# PUBLIKACE

**“Application of the Flying Laboratory for measurements at an emission source with a nominal heat output up to 50 kW”**

**„Využití Flying laboratory pro kontrolu emisního zdroje o jmenovitém tepelném výkonu do 50 kW“**

**V rámci projektu:**

**i-AIR Region**

**Operační program: Interreg V-A Česká republika – Polsko**

**Registrační číslo: CZ.11.4.120/0-.0/0.0/16_026/00-01075**

**Doba realizace projektu: 1.1. 2018 – 31. 12. 2020**

***Marek Kucbel[1], Helena Raclavská[1] Michal Šafář[1], Konstantin Raclavský[1], Barbora Švédová[1], Dagmar Juchelková[2], Rafał Bigda[3]and Jacek Żeliński[3]***

[1] Centre ENET—Energy Units for Utilization of Non-Traditional Energy Sources, VŠB—Technical University of Ostrava, 17. listopadu 15/2172, 708 00 Ostrava-Poruba, Czech Republic
[2] Department of Electronics, VŠB—Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, 17. listopadu 15/2172, 708 00 Ostrava-Poruba, Czech Republic
[3] Institute for Chemical Processing of Coal, ul. Zamkowa 1, 41-803 Zabrze, Poland

2020

PŘEKRAČUJEME HRANICE
PRZEKRACZAMY GRANICE
2014—2020

EVROPSKÁ UNIE / UNIA EUROPEJSKA
EVROPSKÝ FOND PRO REGIONÁLNÍ ROZVOJ
EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

International Exchange
Future of Waste Management
Industry, Operators and Research

UPDATED VERSION
SEPTEMBER 29, 2020

# IRRC

WASTE-TO-ENERGY

OCTOBER 15 AND 16, 2020 | VIRTUAL CONGRESS

## INTERNATIONAL DEVELOPMENT

EU Policies and Implementation
Strategies and Projects
Country Reports

## WASTE INCINERATION

Municipal Solid Waste
Sewage Sludge
Hazardous Waste

Technologies of Waste Incineration
Energy Efficiency and Use
Tools and Methods for Plants in Operation

Boiler, Materials and Corrosion
Flue Gas Treatment
$CO_2$ Capture and Utilisation
Incineration Residues

## ALTERNATIVE WASTE-TO-ENERGY PROCESSES

Solid Recovered Fuels –
Production and Co-Incineration
in the Cement Industry

## SCIENTIFIC CHAIR

**Professor Dipl.-Ing. Dr. techn. Franz Winter**
Vienna University of Technology,
Institute of Chemical, Environmental &
Biological Engineering, Austria

**Professor Ing. Dagmar Juchelková, Ph. D.**
Technical University of Ostrava (VŠB-TUO),
Energy Engineering Department, Czech Republic

**NEW**

**VIVIS-APP**

The event-platform for participants
of the IRRC and our other events –
for iOS and Android



www.IRRC-Waste-to-Energy.com

## Programme Coordination

**Dr.-Ing. Stephanie Thiel,** Scientific Director of Thomé-Kozmiensky Verlag GmbH, Germany

## Steering Committee

**Associate Professor Dr.-Ing. Lale Andreas**
Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Waste Science & Technology, Sweden

**Professor Dr.-Ing. Michael Beckmann**
Technical University Dresden, Director of the Institute of Process Engineering and Environmental Technology, Germany

**Patrick Clerens**
Secretary General, European Suppliers of Waste to Energy Technology (ESWET), Belgium

**Christophe Cord'homme**
Business & Products Development Director, CNIM Constructions Industrielles de la Méditerranée S.A., France

**Professor Dr. Ertugrul Erdin**
Dokuz Eylül Universitesi Mühendislik Fakülltesi, Cevre Mühendisligi Bölümü, Buca-Izmir, Turkey

**Dipl.-Ing. Thomas Feilenreiter**
Managing Director of Steinmüller Babcock Environment GmbH, Germany

**Professor Dr.-Ing. Martin Kranert**
University of Stuttgart, Chair of Waste Management and Emissions, Germany

**Professor Dr. Rundong Li**
Shenyang Aerospace University, Director for Institute of Clean Energy & Environmental Engineering (ICEEE), China

