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Particulate matter measurement by using the particle sizers APS and SMPS

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Abstract

Currently, there is an increasing trend in the use of biomass for energy purposes, due to global pressure on the use of renewable energy sources and a gradual decline in fossil fuel stocks. However, biomass combustion can be considered as a significant source of particulate concentrations in the atmosphere. Measurement of particles from biomass combustion plants is very demanding; the particle size range is large, usually ranging from a few nanometers (nm) to a few micrometers (µm). The measurement of the particles is carried out in terms of mass concentrations, numerous concentrations and their particle size distribution. The selection of metering devices for measuring particulate matter and their size distribution is important because different devices differ in their characteristics and have specific advantages and disadvantages. The large particle number concentrations in the flue gas after biomass combustion exceed the detection capacity of some plants, therefore they are used for measurement with flue gas diluents for measurement. At present, the gravimetric method, the method of particulate matter measuring using an aerodynamic particle sizer (APS) or a scanning mobility particle sizer (SMPS) is often used. The cascade impactor gravimetric method is based on comparing particles based on their aerodynamic diameter. APS is a spectrometer that measures particles between 0.5 and 20 µm in size. The working principle is based on the acceleration of aerosol sample flow through an accelerating orifice. SMPS measures the size distribution and concentration of particles in the size range of 1 nm to 1 µm using differential mobility analysis. When the device SMPS is used with the APS, the range increases to 20 µm. This paper focuses on the measurement of particulate matter by tandem connection of APS and SMPS particle sizers using dilution. Dilution is used to eliminate the mechanisms that arise when sampling particles that may affect their properties. These are nucleation, condensation, evaporation and coagulation. The results are then compared with gravimetric measurements.

Keywords: particulate matter, particle sizer, gravimetric method, APS, SMPS.

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1. Introduction

Currently, there is an increasing trend in the use of biomass for energy purposes, due to global pressure on the use of renewable energy sources and a gradual decline in fossil fuel stocks. Biomass is considered to be one way of replacing fossil fuels in the energy sector. The chemical composition and physical properties of biomass vary according to its origin. The wood energy component of biomass used for heating has the greatest energy potential. However, biomass combustion can be considered as a significant source of particulate concentrations in the atmosphere [1, 2].

At present, achieving air quality and cleanliness can be a major challenge, due to the large number of sources of emissions. Atmospheric pollution is caused by only two sources. The first source is natural phenomena such as forest fires or volcano eruption, the second and much greater source of pollution is human activity. Among all pollutants, particulate matter contributes to more serious effects on the environment and human health. Particulate matter particles ranging from a few nanometers to a few hundred microns in diameter are derived from automobile exhaust gases, the steel industry, power plants, pulp and paper industry, the food industry, as well as commercial buildings and heat sources [3 - 5].

Paradoxically, one of the largest sources of emissions is small heat sources used in homes, including fireplaces, stoves and small boilers with a rated output of up to 50kW. Emissions from the combustion of solid fuels are a significant source of pollutants consisting of gaseous and solid substances.

One of the most common methods of determining the level of pollution is the measurement of particulate emissions for control and regulatory purposes in relation to air quality protection. Sampling of particulate matter from domestic stationary heat sources is still a challenging process. The main focus here is on the measurement of PM10 and PM2.5 particulate matter, which has a negative impact on human health, especially on the respiratory tract, and is able to remain in the atmosphere for a long time. They remain in the atmosphere for several days to weeks until they are separated from the air by contact with a solid surface or liquid such as walls, roads, vegetation, water bodies or rain drops. Several studies have shown that increased concentrations of particulate matter in ambient air correlate with adverse effects on the health of the exposed population, including respiratory and cardiovascular diseases, as well as increased mortality [5 - 8]. Other studies also point out that particulate emissions from biomass combustion also affect boiler performance. Some of these particles are deposited inside the boiler, causing operating problems such as corrosion, contamination, clogging, which reduces combustion efficiency. Emission control and control have an impact on the protection of the environment and human health, and therefore methods for measuring particulate matter have been developed. The most commonly used methods include the cascade impactor gravimetric method, the particle counter dilution method and the optical method [9 - 12].

