On the Development of a PM2.5 Monitoring Network for Real-time Measurements in Urban Environments

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A monitoring network system was designed and developed to be deployed in two Romanian cities during the ROkidAIR project for measuring in real time the PM2.5 concentrations. The system comprises 8 stations that were built following the successful design and testing of a PM2.5 optical instrument prototype. The System's Web services, the data acquisition from the monitoring stations, and the data sending to a GIS-integrated geoportal that includes a decision support system, were firstly evaluated for testing their effectiveness and for eventually defining necessary corrections. After describing the station's structure and the Web services' main functions, the paper presents data about the most important measured operating parameters of the stations, results from data processing, and conclusions for further developments. Preliminary information collected from a reference gravimetric sampler installed for data inter-comparison with the developed stations is also presented.

Keywords: PM2.5 measurement, monitoring network, Web services, operating parameters, predictive maintenance, Rokidair Project

The ROkidAIR project aims to improve the urban air quality monitoring and the forecasting activities focusing on the spatial delimitation of critical areas based on the receptors' vulnerability and their detailed characterization in terms of PM2.5 effects on children's health in two Romanian cities: Targoviste and Ploiesti. These urban agglomerations served as pilot areas during the ROkidAIR project for developing the monitoring network that is planned to be deployed up to the end of the project (April 2017). The system provides synthesized information concerning the PM2.5 concentrations and their evolution obtained from reliable monitoring stations and artificial intelligence (AI) forecasting algorithms [1]. More focused public health interventions at the neighborhood level are envisaged worldwide to reduce and better control the air-pollution related diseases [2]. The monitoring programs and associated modelling tools must provide outputs that can be used to detect temporal trends and spatial variability of air pollutants and should establish more or less empirical links between human activities and the associated environmental effects [3]. The current minimum number of sampling points for fixed measurements of PM2.5 concentrations (1 point for 0-249,000 residents) recommended by the current monitoring standard is not sufficient because the PM2.5 concentrations have an increased spatiotemporal variability at city level. Consequently, the number of fixed sampling points in a city should be increased and the continuous monitoring should be performed using reliable monitors at neighborhood scale [4]. The developed network responds positively to these requirements with the scope of residents' health protection.

The main components of the ROkidAIR system are a local monitoring and analysis system for each pilot city, Ploiesti and Targoviste, the web-based GIS module, the ROkidAIR Decision Support System (DSS), the ROkidAIR databases, the Web services running on a data server and a real time monitoring and service of the ROkidAIR PM2.5 stations [1].

After the ROkidAIR stations were built and deployed on site, the network's Web services were tested for evaluating their effectiveness and acquired data was used for estimating the functionality of some stations' subsystems and for defining future corrections and developments.

Structure of ROkidAIR station

Each ROkidAIR station is equipped with an optical PM2.5 transducer, which is measuring in the 1 ... 10.000 $\mu g/m^3$ interval with a 2 $\mu g/m^3$ precision. The airflow through the PM2.5 transducer is driven by a rotary vane pump, capable of a maximum flow of 6.2 L/min. The flow is controlled using an airflow sensor which is measuring in the 0 ... 5 SLPM interval, with a ±3.0% linearity error and ±0.5% repeatability and hysteresis. Before entering the airflow sensor, the sample air is passed through a Perma Pure gas dryer. Every five minutes, the PM2.5 transducer is calibrated using an airflow that is passing through a *zero-dust* Sartorius membrane having a 0.2 μm equivalent diameter threshold.

Inside and outside temperature and humidity values are measured using digital sensors working in the -40 ... 125 °C and 0 ... 100% rH (relative humidity) intervals, with ±0.2 °C and ±1.8% rH measuring accuracy. The barometric pressure is measured using a sensor, working in the 0 ... 15 psi absolute pressure interval, with a maximum of 2.0 %FSS total error band.