**Professor Dipl-Ing. Dr. techn. Karl E. Lorber**
University of Leoben, Waste Processing Technology and Waste Management, Austria

**Dr.-Ing. Reinhard Maaß**
RM Strategie & Kommunikation, Germany

**Dipl.-Ing. Ulrich Martin**
Managing Director of Martin GmbH für Umwelt- und Energietechnik, Germany

**Dipl.-Phys. Karl-Heinz Müller**
Chief Operating Officer of EEW Energy from Waste GmbH, Germany

**Adj. Professor Dr.-Ing. habil. Abdallah Nassour**
University of Rostock, Chair of Waste and Resource Management, Germany

**Professor Ph.D. Eur. Ing. Dr.-Ing. habil. Tadeusz Pajak**
University of Science and Technology AGH Kraków, Department of Power Systems and Environment, Poland

**Assistant Professor Ing. Martin Pavlas, Ph.D.**
Brno University of Technology, Institute of Process and Environmental Engineering, Czech Republic

**Dipl.-Chem.-Ing. Luciano Pelloni**
Waste Management Advice, Switzerland

**Professor Dipl.-Ing. Dr. mont. Roland Pomberger**
University of Leoben, Chair of Waste Processing Technology and Waste Management, Austria

**Professor Constantinos S. Psomopoulos, Ph.D**
Piraeus University of Applied Sciences, Director of the Electric Power Division and High Voltage Lab, Greece

**Professor Dr.-Ing. Peter Quicker**
RWTH Aachen, Unit of Technology of Fuels, Germany

**Professor Dipl.-Ing. Dr. techn. Harald Raupenstrauch**
University of Leoben, Chair of Thermal Processing Technology, Austria

**Professor Dipl.-Ing. Dr. techn. Helmut Rechberger**
Vienna University of Technology, Institute of Water Quality, Resources and Waste Management, Austria

**Professor Dr.-Ing. Wolfgang Rommel**
Managing Director of bifa Umweltinstitut GmbH, Augsburg, Germany

**Professor Dr.-Ing. Vera Susanne Rotter**
Technical University Berlin, Chair of Solid Waste Management, Germany

**Dipl.-Ing. Dr. mont. Renato Sarc**
University of Leoben, Waste Processing Technology and Waste Management, Austria

**Dr.-Ing. Frank Schumacher**
Managing Director of Zweckverband RBB Restmüllheizkraftwerk Böblingen, Germany

**Professor Ing. Ph.D. Ľubomír Šooš**
Slovak University of Technology in Bratislava, Director of the Institute of Manufacturing Systems, Environmental Technology and Quality Management, Slovakia

**Dipl.-Ing. Josef Staus**
Vice President DIPI R&R EfW of Suez Groupe, France

**Professor Dr.-Ing. habil. Dr. h.c. Petr Stehlík**
Brno University of Technology, Director of the Institute of Process Engineering, Czech Republic

**Dr. Ella Stengler**
Managing Director of CEWEP – Confederation of European Waste-to-Energy Plants e.V., Belgium

**Associate Professor Dr. Pál Szentannai**
Budapest University of Technology and Economics (BME), Deputy Head of Department of Energy Engineering, Hungary

**Professor Dr.-Ing. Oktay Tabasaran**
Istanbul, Turkey and Stuttgart, Germany

**Dr. ir. Robert van Kessel**
Operating Agent, Prewin network, Ugchelen, Netherlands

**Dr. Costas A. Velis**
Lecturer in Resource Efficiency Systems, University of Leeds, Institute for Public Health and Environmental Engineering, United Kingdom

**Dipl.-Masch.-Ing. Thomas Vollmeier**
President of TBF + Partner AG Consulting Engineers, Zurich, Switzerland, Chairman of IRF International Recovery Foundation

**Associate Professor Dr. Sc. Patrik Yrjas, Senior Researcher**
Laboratory of Inorganic Chemistry, Åbo Akademi Johan Gadolin Process Chemistry Centre, Finland

# Application of the Flying Laboratory for measurements at an emission source with a nominal heat output up to 50 kW

*Marek Kucbel[1], Helena Raclavská[1] Michal Šafář[1], Barbora Švédová, [1]Konstantin Raclavský[1], Dagmar Juchelková[2], Jana Růžičková[1], Rafał Bigda[3]and Jacek Żeliński[3]*