This work focuses on the measurement of particulate matter by tandem connection of APS and SMPS particle sizers using dilution. Dilution is used to eliminate the mechanisms that arise when sampling particles that may affect their properties. These are nucleation, condensation, evaporation and coagulation [13 - 18]. The results are then compared with gravimetric measurements.

2. Methods of particulate matter measurement

Measurement of particles from biomass combustion plants is very demanding; the particle size range is large, usually ranging from a few nanometers (nm) to a few micrometers (μm). The measurement of the particles is carried out in terms of mass concentrations, numerous concentrations and their particle size distribution. The se-lection of metering devices for measuring particulate matter and their size distribution is important because different devices differ in their characteristics and have specific advantages and disadvantages. The large particle number concentrations in the flue gas after biomass combustion exceed the detection capacity of some plants; therefore they are used for measurement with flue gas diluents for measurement.

The division of methods for measuring particulate matter is a complex and complex task; most often the methods are divided into methods of concentration measurement, size distribution measurement and chemical analysis. These groups are then ranked with measurement methods that differ in the observation of different physical phenomena. In addition to the use of individual measurement methods, there are also complete systems that consist of the so-called tandem connection of two or more devices.

The most common methods used in practice are gravimetric method, radiometric method, photometric method, method with aerodynamic particle counter and method with spectrometer for scanning particle mobility.

2.1 Gravimetric method

Gravimetric method is the manual single method with sampling of the flow gas by probe. It is based on determination of the median concentrations by sampling from multiple points of measurements cross-section and their subsequent gravimetric assessment. Solid contaminants are usually separated by an external filter. Representative sampling is performed by sampling probe suitable shape and the correct speed under isokinetic condition.

The procedure consists in that the aerosol sample undergoes several stages of impaction. At each stage, particles larger than the cut off diameter of that stage are trapped on the filter. The smaller particles advance with the gas flow that surrounds the collecting plate and are captured in the next stage where the holes are smaller and have conditions for a higher gas flow rate. The particles are collected on microfiber filters. Before measurement, the filters are dried to remove all moisture, then cooled and weighed. After measurement, the filters are re-dried, cooled, and weighed to deter-mine the mass of trapped particles. The sampling rate is important to achieve the isokinetic condition. In order to achieve the isokinetic condition, the velocity at the mouth of the probe must be equal to the velocity of the flowing gas in the flue gas duct. Then the concentration of the particles in the mouth of the probe will be the same as the concentration of the particles in the flue gas flow.

It has been reported in various literature that gravimetric particulate sampling is a fundamental method for measuring particulate matter. It is considered to be an accurate and, above all, inexpensive method for measuring particulate matter. The ad-vantage is that the particles collected in the filter can then be chemically analysed [9, 19, 20]. Flow velocity, or flow of the sample gas is measured by ensuring of isokinetic, for example by aperture track and a total collected amount of gas by gas meter. The principal scheme of a gravimetric method is shown in Fig. 1.

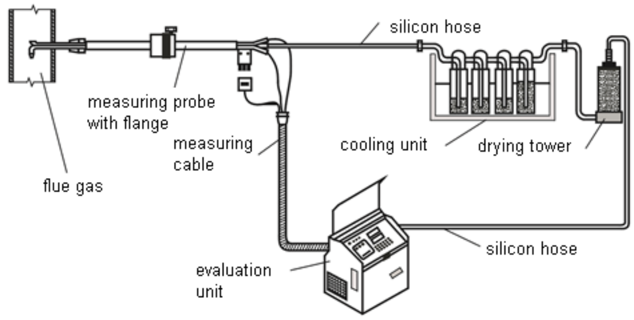

Figure 1. The principle of the gravimetric method

2.2 Radiometric method

The method is based on a point sampling of gas sample and determination of particle concentration in the sample by measuring of the weight of separated particles according to absorption of beta device in the layer of particles. In practice, into stream of sample of exhaust air is placed filter strip and detects absorption of β-device in exposed and unexposed filter. Absorption of β-device detects by measurement of Geiger-Muller reading tube that transmits pulses in proportion to radiation dose. On the basis of the difference in absorption is evaluated captured amount of particles.

