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INFLUENCE OF SMALL FURNACES CONSTRUCTION TYPE ON TSP EMISSIONS DURING WOOD AND BROWN COAL COMBUSTION

VLIV KONSTRUKCE SPLOVACÍCH ZAŘÍZENÍCH NA EMISE TZL PŘI SPALOVÁNÍ DŘEVA A HNĚDÉHO UHLÍ

Abstract

Solid fuel burning household heat sources are considered to be significant producers of total suspended particulates (TSP). In the year 2005, c. 35% of the total particulate matter emissions PM_{10} (in The Czech Republic) came out from household heating [1]. However, low-power combustion devices cannot be considered as identical pollution sources because they can operate on different combustion principles and feature dramatically different emission factors. The article presents results of an experimental determination of particulate matter emissions including TSP dividing into PM_{10} and $PM_{2.5}$ fractions from wood and brown coal combustion in five types of combustion devices.

Abstrakt

Zdroje tepla v domácnostech, které spalují tuhá paliva, jsou považovány za výrazné producenty tuhých znečišťujících látek (TZL, TSP). V roce 2005 cca 35 % z celkových emisí prachu PM_{10} (v ČR) pocházelo z vytápění domácností [1]. Spalovací zařízení malého výkonu však nelze chápat jako identické zdroje znečištění, jelikož mohou pracovat na odlišných principech spalování, a mít tak výrazně odlišné emisní faktory. Článek prezentuje výsledky experimentálního stanovení emisí tuhých znečišťujících látek včetně rozdělení celkových TZL na frakce PM_{10} a $PM_{2,5}$ v pěti typech spalovacích zařízení při spalování dřeva a hnědého uhlí.

1 INTRODUCTION

Ambient particulate matter belongs to significant pollutants influencing human health negatively. Seriousness of the impact of particles on human health is given by their size spectrum, which determines the respiratory tract deposition, and chemical composition, from which the extent of the toxic impact of the deposited particles in an organism is derived.

As mentioned above, the particle size determines their deposition in the respiratory tract. Particles larger than 10μm are captured in the upper respiratory tract (nose, rhinopharynx, mouth). Particles which pass through the upper respiratory tract (smaller than 10μm) are called a thoracic fraction. Coarser particles of the thoracic fraction are then captured in the lower respiratory tract (larynx, bronchia etc.) and a wider spectrum of particles penetrates into human lungs. It is generally stated that, predominantly, these are particles smaller than 2.5μm [2]. These particles with their toxic properties affect the pulmonary tissue directly. Smaller particles which are not captured by lungs (<1μm) are

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exhaled again after being inhaled, eventually they pass through alveolar membrane and penetrate into blood [3]. It results from the above mentioned that, particularly, particles smaller than 10µm entail deposition hazards and subsequent health hazards [2].

Primary particles can originate by various mechanisms. There are e.g. combustion processes when ash and unburned fuel particles are emitted, then erosive processes (weathering of soil and rocks), agricultural, building and other activities during which loose materials are handled, industrial production (ironworks etc.) and mechanical abrasion of surfaces, in particular of tires, roads and brake pads. The health hazard of these matters lies in their chemical composition. Although the matter of solid parts can be made up of inert substances, other substances could adsorb on the surfaces of these particles which might represent a serious health hazard. For example, condensed metal vapours, acids, tars, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins and furans (PCDD/F) and polychlorinated biphenyls (PCBs) belong among substances which are further bound onto particulate matter. These matters represent a serious health hazard for human organism.

Dividing according to determining practice and established regulations corresponds to health hazards. In practice, total pollutant particulate matter emissions, then emissions of particles smaller than 10µm (PM_{10}) and of particles smaller than 2.5µm ($PM_{2.5}$) are determined the most frequently. In some cases, particles smaller than 1µm are determined furthermore. Legislature [9] defines PM_{10} particles as follows: It is a fraction which, when passing through a selectively – outgoing filter, features 50 % fractional separability for 10µm aerodynamic size. Analogically, $PM_{2.5}$ fraction can be defined. This definition is adapted for behavior of real separators which do not feature ideal separation. Though, it can be proved that in case of a symmetrical separability curve, it corresponds by mass to the fraction of particles smaller than 10µm [2].