The station's controller is performing the PM2.5 measurements and transducer calibration, at programmed time intervals, also measuring the airflow and controlling the pump's driver duty cycle for acquiring a programmed airflow of 2.0 L/min (fig. 1). A calibration is performed no earlier than every five minutes, while a PM2.5 measurement is performed no earlier than every minute. The controller is also performing the pressure, temperature and humidity measurements and is controlling the station's heating, venting and drying subsystems. The controller takes date and time information from the GSM network or, when the GSM network is not available, from the station's real-time clock, which is periodically updated.

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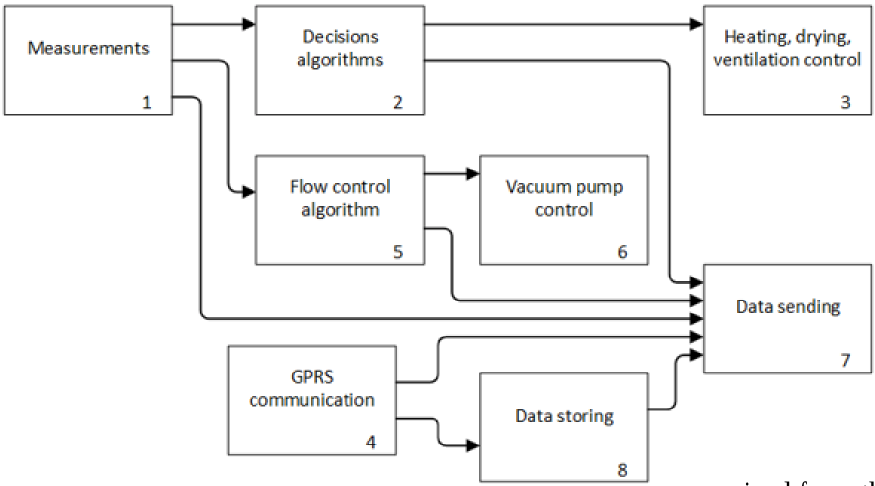

Fig. 1. ROkidAIR PM2.5 monitoring station's controller main functions

Measurement data and information about station's state are sent through a GPRS connection to the network's Web server. If the GPRS connection or the Web server are not available, data is stored locally for a later transmission.

ROkidAIR Web services

The ROkidAIR network's Web server is hosting a group of Web services, developed in the LabVIEW graphical programming language (National Instruments, Austin, TX, USA), for receiving the station's data and for answering to users' queries.

The **RKA_WS** Web Service (fig. 2) is receiving the stations' data and is storing it in data files, resulting one file for each day. If the operation is successful, the sending station is receiving a *RKAOK* message from the Web Service. In extremely rare cases, if the date and time data received from the station is malformed or if the server's file system is corrupted, the station is receiving a *FileERR* message.

The Data Web Service (fig. 3) is responsible for receiving the users' requests for data. The user request has the following format:

http://IP:port/WSname/Data?Data=SSYYMMDDHHmm

where:

- **IP** is the ROkidAIR Web server's IP;
- **port** is the port on which the Web server is listening for data and queries;
- **WSname** is the Web server's name;
- **SS** is the station's index;
- **YY, MM, DD, HH** and mm are the year, month, day, hour and minute as specified by the station's real-time clock.

