



## Cotonou's next breath: Particulate matter monitoring and capturing



Basile Kounouhewa<sup>a</sup>, Gabin Koto N'Gobi<sup>a</sup>, Hervé Houngue<sup>a</sup>, Lothar Müller<sup>b</sup>, Michael Wirtz<sup>c</sup>, Selçuk Yurtsever-Kneer<sup>d</sup>, Helga Fink<sup>e</sup>, Aron Kneer<sup>f</sup>, Stéphan Barbe<sup>b,\*</sup>

<sup>a</sup> Université d'Abomey-Calavi, Faculté des Sciences et Techniques, Département de Physique, Laboratoire de Physique du Rayonnement (LPR), Abomey-Calavi Benin

<sup>b</sup> Technische Hochschule Köln, Fakultät für Angewandte Naturwissenschaften, Leverkusen Germany

<sup>c</sup> TinniT Technologies GmbH, Karlsruhe Germany

<sup>d</sup> Gesellschaft zur Förderung der erneuerbaren Energien e. V., Karlsruhe Germany

<sup>e</sup> Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ), Cotonou Benin

<sup>f</sup> Hochschule Karlsruhe, Institut für Digitale Materialforschung, Karlsruhe Germany

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### ABSTRACT

Air pollution due to high concentrations of small particles is a severe issue in West Africa. In this regard, the international scientific team of the DACCIWA project (Dynamics-Aerosol-Chemistry-Cloud-Interactions In West Africa) recently published the policy relevant findings of this action and clearly claimed the need for long-term and reliable measurements of meteorological data and particulate matter concentrations in South West Africa. This short communication describes the progress achieved in the frame of Beninese-German scientific mission. An experimental setup for the long-term and continuous monitoring of meteorological data and particulate matter pollution was developed and installed in Cotonou (Benin). In addition, two pilot scale particle separators (each 2 m × 2 m) was developed, constructed and taken in to operation. The measured particulate matter concentrations clearly exceed the limits set by the World Health Organization and the European Union.

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### Introduction

The policy relevant findings of the DACCIWA project (Dynamics-Aerosol-Chemistry-Cloud-Interactions In West Africa), an international research action funded by the European Union 7th Framework Programme, were recently published [1]. The main objective of this project was to investigate the relationship between the composition of the atmosphere in South West Africa and aerosol emissions from anthropogenic and natural sources. For this purpose, a large amount of data related to the chemical composition and the physical state of the atmospheric layer over southern West Africa (first 2,000 km above earth

\* Corresponding author.

E-mail address: [stephan.barbe@th-koeln.de](mailto:stephan.barbe@th-koeln.de) (S. Barbe).

surface), were extensively collected from 2014 to 2018. These data were then used to validate, challenge and further develop computer models for accurate forecast. In a press release [2], Professor Knippertz of KIT's Institute of Meteorology and Climate Research (Karlsruhe, Germany) and coordinator of the DACCIWA project mentioned that "The air over the coastal region of West Africa is a unique mixture of various trace gasses, liquids, and particles". Air composition strongly depends on the location but the unique character of this complex air composition relies on the simultaneous presence of sea salt, mineral dust (sand), organic particles, hydrocarbons, oxides of nitrogen and sulfur which may strongly impact cloud formation, weather and climate. This unusual composition results from complex geophysical fluid dynamics (transport of pollution by atmospheric flows), a complicated chemistry and the existence of natural and anthropogenic emission sources.

The Sahara, the world largest source of mineral dust, winds particles from the north and monsoons transport sea salt from the south [2,3]. The West African monsoon system makes the dynamics of atmospheric flows particularly complex and negatively affects the predictability of weather events and climate change in the sub-Saharan area. In this paper, anthropogenic emissions refer to the release of particulate matter and volatile organic compounds due to wood, charcoal and open trash burning, charcoal making and traffic (trucks, cars, buses and two-wheeled vehicles) as described by S. Keita et al. [4]. With an annual population growth rate of 2.75% (Earth Resources Observation and Science (EROS) Center), West Africa is the fastest growing region of the world and strong urbanization has been extensively reported for this part of the world [5-7]. These demographic phenomena have led to a considerable increase of anthropogenic emissions and air pollution especially in large urban areas located on the coastline on the Gulf of Guinea like Abidjan in Côte d'Ivoire, Lomé in Togo and Cotonou in Benin [8].

It is common practice to classify particulate matter into PM classes by means of an aerodynamic diameter  $< 10 \mu\text{m}$  ( $\text{PM}_{10}$ ),  $< 4 \mu\text{m}$  ( $\text{PM}_4$ ),  $< 2.5 \mu\text{m}$  ( $\text{PM}_{2.5}$ ), and  $< 1 \mu\text{m}$  ( $\text{PM}_1$ ). The coarse fraction of  $\text{PM}_{10}$  (aerodynamic diameters between 2.5 and  $10 \mu\text{m}$ ) mainly consists of mineral particles and salt crystals.  $\text{PM}_{2.5}$  and  $\text{PM}_1$  mostly result from anthropogenic activities (e.g. metal fumes, coal dust, coal fly ash, motor exhaust) and usually include metals, hydrocarbons, and secondary particles resulting from chemical reactions with gaseous compounds in the atmosphere [9,10]. There is apparent scientific evidence for the penetration of  $\text{PM}_{2.5}$  and  $\text{PM}_1$  into the lung alveoli where 50% of these particles may remain in the lung tissue [11-13]. A major and alarming key finding of the DACCIWA project is the high concentration of small particles ( $\text{PM}_{2.5}$ ) measured in the air layer over South West Africa which exceeds World Health Organization limits (WHO - annual mean for  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  are  $10 \mu\text{g}/\text{m}^3$  and  $20 \mu\text{g}/\text{m}^3$  respectively) [1]. The results confirm the severe air pollution and high dust particle concentration in Cotonou and Abidjan. Furthermore, inhalation exposure to  $\text{PM}_{2.5}$  and  $\text{PM}_1$  was associated to the reduction of lung function parameters [14-16] which may increase pulmonary and cardiovascular morbidity and mortality. Consequently, the high  $\text{PM}_{2.5}$  concentrations measured by the scientists involved in the DACCIWA project in South West Africa substantially increases the probability of health problems related to pulmonary and cardiovascular dysfunctions in this region. With respect to the African continent and the year 2012, the WHO estimated that 72% of outdoor air pollution-related premature deaths were due to ischaemic heart disease and strokes, while 14% of deaths were due to chronic obstructive pulmonary disease or acute lower respiratory infections, and 14% of deaths were due to lung cancer.