2 EMISSION INVENTORIES

Solid fuel combustion in small furnaces produces a substantial part of TSP emissions and their fractions PM_{10} and $PM_{2.5}$ in the Czech Republic. To realize effective measures for emission reduction, emission assessment describing apportionment of particular source categories needs to be set, otherwise costly measures would go astray. At present, household combustion emission assessment is carried out on the basis of meteorological conditions in heating season (follow-up determination of fuel consumption) and an emission factor. The meteorological conditions are characterized by the number of day-degrees in heating season and the emission factor is used according to the regulation [4]. For brown coal combustion, it is defined by the relation $1*A^r$ in kg/t, where A^r is ash content in fuel (in %). PM_{10} and $PM_{2.5}$ apportionment in total particulate matter amount has been determined so far on the basis of results of measurement performed in Poland [5] (PM_{10} proportion in TSP is 75 % and $PM_{2.5}$ – 25 %). For wood combustion, the emission factor is expressed independently on ash content and it is 5.2 kg/t. PM_{10} fraction proportion is determined to 95 % and then $PM_{2.5}$ to 90 % of TSP. The emission factor is applied regardless to age and species composition of heating devices which results in a considerable inaccuracy when assessing emissions in this category of furnaces. At present, authors of the review work on its particularization so that the emission assessment reflects qualitative development in composition of heating devices. This task represents two separate spheres at minimum: Both knowledge in the sphere of emission factors (e.g. this article content) and information on composition of combustion systems operated in individual households as well.

3 CURRENTLY USED EMISSION FACTORS FOR PARTICULATE MATTER EMISSIONS

For household solid fuel combustion emission determination, three sets of emission factors (thereinafter EF) are applied in EU. There are EFs used in the GAINS emission model [6] (this model has been developed by IIASA international research organization and it is used for projection of greenhouse gas and basic pollutant emissions in Europe), EFs published by the European Environment Agency in the Emission Inventory Guidebook (EIG) [7] and an EF set prepared within the framework of the project The Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance (CEPMEIP) [8]. In all of these EF sets, in contradistinction to the Czech legislature, the EF is relative to the unit of energy contained in the fuel supplied (calorific power). For comparison, the Czech EF is converted for average values of brown coal used for household heating (the average value according to REZZO 3 for 2007 year) and shown in Tab. 1 together with the above mentioned EFs. Wood emission factors for the above mentioned EF sets and the used Czech EF converted to the considered calorific power of 14.62 MJ/kg are shown in Tab. 2.

Tab. 1 Brown coal emission factors overview.

Emission factor source		Combustion device category	Emission factor [g/GJ]		
			TSP	**PM_{10}**	**$PM_{2.5}$**
GAINS		Coal-fired boilers of <50kW output	350	315	280
		Coal-fired boilers of <50kW output, new	210	189	168
		Coal-fired stoves	600	540	480
		Coal-fired stoves (adapted)	420	378	336
		Coal-fired stoves, new	300	270	240
EIG	Simplified calculation	Household heating devices – black and brown coal, <50 kW	444	404	398
	Detailed calculation	Fireplace, open	350	330	330
		Stoves	500	450	450
		Stoves, modern	250	240	220
		Coal-fired boilers of <50kW output	400	380	360
CEPMEIP		Household heating devices – brown coal	350	140	70
CZ*		Brown coal burning devices, <50 kW	387	290	97

*for average values of household heating brown coal — ash content A^r=7%, calorific power Q_i^r=18.1 MJ/kg

Tab. 2 Wood emission factors overview.

