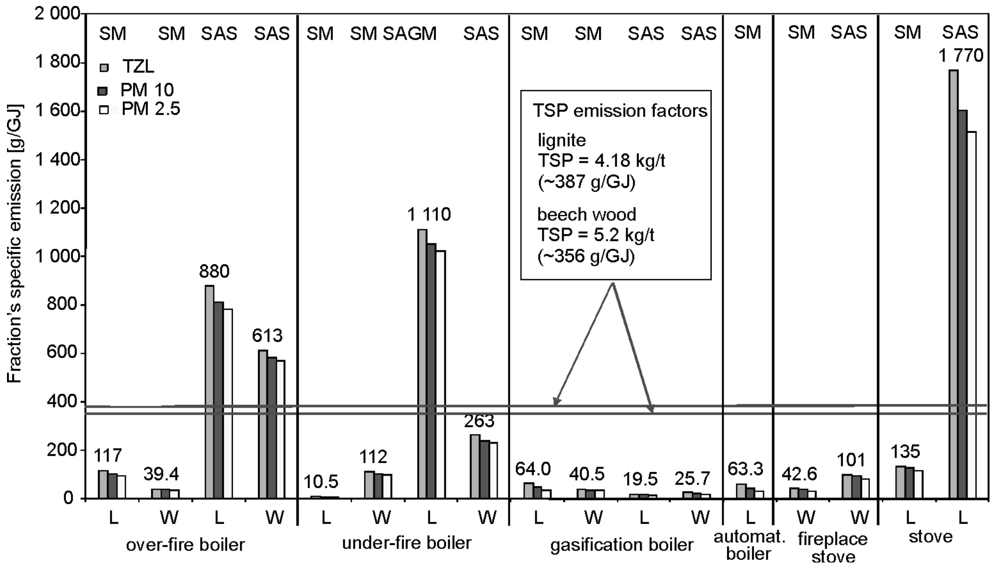

Fig. 5. Emission factors of particle matter fractions when burning lignite and wood: L – lignite, W – wood, SM – stable mode, SAS – sampling after stocking, SAGM – sampling after grate moving

The specific emissions of sampling performed after having intervened to the burning process feature markedly different values. The highest increase of specific emissions occurred in the under-fire boiler where lignite specific emission increased to 1110 g/GJ, which represents ca. 100-fold increase. The highest absolute value was reached for the stove where the specific emission of 1770 g/GJ was determined. The increase for the stove was similar to the increase for the over-fire boiler, 7.5–15.5-fold increase occurred. The specific emission increase for the over-fire boiler and the stove is given by production of a large amount of tar matter after fuel stoking. For the rest of the tests, the increases were significantly lower; for the gasification boiler, even decrease of the specific emission occurred.

The above described unstable conditions after servicing feature different durations, from several minutes to tens of minutes. With regard to mostly significantly different values of specific emission values under unstable conditions and with regard to their duration, it is obvious that they influence the resulting values of specific emissions. In light of influence on health of living organisms, attention is paid to small (respirable) proportions. Size of particles emitted by individual combustion devices when burning particular fuels is shown in Fig. 6. Evident significant differences exist of proportions of particular fractions.

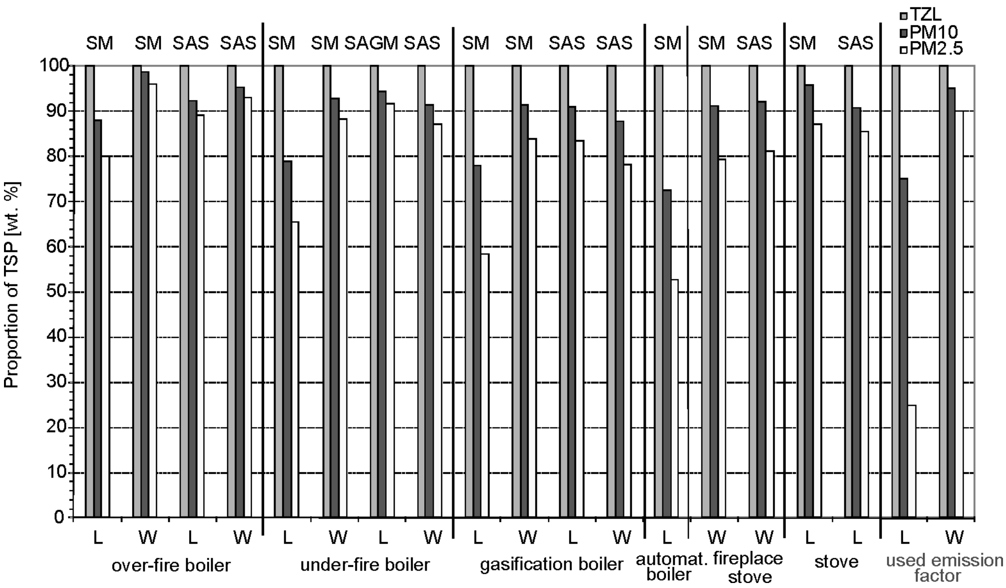

Fig. 6. Proportions of TSP fractions when burning lignite and wood:
L – lignite, W– wood, SM – stable mode, SAS – sampling after stocking, SAGM – sampling