As emitters are used 14C isotopes or 85Kr isotopes with low activity. The spatial density of electrons is given for a type of emitter practically independent of the chemical composition of particles. Sampling is performed similarly to gravimetric method by probe with suitable shape under isokinetic conditions controlled according to the measured velocity at the point of collection [21, 22]. The principal scheme of radiometric method is shown in Fig. 2.

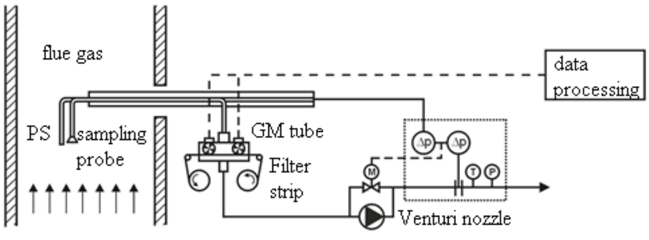

Figure 2. The principle of the radiometric method

2.3 Photometric method

Photometric method is continuous method, which determines mean concentration of particles along the beam directly in flues without sampling. Usually used for major sources. Principle of the method is the attenuation of the intensity of electromagnetic radiation in a straight line, caused by absorption and scattering of radiation on particles in range of visible (400 <λ <750 nm) and ultraviolet (λ <400 nm) part of spectrum. The principle is expressed by Lambert-Beer's law. Devices on the principle of photometric method (photometers) use one or more beams. Device with two beams is shown in Fig. 3. Beam passed with a layer of exhaust gas stream is reflected from the reflector and goes back. This increases the sensitivity of measurement. Light source is usually low voltage lamp (visible light area) or mercury vapour lamp (spectral lines in the visible and UV radiation). Spectral photometers use only certain wavelengths by inserting filters into the optical path and allow measuring the particulate matter concentration also measuring the emission of gaseous compounds (SO_2, NO_2) on the basis of the different absorption bands of the substance.

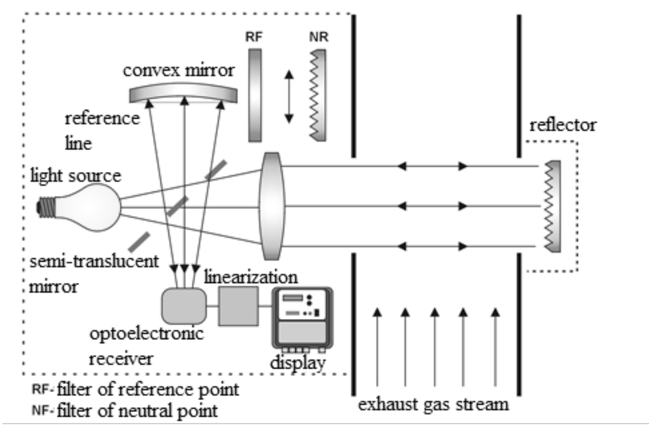

Figure 3. The principle of the photometric method

2.4 Method with aerodynamic particle counter

The aerodynamic particle counter is a spectrometer capable of measuring the particle size distribution in the 0.5 µm to 20 µm size range (Fig. 4). Its operating principle is based on accelerating the flow of the aerosol sample through the throat. The aerodynamic particle size determines the acceleration rate. Larger particles accelerate more slowly due to greater inertia. At the nozzle, particles emerge through two laser beams partially covered in the detection area. The light is scattered as each passing particle passes through the overlapped beams. The flight time between the two laser beams is then used to calculate the aerodynamic diameter. One elliptical mirror, positioned 90 ° to the laser beam axis, captures and concentrates light on an avalanche photodetector (APD), in which light pulses are converted into electrical pulses.

2.5 Method with spectrometer for scanning particle mobility

The measurement of the particle size mobility and concentration thereof is carried out using an SMPS particle size measurement system (Fig. 5). These systems are widely used in many scientific fields related to aerosols, for

example in applications dealing with the atmosphere, combustion or nanomaterial processing.
The particle mobility scanning spectrometer has a modular design made up of components, allowing the user to customize his equipment to suit his experimental needs. It consists of an electrostatic classifier, a DMA mobility analyser, followed by a CPC condensation particle counter. By selecting suitable components, measurements from 1 nm to 1 µm can be achieved [13].