Emission factor source		Combustion device category	Emission factor [g/GJ]		
			TSP	**PM_{10}**	**$PM_{2.5}$**
GAINS		Wood fired boilers of <50kW output	250	240	233
		Wood-fired boilers of <50kW output, new	52	49	47
		Wood-fired stoves	750	672	651
		Wood-fired stoves, adapted	259	249	241
		Wood-fired stoves, new	140	134	130
		Fireplace	750	720	698
EIG	Simplified calculation	Household heating devices – wood, <50 kW	730	695	695
	Detailed calculation	Fireplace, open	900	860	860
		Stoves	850	810	810
		Wood-fired boilers of <50kW output	500	475	475
		Pellet-fired boilers of <50kW output	80	76	76
CEPMEIP		Household heating devices – wood, low-emission	150	143	135
		Household heating devices – wood, high-emission	300	285	270
CZ*		Household heating devices – wood, <50 kW	356	338	320

*for wood with considered parameters — calorific power Q_i^r=14.62MJ/kg

4 USED COMBUSTION DEVICES AND FUEL

TSP experimental determination was carried out on 5 combustion devices representing fundamental conceptions of combustion which are used in our country for heating requirements nowadays. These are automatic boilers, over-fire boilers, under-fire boilers and gasification boilers and fireplace stoves, see Fig. 1.

An over-fire boiler is a hand-fired device. A fuel batch is fire-penetrated all at once, whereas flue gas goes through the whole fuel bed. A flue way is formed by a single pass. The used boiler, as the only one, is not certified for brown coal burning (though, it is often used for this fuel by users, therefore experiments with this fuel were carried out as well). The other boilers are certified for brown coal burning, namely nut coal 1 (20-40 mm), or nut coal 2 (10-25 mm) as the case may be for the automatic boiler.

An under-fire boiler represents a hand-fired device. Fuel burning from the bottom is replenished with fuel which gradually slides down from a reservoir into the hearth. Flue gas does not pass through the stoked fuel bed. A 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 phase, gas burns in a separate combustion chamber. A 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. A flue way is formed by a single pass only, thus flue gas flows only upwards, though, the boiler is fitted with a deflector for a capture of particulates.

The used fireplace stove conception makes use of the over-fire combustion system therefore the conception corresponds to the over-fire boiler.

During the tests, brown coal and wood of parameters shown in Tab. 3 were used.

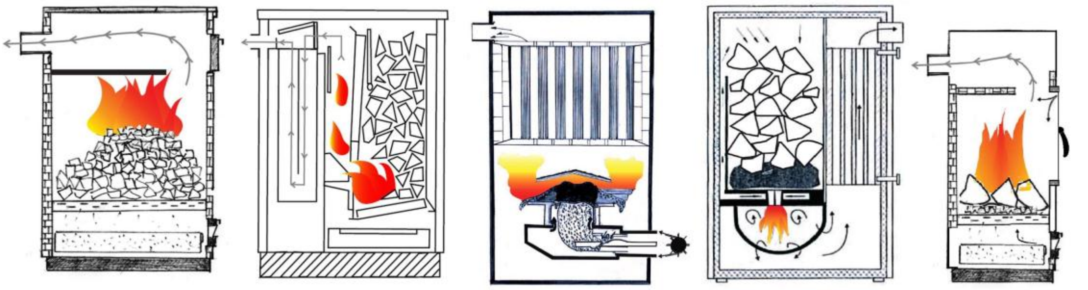

Fig. 1 Scheme of the over-fire, under-fire, automatic and gasification boiler and the fireplace stove.

Tab. 3 Used fuel parameters.