[1] Centre ENET—Energy Units for Utilization of Non-Traditional Energy Sources, VŠB—Technical University of Ostrava, 17. listopadu 15/2172, 708 00 Ostrava-Poruba, Czech Republic

[2] Department of Electronics, VŠB—Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, 17. listopadu 15/2172, 708 00 Ostrava-Poruba, Czech Republic

[3] Institute for Chemical Processing of Coal, ul. Zamkowa 1, 41-803 Zabrze, Poland

**Abstract:** An Unmanned Aerial Vehicle (drone) together with the Flying Laboratory DR1000 Scentroid was used for checking the emission limits of a given emission class at a boiler during the burning of soft wood (spruce) and slabs. Air quality in the Moravian-Silesian Region (the Czech Republic) and the Upper Silesia Region (Poland) is among the most polluted in Europe, especially in the winter season when the concentration of $PM_{10}$ is repeatedly exceeded. Local boilers represent a major contributor to the high air contamination, producing mainly particles of size less than 1 µm with adverse human health effects. Biomass burning in local furnaces produces 85-88% of the particles with the size of less than 1 µm while burning the slabs increases the share of particles in class 1-2.5 µm by about 2% for the boiler of the emission class 2.

## 1 INTRODUCTION

Improving air quality requires new approaches and methods to identify and understand the behaviour of air pollutants and their impact on human health more accurately (*Markowicz and Chiliński, 2020*). Currently, Unmanned Aerial Vehicle (drone, UAV) equipped with miniature sensors to detect gaseous emissions and dust particles can compensate for the lack of information from traditional measurements (*Ren et al., 2019*).

Particulate matter (PM) is currently considered the best indicator for the health effects of ambient air pollution (*Vicente et al., 2018*). Particulate matter was classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1). Ambient air pollution and particularly airborne particulate matter cause adverse human health effects including respiratory illnesses, cardiovascular diseases and carcinogenic effects (*Fanizza et al., 2018*).

"Across Europe and North America, central Europe is the region with the highest proportion of outdoor particulate matter with an aerodynamic diameter of fewer than 2.5 micrometres ($PM_{2.5}$) that can be traced to residential heating with solid fuels (21% in 2010). $PM_{2.5}$ is one of the major air pollutants produced by burning solid fuels" as biomass and coal (*Chafe et al., 2015*). The weather conditions combined with high industrialisation of regions in the Czech Republic and Poland influence the origin of long smog episodes with concentrations of $PM_{10}$ in the atmosphere at the level of hundreds of micrograms (*Moravian-Silesian Region, c2019)*. The primary pollution source of $PM_{10}$ in the area of Polish and Czech border between Ostrava and Katowice (Silesia Region) is residential heating (*Bitta et al., 2018*).

Between years 2014-2020, citizens of the Czech Republic were able to draw on so-called "boiler subsidies" and have their first- and second-emission class boilers replaced with a new environmental heat source with financial support from the state (European Union funds). Almost 23,000 old boilers have been replaced in the Moravian-Silesian Region (MSR). According to initial estimates, a total of 50,000 boilers would be replaced in the MSR and more than 680,000 in the Region of Silesia. In Poland, boilers can already be checked by the municipal police without previous warning. In Katowice, local heating plants are also monitored using UAVs that analyse smoke from chimneys. If the smoke does not comply with the control conditions, the police can enter the house and take samples of ash from the boiler for analysis. If the ash analysis confirms the incineration of an unauthorised fuel (waste), the owner may be fined (*Motolova, 2019*).

The aim of this work is to verify the possibility of using innovative methods of sensor technology (DR1000 Flying Laboratory together with UAV) to monitor emissions from combustion plants with a nominal heat output of up to 50 kW. The results may contribute to the identification of particulate behaviour in the air as part of the process of minimising health risks, including changes in legislation to promote remedial action.

## 2 SAMPLING POINTS AND METHODS

During the experiments, particles (PM) were monitored, including their size distribution, released during the burning of spruce wood and slabs as standard energy fuel in boilers of various emission classes (EC): EC2 with manual loading (VIADRUS U22 (LP) with an output of 20 kW), EC3 by automatic loading (Hercules DUO, VIADRUS and with an output of 25 kW), and EC5 with manual loading (VIADRUS U22 Economy with an output of 25 kW). Emissions measurements were taken after an hour of boiler operation.