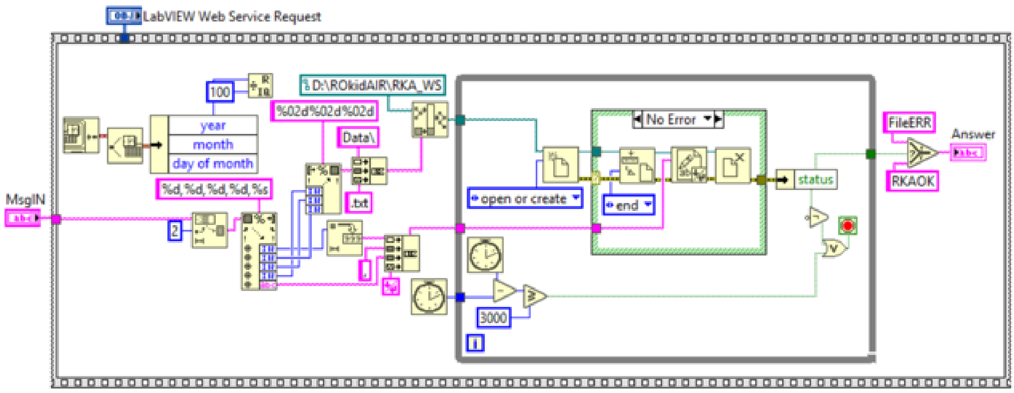

Fig. 2. RKA_WS Web Service's diagram programmed in LabVIEW™

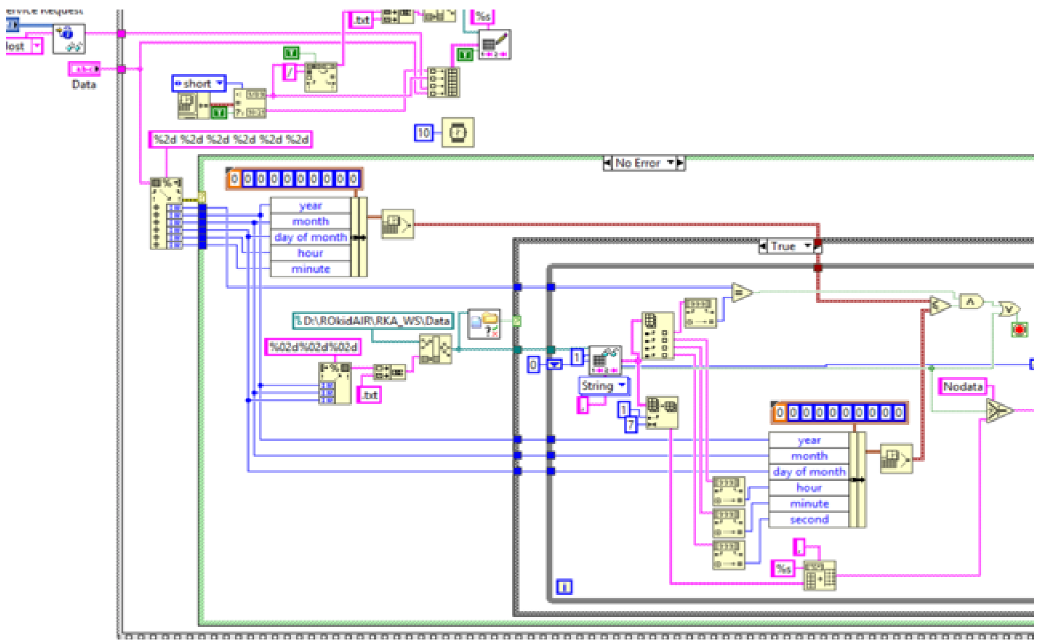

Fig. 3. Data Web Service's diagram programmed in LabVIEW™

The users' requests for data are logged into daily files, which include the information about the remote host from where the request was made.

If the user's request can be fulfilled, the Data Web service is returning an answer having the next format:

Answer = HH,mm,ss,CC,TT,HH,pp

where:

- **HH**, mm and ss are the hour, minute and second values of the registered record;
- **CC** is the measured PM2.5 value, in μg/m^3;
- **TT, HH** and **pp** are the measured external temperature, relative humidity and barometric absolute pressure, in °C, % rH and mmHg.

If the request's date information is malformed or if there is no datafile for the specified date value, then the Data Web service is returning a Nofile message. If the datafile exists but there is no data for the specified station's index, hour and minute data, then the Web service is returning a **Nodata** message.