Sample description	w_t^r	A^r	A^d	C^r	H^r	N^r	O^r	S^r	V^{daf}	Q_i^r
	%	%	%	%	%	%	%	%	%	MJ/kg
Brown coal (20-40 mm)	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

Note: w_t^r total water in raw fuel, A^r ash in raw fuel, A^d ash in dry sample of fuel, C^r carbon in raw fuel, H^r hydrogen in raw fuel, N^r nitrogen in raw fuel, O^r oxygen in raw fuel, S^r sulphur in raw fuel, V^{daf} proportion of volatile combustible, Q_s^r gross calorific power of raw fuel, Q_i^r calorific power of raw fuel.

5 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. PM determination was performed by the gravimetric method. The measuring method principle is based on "isokinetic" aspiration of a gas sample from the DT (sampling point no. 2) and a capture of particular fractions. The impactor (Fig. 3) serves for particulate matter sampling and their dividing to PM_{10} and $PM_{2.5}$ according to fractions. It is a probe with a retainer in which fractions are separated by centrifugal forces with the help of a jet system and they are captured on filters subsequently. Sampling is carried out always in the DT of 150mm diameter in which, thanks to dilution, there is a lower concentration of solids and a constant flue gas velocity of c. 5 m/s. Flue gas is aspirated through a nozzle and a probe with the help of a sampling track which enables to setup a required flow rate and, at the same time, it provides data on sampled amount of dry flue gas under normal conditions.

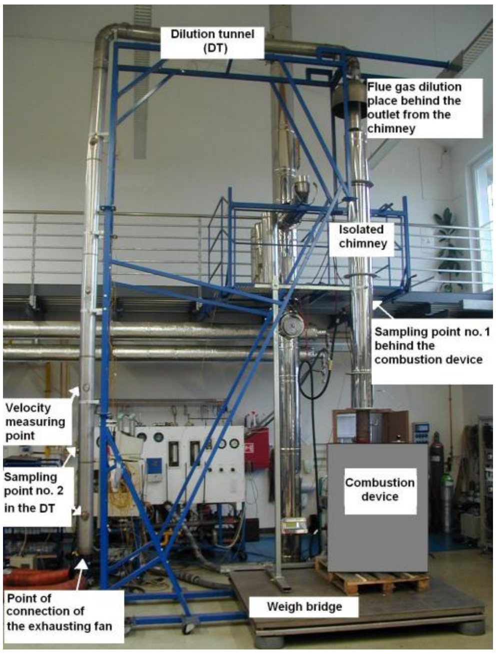

Fig. 2 Dilution tunnel scheme.

Fig. 3 Component parts of the impactor.

6 RESULTS OF EXPERIMENTS

Graph (Fig. 4) presents the results of determination of particulate matter emission factors related to fuel weight. 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 a 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.

Within stable modes without servicing, different emission factors were determined for particular devices and fuels, however, differences were not very significant. The highest values of 2.22 kg/t_{fuel} were reached when burning brown coal in the over-fire boiler. When burning wood in the over-fire boiler, a value of 0.618 kg/t_{fuel} was determined. On the contrary, the lowest value of 0.201 kg/t_{fuel} was determined when burning brown coal 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 a capture of emitted particles from the under-fired brown coal bed, has become evident. However, for wood burnt in the under-fire boiler, the emission factor was determined considerably high (1.75 kg/t_{fuel}). This fact bears evidence of different characteristics of particles emitted when burning wood and brown coal and also of different properties of under-fired wood and coal beds. For other stable-mode-operated devices and fuels, the determined emission factors were relatively well-balanced and they ranged between 1.22 to 0.81 kg/t_{fuel}.