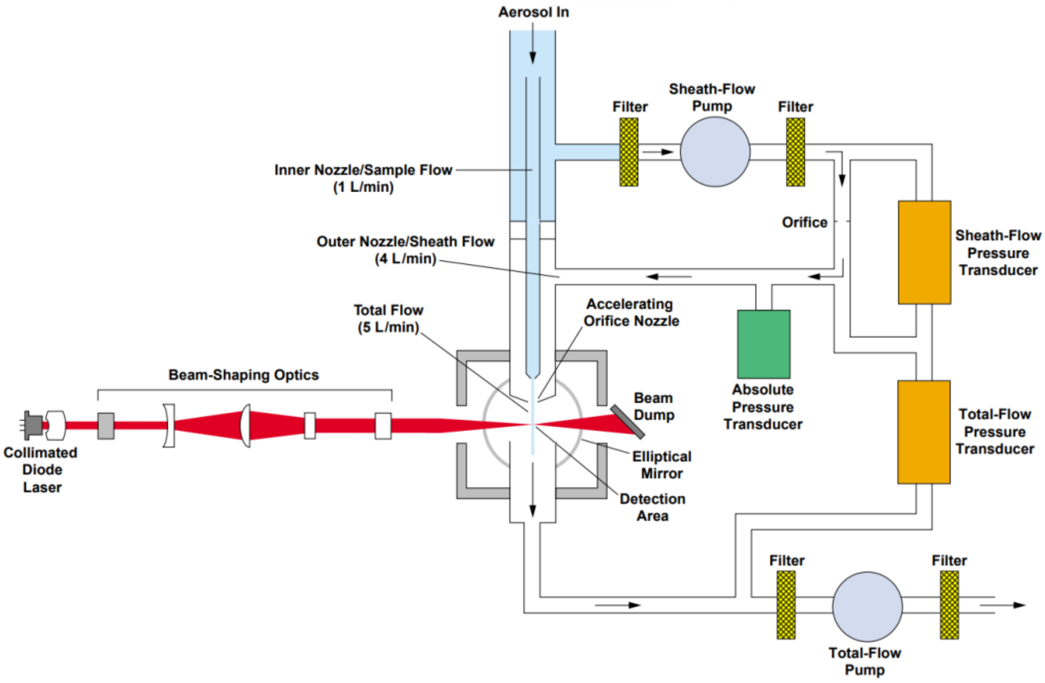

Figure 4. The principle of the method with aerodynamic particle counter [13]

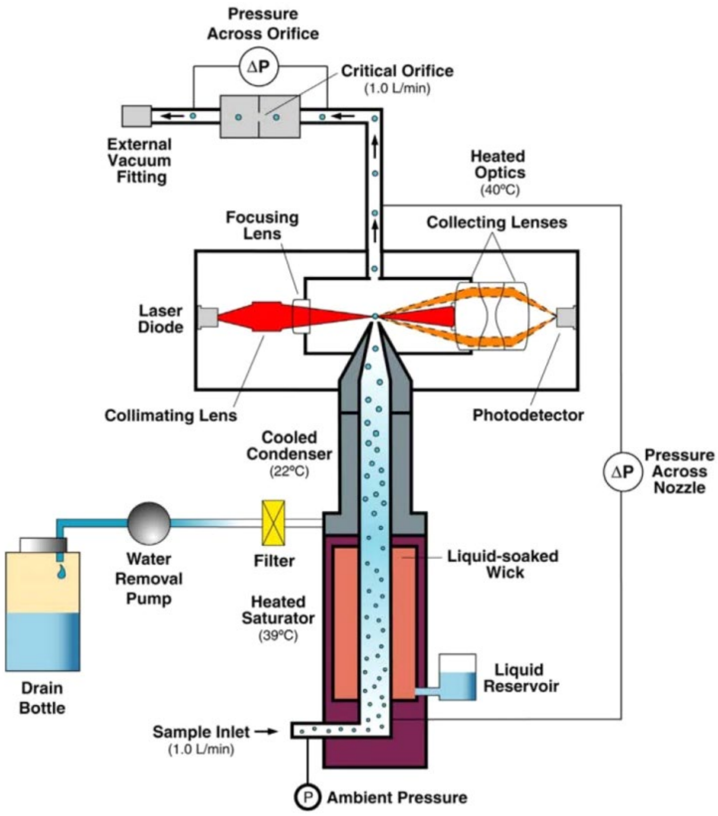

Figure 5. The principle of the method with spectrometer for scanning particle mobility [13]