Some other Web services are available on the ROkidAIR Web server for answering the requests about stations' internal parameters (internal temperature and humidity; actual flow through the airflow sensor; pump's drive duty cycle for obtaining the specified flow; heating, venting and drying subsystems states) or for daily sending all the registered data through email. Because the station's real-time clock may encounter some data loss on long time intervals, a separate application is checking for the continuity of the time information in each daily datafile.

Measured operating parameters of ROkidAIR stations

Four of the eight ROkidAIR stations (table 1) were deployed for complex functioning tests and inter-comparisons starting with November 2016 in the cities of Bucharest and Targoviste.

Data send by the stations were recorded during November 23[rd] and December 15[th], 2016. Dividing the number of datasets sent by a station during a time interval by the length of that time interval, in minutes, the following use rates from table 2 were obtained for three of the stations.

The variation of the time interval between two successive data sets, for station 4, is shown in figure 4, with details in figure 5. These results are mainly because a station is performing a calibration after each group of four measurements.

Table 1

THE TEMPORARY LOCATIONS OF ROkidAIR STATIONS FOR FUNCTIONING/RELIABILITY TESTS

Station IDs	Date and time of deployment	Location	GPS coordinates
3	18.11.2016, 16:34	Bucharest	44°26'38.0"N, 26°03'13.5"E; 44.443875, 26.053746
2	21.11.2016, 13:30	Târgoviște	44°56'36.3"N, 25°27'10.6"E; 44.943417, 25.452937
4	22.11.2016, 14:18	Bucharest	44°26'38.0"N, 26°03'13.5"E; 44.443875, 26.053746
5	22.12.2016, 15:46	Bucharest	44°26'30.8"N, 26°03'00.0"E; 44.441898, 26.050003