On 5 December 2019, slabs (S) were combusted in boiler EC2 and EC3. Slabs are wastes generated in the wood board production; they may contain a certain proportion of bark. Spruce wood (S.W.) was burned in the EC3 and EC5 boiler on 20.2. 2020. The average outdoor temperature on 5 December 2019 was 7.4 ± 0.4 °C, the measured average relative humidity was 54.4 ± 2.58 per cent, and the average wind speed was 5.6 ± 1.7 m/s. On 20 February 2020, the conditions were comparable to the previous sampling: average temperature of 7.2 ± 0.3 °C, the relative humidity of the air 55.2 ± 1.12 per cent, and the wind speed of 6.2 ± 2.32 m/s. The identification of air pollutants from local boilers was carried out by the Flying Laboratory device DR1000 (Scentroid, Stouffville, ON, Canada). DR 1000 allows the use of up to five sensors at a time: VOC (detection limit: 0-75 ppm; type: photoionization detector), electrochemical detectors for $NH_3$ (detection limit: 0-20 ppm), NO (detection limit: 0-20 ppm), $NO_2$ (detection limit: up to 13 ppm) and $SO_2$ (detection limit: 0-21 ppm). The sensors for measuring $PM_1$, $PM_{2.5}$ and $PM_{10}$ have a measurement range of 0-1000 µg/m$^3$; type: Laser Scatterer (http://scentroid.com). The sensors were mounted on the hexacopter UAV DJI Matrice 600 Pro (DJI, Shenzhen, China) with dimensions 1668 mm × 1518 mm × 727 mm. Measurements with the Flying Laboratory DR1000 were made at the height of 50 cm from the chimney mouth, and a 1.5 m sampling probe was in the immediate vicinity of the chimney mouth (Fig.1).

**Figure 1.** Transport of the Flying Laboratory using UAV before measurement (left), the position during measurement (right).

## 3 RESULTS AND DISCUSSION

With effect from 1 January 2020, Commission Regulation (EU) 2015/1189 of the European Parliament and of the Council with regard to eco-design requirements for solid fuel boilers began to apply, regulating launching these products in the market and putting them into service. According to the Air Protection Act 201/2012 Coll., as amended, with effect from 1 September 2022, it will not be possible to operate boilers of emission class 1 and 2, while the higher emission class boilers must comply with the eco-design according to EN 303-5:2012 “Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking”. At the same time, this standard indicates the permissible concentrations of dust particles for an emission source with the heat output of up to 50 kW (Table 1). With effect from September 2022, it will not be possible to operate EC1 and EC2 boilers. If the ban is breached, the Czech Republic faces a fine of up to about €1850. The use of UAV sensors would be an appropriate option to make control measurements. Flying laboratories can combine different sensors as required. The most commonly used sensors are CO, $CO_2$, $SO_2$, $NO_X$, formaldehyde, volatile organic matter, and a dust particle counter of different particle classes $PM_1$, $PM_{2.5}$ and $PM_{10}$, and many more (http://scentroid.com). Currently, Czech national legislation does not allow checks using UAVs, preferring analysis of ashes. As part of the iAIR-Region project, a new methodology is being developed in the trans-border cooperation to use UAVs to monitor air pollution and its origin, or to determine the share of local heating pollution from both countries. All monitored boilers burning spruce wood met the emission limits for the average dust particle concentrations defined by the legislation for biomass burning (Table 1 and Table 2). A high concentration of dust particles in slab combustion for the class 2 boiler was found merely for a short time interval. The permitted emission limit (200 μg/m$^3$) was exceeded for $PM_1$, measuring up to 566 μg/m$^3$, $PM_{2.5}$ 603 μg/m$^3$ and $PM_{10}$ 660 μg/m$^3$.

**Table 1.** Dust emission limit values (concentrations) for an emission source with the heat output of up to 50 kW (mg/m$^3_N$ at 10 % $O_2$ )

| **Loading** | **Fuel** | **EC 1*** | **EC 2*** | **EC 3** | **EC 4** | **EC 5** |
|---|---|---|---|---|---|---|
| *Manual* | Biomass | 200 | 180 | 150 | 75 | 60 |
| | Fossil | 180 | 150 | 125 | 75 | 60 |
| *Automatic* | Biomass | 200 | 180 | 150 | 60 | 40 |
| | Fossil | 180 | 150 | 125 | 60 | 40 |

Explanations: Emission class – EC, * According to the former standard EN 303-5:1999, currently the limits for EC1 and EC2 are invalid.