3. Materials and methods used in experiments

Experiment was realized on small heat source - fireplace stove. The fuel was chosen beech wood weighing approximately 1.3 kg. It was inserted in the same way into the fireplace stove. The chimney draft had to be adjusted and also maintained at 12 ± 2 Pa. The fuel was loaded on the grate at a temperature of 135 °C in the flue gas duct. After insertion of the fuel, the measurement of particulate matter was started using TSI devices and after about 6 minutes a gravimetric probe was inserted into the flue gas duct to compare the measured results. The conditions during the measurements were the same, only the setting of the combustion air supply was changed. In order to minimise measurement error, the fuel with the same properties was applied in all tests. Technical parameters of used beech wood without bark content are presented in Tab.1.

Table 1. Technical parameters of used beech wood

Parameter	Value	Standard
Moisture (105 ± 2 °C)	11.12 %	STN EN ISO 18134-1 [23]
Ash content (550 °C)	0.391 %	STN EN ISO 18122 [24]
Total energy content	17.59 MJ/kg	STN EN ISO 18125 [25]
Calorific value	15.98 MJ/kg	STN EN ISO 18125 [25]
H content	6.03 $\%_{dry}$	STN EN ISO 16948 [26]
N content	0.08 $\%_{dry}$	STN EN ISO 16948 [26]
C content	48.89 $\%_{dry}$	STN EN ISO 16948 [26]
Deformation temperature of ash	1350 °C	STN ISO 540 [27, 28]
Volatile content	80.29 $\%_{dry}$	STN EN ISO 18123 [29]
Solid carbon content	19.32 $\%_{dry}$	STN 44 1355 [30]

During the experiment two methods for PM concentration determination were used: gravimetric method and combination of APS and SMPS devices in tandem connected.

The wiring diagram of this experimental measurement is shown graphically in the Fig. 7. Sampling of gaseous emissions is ensured by a probe with ceramic filter and thermocouple, which is inserted in the measuring section downstream of the heat source. The evaluation is carried out using the ABB gas emission analyser, which is connected to the computer via the AHLBORN control panel. Data entry is performed using AMR WinControl 6 software.

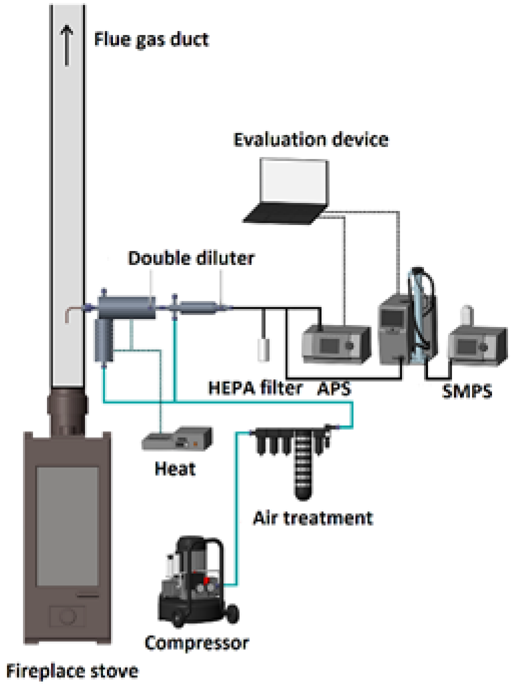

Figure 6. The wiring diagram of experimental measurement

During experiments were used these methods of particulate matter measurement:

- Gravimetric method with a gravimetric probe with a three-stage cascade impactor TCR Tecora Isostack Basic.
- APS and SMPS method with tandem connection of the TSI APS 3321 and TSI SMPS 3938 devices using flue gas dilution.