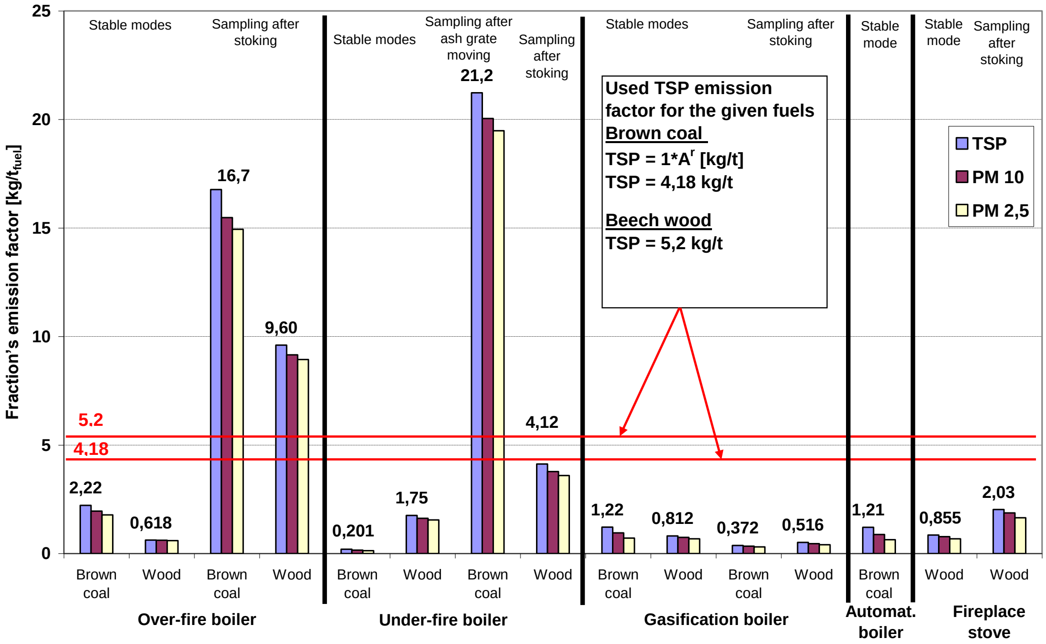

Fig. 4 Emission factors of particulate matter fractions when burning brown coal and wood.

However, the resulting emission factors from sampling performed after having intervened in the burning process feature markedly different values. The most significant effect on TSP production was noted for the under-fire boiler and the over-fire boiler, as it is shown in the graph. For the over-fire boiler, the brown coal emission factor has increased to 16.7 kg/t_{fuel}, which represents 7.5 times increase, and the wood emission factor to 9.60 kg/t_{fuel}, which represents 15.5 times increase compared to the stable mode. The emission factor increase for the over-fire boiler is given by production of a large amount of tar matter after fuel stoking. For the under-fire boiler, the brown coal emission factor has increased to 21.2 kg/t_{fuel}, which represents c. 100times increase, and the wood emission factor to 4.12 kg/t_{fuel}, which represents 2.4 times increase compared to the stable mode. The emission factor increase for the under-fire boiler after servicing is given by a release of solid particles captured in the bed. For brown coal, the bed has a good capability to capture penetrating particles, however, when intervening in the bed, a large part of them releases. On the other hand, when burning wood, the above-grate bed does not capture particles so markedly, therefore much of them do not release even after intervening in the bed. For the gasification boiler, the emission factor decrease occurred after the interference. When burning brown coal, the emission factor decreased to 0.373 kg/t_{fuel} which represented a decrease to one third of its value in the stable mode. When burning wood, a decrease to 0.516 kg/t_{fuel} occurred which represented a decrease to two thirds of its value in the stable mode. A slide of bed was observed visually after stoking which probably resulted in an increased capture of particles in the bed. Released particles from the bed were further captured in the combustion chamber and follow-up passes because the situation noted after ash grate moving in the under-fire boiler did not repeat. After beech wood stoking into the fireplace stove, the emission factor increase to 2.03 kg/t_{fuel} occurred which represented 2.4 times increase. Analogous to the over-fire boiler, this increase is given by tar matter production; thanks to a smaller batch of fuel and superior distribution of combustion air, this increase is not as significant as for the over-fire boiler.