Table 2

USE RATES OF THE ROkidAIR STATIONS

Station ID	2	3	4
Use rate	0.779	0.777	0.775

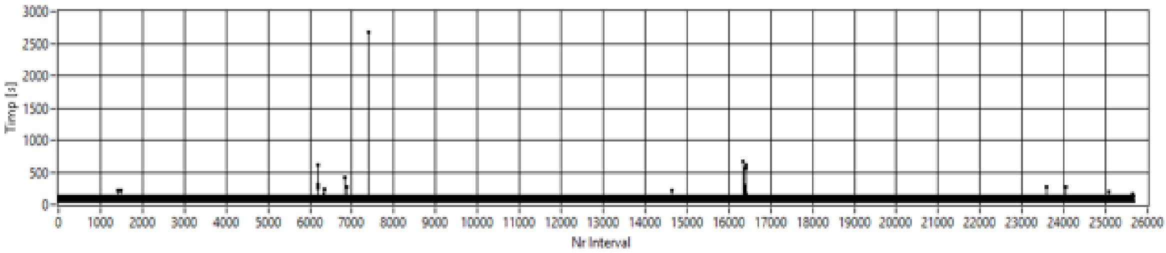

Fig. 4. Time interval between two successive data sets, for station 4

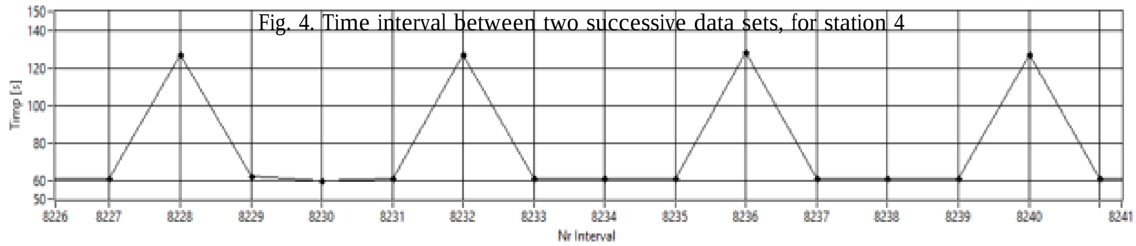

Fig. 5. Detailed time interval between two successive data sets for station 4

Table 3

MEAN TIME INTERVALS

Station ID	2	3	4
Mean time interval [s]	76.64	75.85	77.17

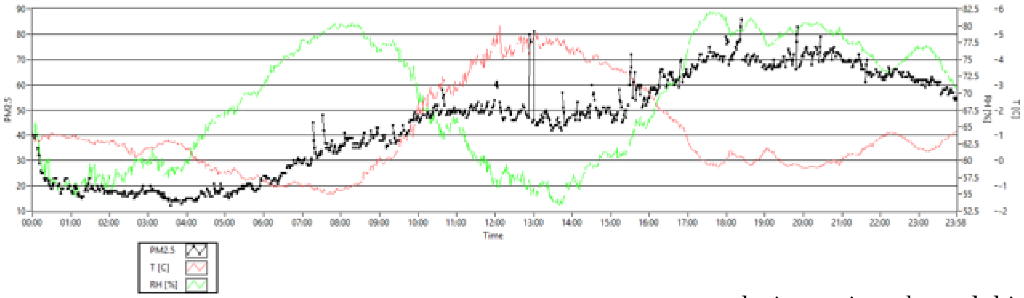

Fig. 6. Data received from station 4 on December 8th, 2016 – PM2.5 (μg m^{-3}), temperature (°C), rH (%)

Table 3 presents the mean values by averaging only for the time intervals smaller than 180 s.

An example of collected data from PM2.5 stations is shown in figure 6.

The stations' software was configured to maintain the internal temperature between 10 and 15°C. Thus, the internal heating subsystem starts when the internal temperature is less than 12°C and stops when it succeeded to rise the internal temperature to 15°C.

Looking at a station's internal parameters' values (fig. 7), it can be seen that the heating subsystem, running continuously, succeeded to keep the internal temperature above 10°C when the external temperature went down from 1°C at midnight to -1°C at 8:00 a.m. When the external temperature started to rise during the day up to 5°C, the heating subsystem worked intermittently and the internal temperature oscillated between 12 and 15°C.

By computing the heating speed [°C/min] as the internal temperature difference between two moments when the heating subsystem is working (fig.8), it can be easily observed that the station's internal temperature is strongly dependent on the external temperature. One preliminary conclusion could be that the heating speed is almost zero when the external temperature is decreasing and starts growing when the external temperature is increasing. In addition, it can be estimated that the heating speed remains significant only when the heating subsystem works intermittently, and this is happening as long as the external temperature is above 4°C.

The average heating speed values were 0.07°C/min for station 2, 0.24°C/min for station 3 and 0.13°C/min for station 4. The low value obtained for station 2 is confirming the fact that it was placed in more severe thermal conditions (the average external temperature for station 2 in Targoviste was -1.27°C, while for stations 3 and 4 in Bucharest was 0.88°C and 1.22°C respectively).

The stations' heating subsystems are using heating elements made in a thick film technology, on stainless steel substrates, with a rated power of around 40 W. There are two types of heat sinks, which were used for the stations' heating subsystems. Station 3 is using a Citizen KU-KK5007 heat sink, made from AlMg3 alloy, 50 x 50 x 27 mm, 5 mm base thickness, while stations 2 and 4 are using Fischer ICKS heat sinks, made from aluminum, 50 ´ 50 x 25 mm, 3.5 mm base thickness. Even if initially it was believed that the larger Fischer heat sinks will be more effective because it looks that they were staying cooler so the heat it was faster dissipated in the station's enclosure, station 3's smaller heat sink recorded a heating speed average almost double than the one recorded at station 4. In addition, the maximum value of the heating speed was slightly bigger for station 3, i.e., 2.2°C/min compared with 1.6°C/min for station 2 (due to a colder environment) and 2.0°C/min for station 4.