4. Results of experiment

During the measurement on an experimental measuring device which compared the measurement of particulate matter by gravimetric method and the method using TSI APS 3321 and TSI SMPS 3938, it was found that the measured values of total concentrations of C and Cr particles by both methods were approximately the same .
The greatest agreement between the measured values was at particle concentrations of less than 2.5 µm. The average difference between the measured values from APS, SMPS devices and gravimetric method was nearly 12.65%, while the smallest difference in the measured values was approximately 0.33%, indicating that APS and SMPS devices are quite accurately for particle concentrations of less than 2.5 µm. Comparison the measured concentration values of particulate matter with a diameter of less than 2.5 µm is shown in the Fig. 7.

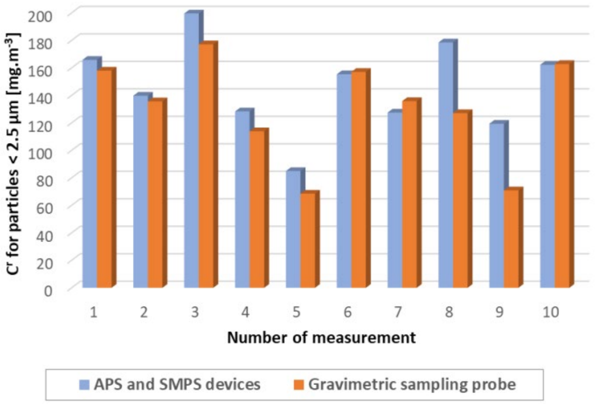

Figure 7. Particulate matter concentration for particles smaller than 2.5 μm

With increasing particle diameter, the APS and SMPS devices measured several times lower concentrations than during the gravimetric method. High differences were observed already when measuring the concentrations of particles in the range from 10 μm - 2.5 μm. The mean difference between the measured concentrations values from the two methods used was up to 91.36%. A comparison of the measurement values is shown in Fig. 8.

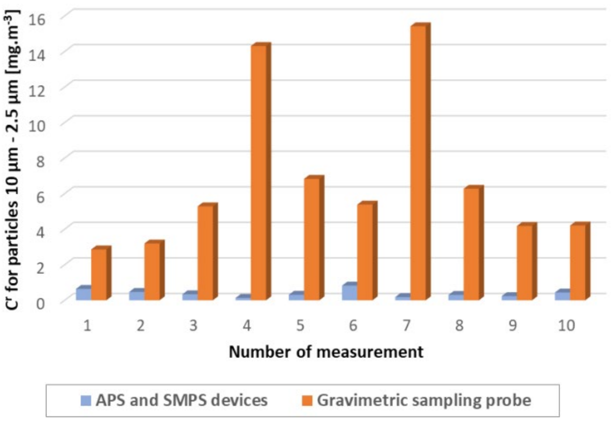

Figure 8. Particulate matter concentration for particles 2.5 μm - 10 μm

The greatest difference was found during measuring concentrations of particles larger than 10 μm. The average difference was up to 99.17%. This means that the results measured by APS and SMPS devices almost did not match at all the values measured by the gravimetric probe. A comparison of the measured particle concentration values greater than 10 μm is shown in the Fig. 9.