The above described unstable conditions after servicing feature a different length of duration in the order of minutes up to tens of minutes. With regard to mostly significantly different values of emission factors on unstable conditions and with regard to the length of duration of these statuses, it is obvious that they influence resulting values of emission factors.

In light of influence on living organisms' health, attention is paid to small (respirable) proportions. Size of particulates emitted by respective combustion devices when burning particular fuels is shown in graph (Fig. 5). There is an evident meaningful spread of proportions of individual fractions.

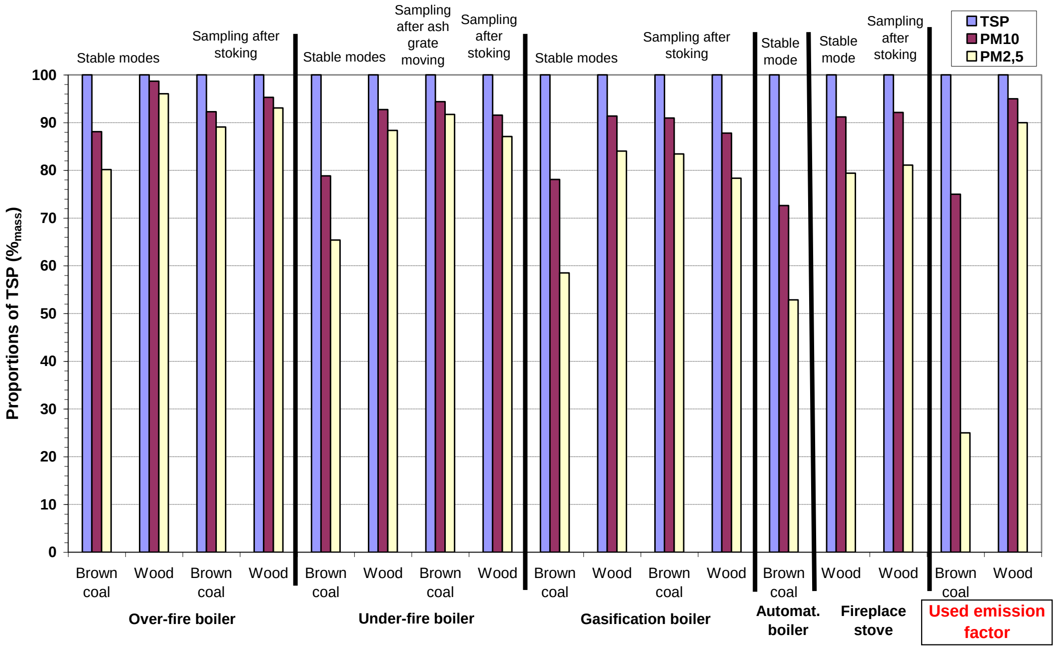

Fig. 5 Proportions of TSP fractions when burning brown coal and wood.

When comparing stable modes, the significantly higher production of PM_{10} and $PM_{2.5}$ fine fractions from wood combustion can be seen. The fine particulate proportion level is further influenced by the used combustion device. The highest proportions of fine fractions were determined for the over-fire boiler where PM_{10} proportion ranged about 88 % for brown coal and over 98 % for wood. As to $PM_{2.5}$ fraction, it was 80 % for coal and almost 96 % for wood. As to other boilers, there were markedly lower proportions of fine fractions noted, namely from brown coal combustion. A lower proportion was determined for the under-fire boiler, a further decrease was obvious for the gasification boiler and the lowest proportion of fine fractions was reached for the automatic boiler (brown coal only) - PM_{10} – 73 %, $PM_{2.5}$ – 53 %. When burning wood, a lower production of fine fractions was found out as well, although the decrease in comparison to the over-fire boiler is not as expressive as when burning brown coal. The lowest proportions of fine fractions from wood combustion were determined for fireplace stoves - PM_{10} – 91 %, $PM_{2.5}$ – 79 %.