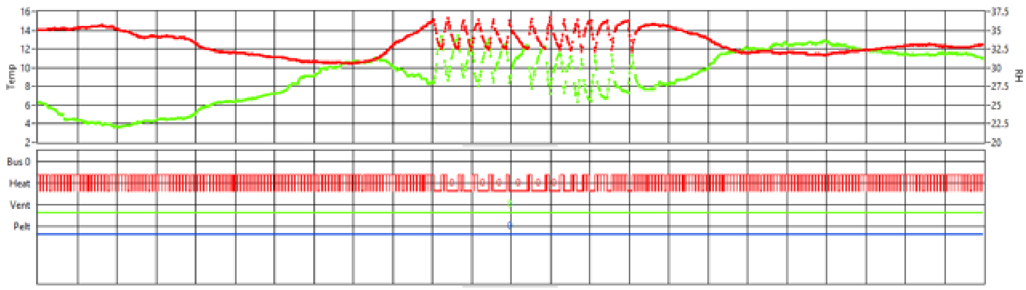

Fig. 7. Internal parameters of Station 4 on December 8th, 2016

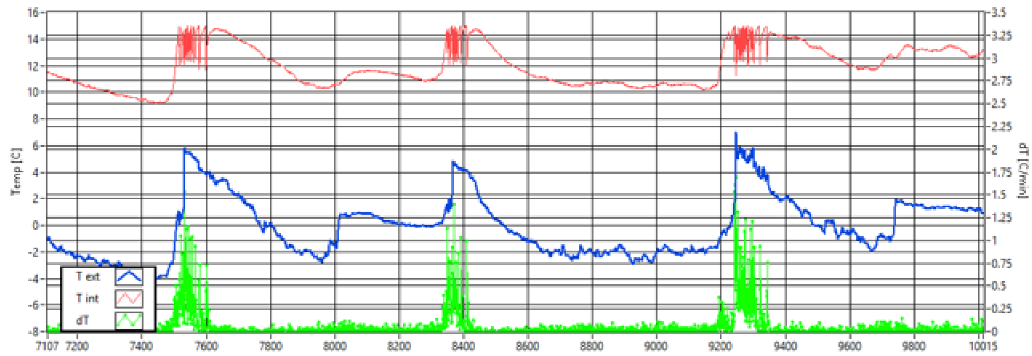

Fig. 8. Heating speed variation for station 4

Table 4
AVERAGE AND MAXIMUM COOLING SPEEDS

Station ID	2	3	4
Average cooling speed [°C/min]	-0.28	-0.46	-0.29
Maximum cooling speed [°C/min]	-1.6	-2.0	-1.5

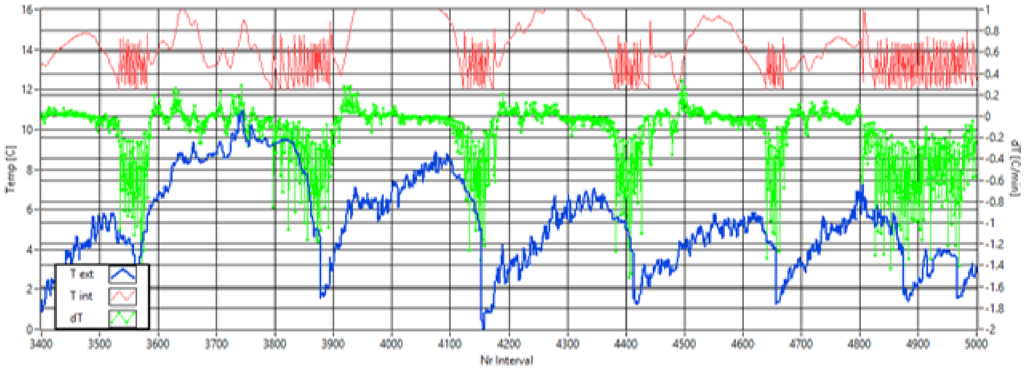

Fig. 9. Cooling speed variation for station 4

Table 5
AIRFLOWS STATISTICAL PARAMETERS

Station ID	2	3	4
Airflow mean value [l/min]	2.052	2.048	2.050
Airflow standard deviation [l/min]	0.028	0.022	0.024
Airflow min/max [l/min]	1.89 / 2.95	2.02 / 2.15	2.02 / 2.33