By comparing PM emissions from boilers of different emission classes, it has been shown that the combustion of spruce waste - slabs in the boiler of the emission class 2 produces the highest concentrations of $PM_1$, $PM_{2.5}$ and $PM_{10}$ (Table 2). Average PM concentrations were up to 3.3 times higher for the boiler EC2 than for the boiler EC3 when the slabs were burned. When slabs were burned in the EC2 boiler, measured concentrations of PM were about seven times higher than when spruce wood was burned in the EC3 and EC5 boilers (Table 2). Average PM concentrations when burning spruce wood are almost comparable for the EC5 and EC3 boilers (Fig.2).

**Table 2.** Concentrations of PM particles measured by the Flying Laboratory DR1000 during the combustion of slabs and spruce wood in the boilers EC2, EC3 and EC5.

| | | **EC 2 *S*** | | **EC 3 *S*** | | **EC 3 *S.W.*** | | **EC 5 *S.W.*** | |
|---|---|---|---|---|---|---|---|---|---|
| | *Unit* | AVG *(Min-Max)* | S.D. | AVG *(Min-Max)* | S.D. | AVG *(Min-Max)* | S.D. | AVG *(Min-Max)* | S.D. |
| *$PM_1$* | (μg/m$^3$) | 76.4 *(24.5-566)* | 139 | 23.5 *(12-28)* | 4.63 | 10.6 *(4-22)* | 22 | 11.4 *(5-26)* | 4.38 |
| *$PM_{2.5}$* | (μg/m$^3$) | 81.5 *(26.5-603)* | 147 | 24.7 *(13-29)* | 4.73 | 10.9 *(4-23)* | 23 | 11.9 *(6-27)* | 4.58 |
| *$PM_{10}$* | (μg/m$^3$) | 89.9 *(29-664)* | 161 | 27.2 *(14-32)* | 5.28 | 12 *(4-25)* | 25 | 13 *(6-30)* | 5.05 |

Explanation: S – slab, S.W. – spruce wood, AVG – arithmetic mean, S.D. – standard deviation, Min – minimum, Max – maximum, EC – emission class.

The average percentages of dust particles in each particle size class < 1μm, 1-2.5 μm and 2.5-10 μm during combustion of slabs and spruce wood in boilers of different emission classes are illustrated in Fig. 2. Particles < 1 μm are dominant, accounting for 85-88% of $PM_{10}$ and posing a significant risk to human health. Ultrafine particles originate from combustion, high-temperature processes, and as a product of atmospheric reactions (Hsieh et al., 2009). By comparing the PM concentration in the combustion of slabs and spruce wood in the EC3 boiler, a slight difference in the particulate concentrations in the particle size class 1-2.5 μm was found. Particle proportion produced in this class was approximately by 2% higher than when spruce wood was burned. The difference was compensated by the loss of particles below 1 μm. The higher emission class boilers (EC5) have about a 3% higher proportion of particles smaller than 1 μm.

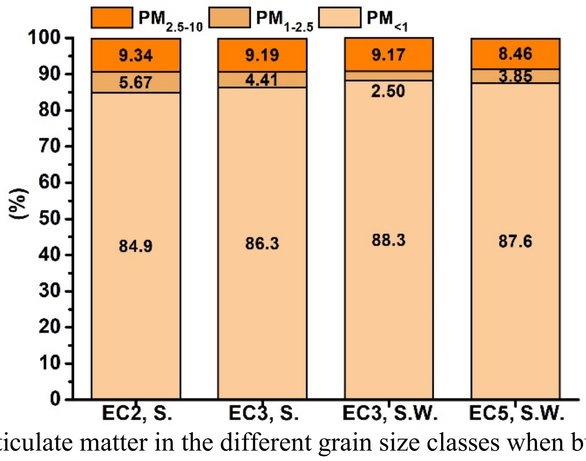


**Figure 2.** Percentages of particulate matter in the different grain size classes when burning spruce wood and slabs in boilers of different emission classes