By operator intervention into the combustion process, an important change in emitted particulate size spectrum occurred. When burning brown coal, a substantial increase of fine fractions always occurred because of operator intervention; PM_{10} proportions exceeded 90 % and $PM_{2.5}$ proportions ranged between 84 up to 92 %.

A reverse trend was found out for wood combustion, when lower proportions of fine fractions were mostly determined after operator intervention. For all the boilers, a decrease of both fine fraction proportions in the order of 2 – 5 % occurred. For the fireplace stove, a mild increase of the fine fraction proportion occurred.

7 COMPARISON OF RESULTING FACTORS TO FACTORS USED IN THE CZECH REPUBLIC NOWADAYS

The aim of the performed measurements was to determine emission factors from coal and wood combustion and proportions of PM_{10} and $PM_{2.5}$ fractions in TSP on the basis of measured specific emissions for particular phases of burning.

When comparing to the emission factors used for yearly balances of particulate matter production, there is a noticeable difference (see Fig. 4). The TSP emission factor is given as 10 % of ash proportion in brown coal, or else it is $1*A^r$ in kg/t, and for wood it is given independently on ash proportion as 5.2 kg/t (horizontal lines in the graph). The used factors are higher than the obtained emissions for the observed combustion devices and burnt fuels. On the contrary, in the case of EF values determined for unstable modes, their values are sometimes higher than the used EF. For the over-fire boiler and the stove, it can be expected that the TSP production decrease is not rapid and thus the representative emission factor is about an average value. Weighted average of emission factors, which considers duration of individual samplings, determined on the basis of values for a stable and unstable mode in the over-fire boiler is 9.59 kg/t_{fuel} for coal and 3.42 kg/t_{fuel} for wood; for the stove it is 1.38 kg/t_{fuel} then. 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 found out for the stable mode.

A significant difference between the used proportions for fine fractions and the actually observed proportions can be seen at the size spectrum. $PM_{2.5}$ particulate proportion used for calculations of a yearly balance of small furnace emissions, which is 25 % of TSP for coal at present, is much higher according to the tests, respectively 3times on the average. A similar situation can be seen for PM_{10} proportion as well. The used level of 75 % proportion of PM_{10} in TSP could be observed for the automatic boiler only. The other combustion devices feature proportions c. 15 % higher. It should be noted, that the fine particulate proportion increase is due to interventions in combustion processes, nevertheless, even the stable modes highly exceed the proportions used so far. For wood, differences between the used and determined proportions can be seen as well, though, in contrast to brown coal the differences are not very high and they range between -11 to +3 %, whereas $PM_{2.5}$ particulate proportions are lower.

8 CONCLUSIONS

The aim of this paper was to present determined specific emissions of total suspended particulates and of fine fraction proportions from brown coal and wood combustion in various design combustion devices and, furthermore, to draw the attention to a difference between the values observed and the emission factors used for small furnace emission balances.

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, lower specific emissions than the used EF were determined for all the boilers. For the over-fire boiler, the emission factor average value exceeds the used emission factor for brown coal more than two times; for wood, the determined value almost comply with the used EF.

Similar discrepancies can be found for particulate size-grading as well. In the Czech Republic today, the used proportion of PM_{10} – 75 % and $PM_{2.5}$ – 25 % has resulted from experiments performed in Polish stoves with Polish coal [5] and it is used also for boilers nowadays. The tests proved that in contrast to the used apportionment, there is a much higher proportion of fine particles in real.

On the contrary, the used proportions of PM_{10} particles – 95 % and $PM_{2.5}$ – 90 % for wood are slightly overvalued, although they are exceeded for the over-fire boiler.

It is evident from the presented results that species composition of combustion devices affects the actual emission balance significantly, however, it is not included into emission calculation because of lack of information.

The goal of the discussion mentioned above is to provide new data to begin validation and adaptation of emission factors used for TSP, PM_{10}, $PM_{2.5}$ emission balance from brown coal and wood burning in small furnaces.

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