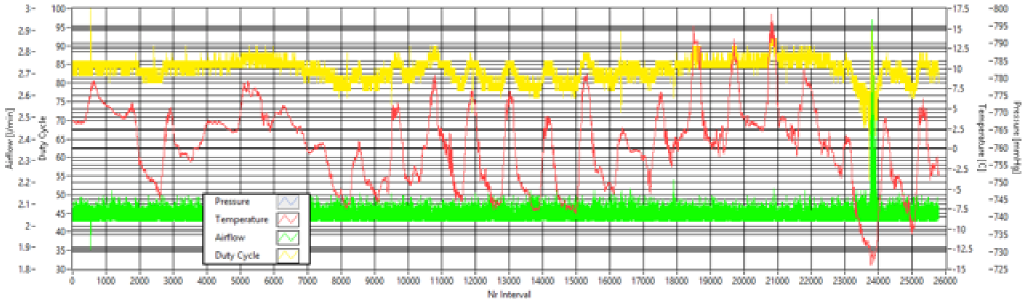

Fig. 10. Airflow and duty cycle variations for station 2

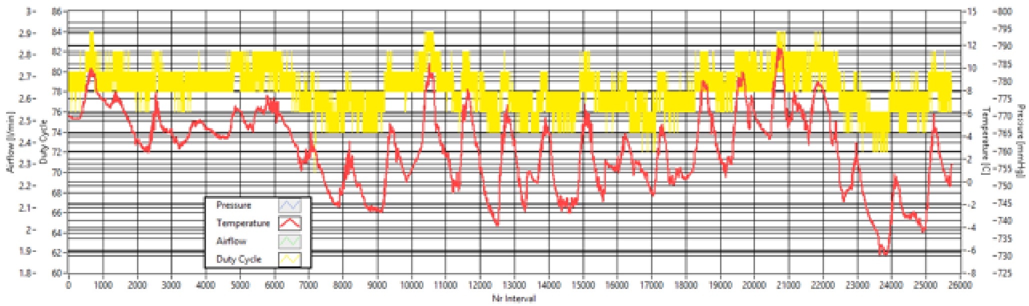

Fig. 11. Temperature and duty cycle variations for station 4

The cooling speed variation is obviously dependent on the external temperature (fig. 9). Comparing the average and the maximum cooling speeds (table 4), it seems that the effect of the heat sink model can also be observed, station 3 having greater cooling speed values.

All the three stations succeeded to keep the controlled airflow close to the reference value of 2 l/min (table 5). Extremely high maximum value of the station 2's airflow was recorded when also a very low external temperature was occurring (figure 10), even if this decrease in temperature was accompanied by a decrease of the pump's duty cycle at the reference airflow.

For all the three stations, a strong correlation between the external temperature and the pump's duty cycle when reaching the reference airflow can be observed (fig. 11). The meaning of this correlation is that the higher the temperature, the greater has to be the pump's speed for reaching the reference airflow of 2 L/min. A difference of 10 duty cycle units for a 12 °C gradient can lead to an estimation of a needed 110 ... 120 duty cycle units for a 40 °C temperature, which means that the risk for forcing the pump at increased summer temperatures is low.

Gravimetric reference sampler results

On November 22nd, 2016, at 2:45 p.m., a Leckel GmbH SEQ47/50 reference gravimetric sampler [7] was deployed in Bucharest (fig.12a), for inter-comparison purposes, in the same location with the ROkidAIR stations 3 and 4.