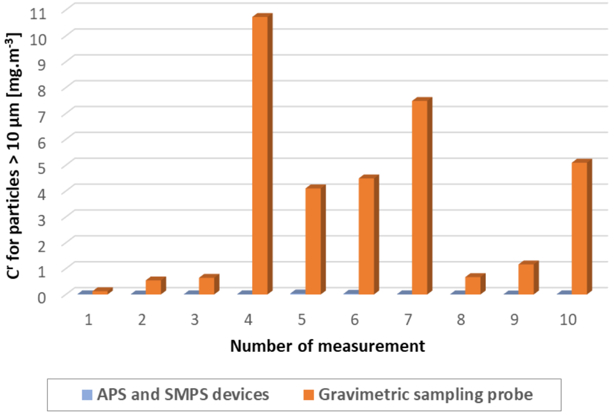

Figure 9. Particulate matter concentration for particles larger than 10 μm

Concentration values measured with TSI APS 3321 for particles with a particle diameter in the range of 2.5 μm to 10 μm and for particles larger than 10 μm were not consistent with the concentration values measured using the gravimetric method. The mean differences between the measured particle concentration values greater than 2.5 μm from both methods used were higher than 90%. In general, when measuring larger diameter particles, there is a higher loss on the route from the sampling point to the metering device, compared to measuring smaller diameter particles where the losses are lower. This may be the reason why the particle concentrations measured with TSI APS 3321 were significantly lower than those measured by the gravimetric method. Losses that affect larger diameter particles include mainly internal impaction and gravitational loss.

5. Conclusion

Increased particulate concentrations in ambient air are directly related to adverse health effects of the exposed population, including respiratory and cardiovascular diseases, as well as increased mortality. Other studies also point out that particulate emissions from biomass combustion also affect boiler performance. Some of these particles settle inside the boiler, causing operational problems such as corrosion, contamination, clogging, which reduces combustion efficiency. Emission control and control have an impact on the protection of the environment and human health, and therefore methods for measuring particulate matter have been developed. The most commonly used methods are the gravimetric method, which is principally simple but requires many manual steps where there is a higher risk of measurement errors, such as loss of particles during careless filter handling, errors due to imperfect probe cleaning between measurements, or weighing errors. For this reason, this measurement method is currently being replaced by other, newer and simpler methods, such as the measurement method using an aerodynamic particle counter and a particle mobility scanning device.

The aim of the experiments was to design and appropriately set up an experimental measuring device so that it is possible to measure solid pollutants arising from the biomass combustion process in a small heat source at the same time using the gravimetric method with three-stage impactor and tandem method using APS method and measurements using both methods were performed simultaneously to allow direct comparison. The gravimetric probe measurement method was considered the reference measurement method.

By analysing and comparing the measured results, it was found that the measurement of the total particle concentration using the gravimetric method was similar to that of the APS with SMPS equipment, except for differences in the measurement of the concentration of larger diameter particles. The greatest agreement between the measured values was recorded at concentrations of particles smaller than 2.5 µm, which had the largest share of the total concentrations in all measured sizes. The measured values of particle concentrations of less than 2.5 µm come from the whole measurement range of the SMPS and from the measurement range of the APS. This implies that measurement with the SMPS can be considered as an accurate measurement method. APS has demonstrated measurement accuracy in the particle area less than 2.5 µm, but with increasing particle size, the device has measured concentrations several times smaller than the gravimetric method. Some studies confirm the inaccuracy of the APS equipment. The internal impaction losses and the gravitational loss of the particles were minimized by appropriately assembling the wiring so that the routes from the flue gas collection point to the metering device were as short as possible, containing as few bends and horizontal sections as possible.

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References

[1] Sadaka, S., Johnson, D. M.: Biomass Combustion, Agriculture and Natural Resources, 1156, 2014

[2] Vitazek, I., Vitazkova, B., Ploth, J.: Production of Gas Emissions from Biomass Heat Source. Engineering Mechanics, vol. 20, 2013, No. 3/4, 289-298.

[3] J. Ristvej, A. Zagorecki, K. Holla, L. Simak, M. Titko: Modelling, simulation and information systems as a tool to support decision-making process in crisis management, 2013, In: Modelling and Simulation 2013 - European Simulation and Modelling Conference, ESM 2013, pp. 71-76

[4] Pilat, P., Patsch, M., Malcho, M.: Solar Heat Utilization for Adsorption Cooling Device, EPJ Web of Conferences, vol. 25, 2012.

[5] Sitek, T., Pospíšil, J., Poláčik, J., Špiláček, M., Varbanov, P.: Fine combustion particles released during combustion of unit mass of beechwood, Renewable Energy, 140, 390-396, 2019

[6] Zagorecki, K., J. Ristvej, K. Klupa: Analytics for protecting critical infrastructure, 2015, In: Communications - Scientific Letters of the University of Zilina, 17(1), pp. 111-115

[7] Chen, T. B., Cheng, S. Y., Yeh, C. H.: Performance of a TSI aerodynamic particle sizer. Aerosol Science and Technology 4, 89-97 (2007).