## 4 CONCLUSION

The use of UAVs together with sensors for PM determination has shown that using standard fuels (biomass), sources with the nominal heat output of up to 50 kW meet the prescribed emission limits for dust particles according to EN 303-5 in their real operation. Currently, the limiting factors for the use of UAVs are both legislative and meteorological conditions (especially wind speeds up to 10 m/s, no rain or increased humidity, and air temperatures can range from -10 °C to +40 °C). The use of UAVs with sensors allows for a new angle to look at air pollutant concentration changes in the online system, while the cost of analyses alone is low (almost zero regardless of the input investment and drone insurance) compared to conventional methods. An unmanned aerial vehicle with sensors could become an effective tool for monitoring local boilers.

**ACKNOWLEDGEMENT**

This study was supported by the cooperation programme Interreg V-A in the Czech Republic and Poland, Registration number: CZ.11.4.120/0.0/0.0/16_026/0001075 and by the research project of the Ministry of Education, Youth and Sport of the Czech Republic: SP2020/22 "Innovative methods for monitoring particulate matter from combustion processes".

# REFERENCES

- A review of UAV monitoring in mining areas: current status and future perspectives. *International Journal of Coal Science & Technology*, 2019. 6(3), 320-333.
- Basic information and legislation [online]. [2020-11-01] https://www.msk.cz/cz/zivotni_prostredi/zakladni-informace-a-legislativa-41567/
- BITTA, J., PAVLÍKOVÁ, I., SVOZILÍK, V., JANČÍK, P. Air pollution dispersion modelling using spatial analyses. *ISPRS International Journal of Geo-Information*, 2018, 7, 489.
- Boiler financial suport. "Kotlíkové dotace" [online]. c2020 [2020-10-01]. https://lokalni-topeniste.msk.cz/sites/default/files/leta%CC%81k_kotliky_3.kolo_2019.pdf. In Czech.
- Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel boilers (Text with EEA relevance).
- EN 303-5:1999 Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking.
- EN 303-5:2012 Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking.
- FANIZZA, C., DE BERARDIS, B., IETTO, F., SOGGIU, M.E., SCHIRÒ, R., INGLESSIS, M., FERDINANDI, M., INCORONATO, F. Analysis of major pollutants and physico-chemical characteristics of $PM_{2.5}$ at an urban site in Rome, *Science of Total Environment,* 2018, 616–617, 1457–1468.
- Flying Laboratory DR1000. *Scentroid - Future of sensory technology* [online]. Whitchurch-Stouffville, 2015 [2020-11-01]. Available: http://scentroid.com/
- HSIEH, L.Y., Kuo, S.CH., Chen, Ch.-L., Tsai, Y.I. Size distributions of nano/micron dicarboxylic acids and inorganic ions in suburban PM episode and non-episodic aerosol. *Atmospheric Environment*, 43 (29), 2009, 4396 - 4406.
- CHAFE, Z., BRAUER, M., HÉROUX, M.-E., KLIMONT, Z., LANKI, T., SALONEN, R.O., SMITH, K. *Residential heating with wood and coal: health impacts and policy options in Europe and North America.* World Health Organization: World Health Organization.
- MARKOWICZ, K.M., CHILIŃSKI, M.T. Evaluation of two low-cost optical particle counters for the measurement of ambient aerosol scattering coefficient and Ångström exponent. *Sensors*. 2020, 20 (9).
- Ministry of Environment of Czech Republic. The Air Protection Act. 201/2012 Coll.; Ministry of Environment of Czech Republic: Prague, Czech Republic, 2012.
- MOTOLOVÁ, Ž. Polish citizens will advise the region on chimney inspections, Czechs to neighbours with the exchange of boilers. "Poláci poradí kraji s kontrolami komínů, Češi sousedům s výměnou kotlů" [online] *iDnes.cz* [2020-10-01] 3.6.2019. https://www.idnes.cz/ostrava/zpravy/kotel-ovzdusi-polsko-cesko.A190603_480038_ostrava-zpravy_jaga?. In Czech
- VICENTE, A.B., JUAN, P., MESEGUER, S., DÍAZ-AVALOS, C., SERRA, L. Variability of $PM_{10}$ in industrialized-urban areas. New coefficients to establish significant differences between sampling points, *Environmental Pollution,* 2018, 234, 969-978.