First 14 filters cylinder was installed in the reference sampler on November 22nd. The filters cylinders were replaced on December 5th at 16:32 and on December 20th at 11:26. Sampler's impaction plate was checked weekly. The amount of dust on the impaction plate after six days (fig. 12b) was significant, mainly due to the ongoing construction work close to the area where the sampler and the two stations were deployed, and it looked maintaining the same deposition rate also when the plate was checked on December 5th (fig. 12c).

While checking the sampler on December 20th (fig. 12d) and on December 27th (fig. 12e), it was indicating a zero flow and data from which it could be concluded that the sampler stopped for certain periods of time. This behavior could be due to high values of air relative humidity (up to 90%) and dust concentration (up to 280µg/m^3), which are leading to filter clogging, case when the sampler is stopping and waiting until the end of the 24 h period of normal sampling time and then starting with a new filter.

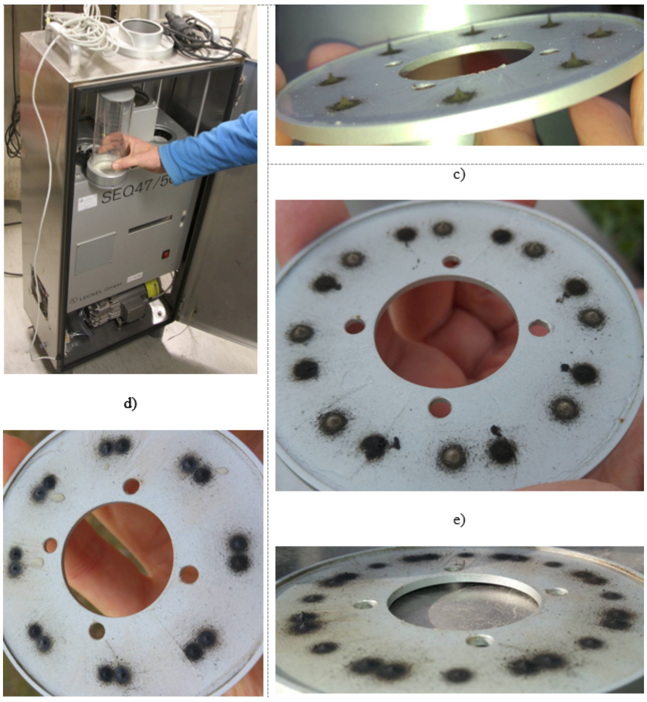

Fig. 12. Dust gathered on the impaction plate of the Leckel GmbH SEQ47/50 reference gravimetric sampler (a); after six days, on November 28th (b); after 13 days, on December 5th (older traces are black and distorted) (c); impaction plate on December 20th (older traces are darker) (d); impaction plate on December 27th (e)

Conclusions

A first initial conclusion was that the 23 days interval, during which data were received from the stations, was long enough for drawing a first set of conclusions.

A closer approach into the stations' software will hopefully allow a reduction in the mean time interval between two successive data sets, reducing it to a desired value of 60 s. Tests will have to be performed on the rotary vane pumps to determine if a four minutes' continuous run between two calibrations will be possible without heating the pumps, thus allowing the mean time interval to depend only on the speed of the data reading from the PM2.5 sensor.

Improvements on the stations' software will be applied for a better local data management and for allowing to remotely changing some stations functional parameters. Additional Web services will be developed and installed on the Web server, allowing, for example, requests for receiving complete daily data sets. The number of running stations is expected to increase, together with the time interval for which data is going to be available, so the data volume that will be processed will require automated predictive maintenance procedures to be considered. Parameters like the mean time interval, heating speed, airflow standard deviation or extreme values and duty cycle variation will be used for estimating the stations' behaviour.

A dynamically setting of the internal temperature interval according to the external temperature will be considered, thus obtaining an easier workload for the heating system during extremely cold weather conditions. Improving the station thermal isolation and increasing the power of the heating subsystem will be also evaluated. Extreme airflow values, like those presented in figure 10, will be further investigated. An automated station's emergency shut down, with a prior message sent to the server, will be implemented.

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