[8] Catlos, M., Kurdel, P., Sedlakova, A.N., Labun, J., Ceskovic, M.: Continual Monitoring of Precision of Aerial Transport Objects. Proceedings 8551683, 76-81 (2018).

[9] Amaral, S. S., De Carvalho, J. A., Costa, M. A. M., Pinheiro C.: An overview of particulate matter measurement instruments. Atmosphere 6(9), 1327-1345 (2015).

[10] Pagels, J. H., Johansson, L., Hagström, M.: Intercomparison of SMPS; ELPI and APS 3320 during sampling of particles emitted from a domestic wood pellet burner. Conference: 6th International Aerosol Conference, IAC, Volume: in proceeding page 151 (2002).

[11] Strand, M., Lillieblad, L., Sanati M.: Aerosol formation and effect in biomass combustion and gasification. Report nr 2/2005, Vaxjo University (2005).

[12] Price, H. D., Stahlmecke, B., Arthur, R.: Comparison of instruments for particle number size distribution measurements in air quality monitoring. Journal of Aerosol Science 76, 48-55 (2014).

[13] TSI Homepage, https://tsi.com/home, last accessed 2016.

[14] DEKATI Homepage, https://www.particleinstruments.com/sites/default/files/pdfs/Dekati_Diluter_Brochure122018%20%281%29.pdf, last accessed 2018.

[15] World Health Organisation, 2006. Air quality guidelines : particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Germany : Druckpartner Moser, 2006

[16] Boman, C., Nordin, A., Öhman, A M., Bostrom, D., Westerholm, R.:Emissions from small-scale combustion of biomass fuels - extensive quantification and characterization. Energimyndigheten, 2005

[17] Laden, F., Neas, L. M., Dockery, D. W., Schwartz, J.: Association of fine particulate matter from different sources with daily mortality in six U.S. cities, Environ Health Perspect. 2000 Oct; 108(10): 941–947

[18] Lopes, V. S. B, 2016. Effect of particle size on the burnout and emissions of particulate matter from biomass combustion in a drop tube furnace, Tecnico Lisboa, 2016

[19] Jicha, M., Katolicky, J., Pospisil, J.: Dispersion of pollutants in a street canyon and street intersection under traffic-induced flow and turbulence using a iow Re k-ε model, International Journal of Environment and Pollution, 18 (2), 2002, 160-170

[20] Rimar, M., Fedak, M., Dudinak, P.: Process of Nitrogen Oxides Generation in Pressure Burners, Manufacturing and industrial engineering, 2007, issue 3, 81 - 84

[21] Neuenschwander, P., Good, J., Nussbaumer, Th.: Combustion efficiency in biomass furnaces with flue gas condensation, Biomass for Energy and Industry, 10th European Conference and Technology Exhibition June 8–11 1998, Würzburg

[22] Dzurenda, L., Banski, A.: Dependence of the boiler flue gas losses on humidity of wood biomass, Archives of thermodynamics, Vol. 36 (2015), No. 4, 77–86
[23] STN EN ISO 18134-1: 2015: Solid biofuels. Determination of moisture content. Oven dry method. Part 1: Total moisture. Reference method
[24] STN EN ISO 18122: 2015: Solid biofuels. Determination of ash content
[25] STN EN ISO 18125: 2017: Solid biofuels - Determination of calorific value
[26] STN EN ISO 16948: 2015: Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen
[27] STN ISO 540: 2010: Hard coal and coke.Determination of ash fusibility
[28] Horak, J., Jankovska, Z., Straka, F., Buryan, P., Kubesa, P., Hopan, F., Krpec, K.: Problems of Determination of Characteristic Temperatures of Biomass Ash Fusibility (in Czech), Chemickelisty, vol. 107, No. 6, 2013, 502-509.
[29] STN EN ISO 18123: 2015: Solid biofuels - Determination of the content of volatile matter
[30] STN 44 1355: 1993: Solid mineral fuels. Unburnt residue. Determination of hydrogen and carbon