When comparing stable modes, significantly higher production of PM_{10} and $PM_{2.5}$ fine fractions can be seen when burning wood. The fine particle proportion is influenced by the combustion device used. The highest proportions of fine fractions were determined for the over-fire boiler and the stove. For the over-fire boiler, PM_{10} proportion ranged about 88% for lignite and over 98% for wood. As to other boilers, there were markedly lower proportions of fine fractions, namely when burning lignite. The lowest proportions were determined for the automatic boiler: PM_{10} 73% and $PM_{2,5}$ 53%.

By operator intervention into the combustion process, an important change in the emitted particle size spectrum occurred. When burning lignite, a substantial increase of fine fractions occurred mostly because of operator intervention; PM_{10} proportions exceeded 90% and $PM_{2.5}$ proportions ranged from 84 to 92%. A reverse trend was noted for the stove. The reverse trend was found out for wood combustion, when lower proportions of fine fractions were mostly determined after operator's intervention. For all the boilers, a decrease of both fine fraction proportions of the order of 2–5% occurred in contrast to stable modes. For the fireplace stove, a mild increase of the fine fraction proportion occurred.

4. COMPARISON OF THE SPECIFIC EMISSION VALUES TO THE EFS USED

For the over-fire boiler and the stove, it can be expected that the TSP production decrease after stoking will not be rapid and thus the representative emission factor will be near an average value. For the boiler, the average values are 499 g/GJ for lignite, 326 g/GJ for wood, For the fireplace stove – 71.8 g/GJ and for the classic stove – 953 g/GJ. For the under-fire boiler, a rapid decrease to the values obtained in the stable mode can be expected; moreover, the under-fire boiler features a longer stoking-up period and a longer flue way than the over-fire boiler. For the above-mentioned reasons, the representative emission factors will range near the value which was found-out for the stable mode.

When comparing to the emission factors used in the Czech Republic for yearly balances of particle matter production, there is a noticeable difference (see Fig. 5). The used factors are higher than the specific emissions obtained for the under-fire and gasification boiler. On the contrary, the specific emissions determined for the over-fire boiler correspond to EFs. For the classic stove, the specific emissions exceed the used EF more than twice. Other emission factors used in EU are also higher in comparison to the experimentally obtained values, when compared to the emissions from more up-to-date boilers and fireplace stoves. On the contrary, for the over-fire boiler and the classic stove, they are lower than the specific emissions determined by the experiment. When comparing, there is a problem of different dividing of combustion devices to new, adapted and old.

A significant difference between the used proportions for fine fractions and the actually obtained proportions can be seen at the size spectrum. The determined proportions of fine particles which originate during lignite burning are higher than for the used EFs. By contrast, proportions of fine particles which originate during wood burning are lower than for the used EFs. For wood, the differences can be caused by fuel humidity. It is presumable that the specific emissions would be higher with higher fuel humidity.

5. CONCLUSION

The measurements proved that individual small furnaces, though they burn the same fuel, feature big differences in TSP specific emissions. Aside from the over-fire boiler and classic stove, lower specific emissions than the used EFs were determined for all the boilers. As to fine fractions, we can state that the determined proportions of fine particles which originate during lignite burning are higher than for the used EFs, contrariwise proportions of fine particles which originate during wood burning are lower than for the used EFs.

When comparing proportions of fine fractions, it is evident that larger proportions of fine fractions are emitted during wood burning.

The presented results show that composition of combustion devices affects significantly the real emission balance however, it is not included into emission calculation in the Czech Republic because of lack of information.

The main parameter affecting particle matter emissions is a type (design) of a combustion device. Dividing to new, adapted and old combustion devices is not an adequate parameter for EF specification. Over-fire boilers represent an old design and they produce considerably high particle matter emissions. In the Czech Republic, this type of a boiler is one of the best sold devices. Compared to that, older under-fire, gasification or automatic boilers can produce relatively low specific emissions which, in addition, are not influenced by servicing very much.

Fuel sort and combustion process setup has a big influence as well. The authors find EF specification for combination of fuel and a combustion device type more suitable for calculation of emission balances of small furnaces.

The presented specific emissions from individual combustion devices will be precised by repeated sampling. Experiments with other fuels will be performed.

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