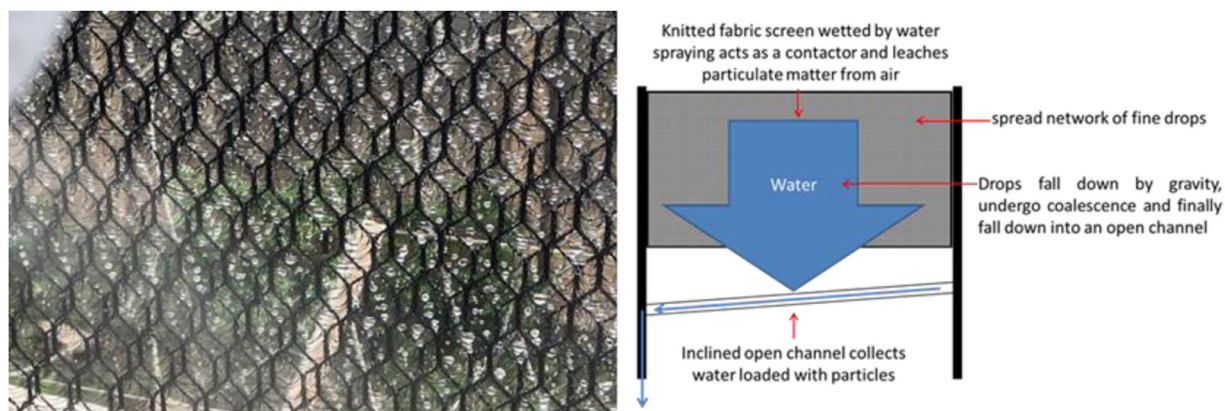
This pollution also impacts on weather and climate by contributing to the aerosol burden which is already very high in South West Africa reducing the amount of sunlight reaching the surface of the Earth and impacting on the formation, the composition, the structure and the breakdown of clouds [1]. Low-income countries like the nations from the sub-Saharan area are known to be particularly vulnerable to rising temperatures and climate change due to the accumulation of greenhouse gas in the atmosphere [17]. Climate change is already visible in the sub-Saharan area [18,19]. According to the DACCIWA scientists, understanding of the West African monsoon system is a crucial step for improving weather forecast. They urge policy makers to improve emission inventories and observations by supporting long-term measurements of air pollutants especially in urban and suburban areas [1]. There is a severe lack of reliable and accessible meteorological data in South West Africa which are essential for the development of accurate computer models. These numerical approaches offer a precious assistance to scientists involved in climate scenario development for South West Africa. DACCIWA experts clearly claimed the urgent need to support African National Weather Services in their effort to monitor weather and climate. This short communication describes the first attempt of the authors to address the issues and challenges indicated by the scientific team of the DACCIWA project. For this purpose, a state of the art weather station and an environmental aerosol monitoring system have been installed in Cotonou for the long-term measurement and collection of reliable and accessible data (meteorological data and small particle concentrations -  $\text{PM}_{10}$ ,  $\text{PM}_4$ ,  $\text{PM}_{2.5}$  and  $\text{PM}_1$ ). This step as well as data accessibility aim to sensitize the public and political decision maker about this urgent human issue. Furthermore, the assessment particle removal from air by means of wetted knitted fabrics was prepared in this work.

## Weather station, environmental aerosol monitor and data management

With a population of approx. 11.5 million (World Bank, 2018), Benin shares borders with Nigeria, Togo, Burkina Faso and Niger. The country has a 121 km-long coastline on the Gulf of Guinea and the resulting port activity strongly contributes to Benin's economy. Cotonou has a population of approx. 679,000 (United Nations, 2013) and is Benin's largest city. The town is located on the coastline and regarded as the economic center of the country. The energy self-sufficient monitoring equipment (Fig. 1) was installed in Cotonou (6.35 N 2.41 E) and mainly consists of an aerosol monitor, a weather station, a data logger and a photovoltaic power station. In order to estimate the impact of anthropogenic emissions and their interactions with natural sources, it is common practice to monitor air pollution at different types of sites (e.g. traffic site, quiet zones,



**Fig. 1.** Left - photograph of the assembled monitoring equipment before it has been shipped from Karlsruhe (Germany) to Cotonou (Benin). Right - Photograph of the monitoring equipment positioned at the top of a Pylon over the Boulevard de la Marina in Cotonou)

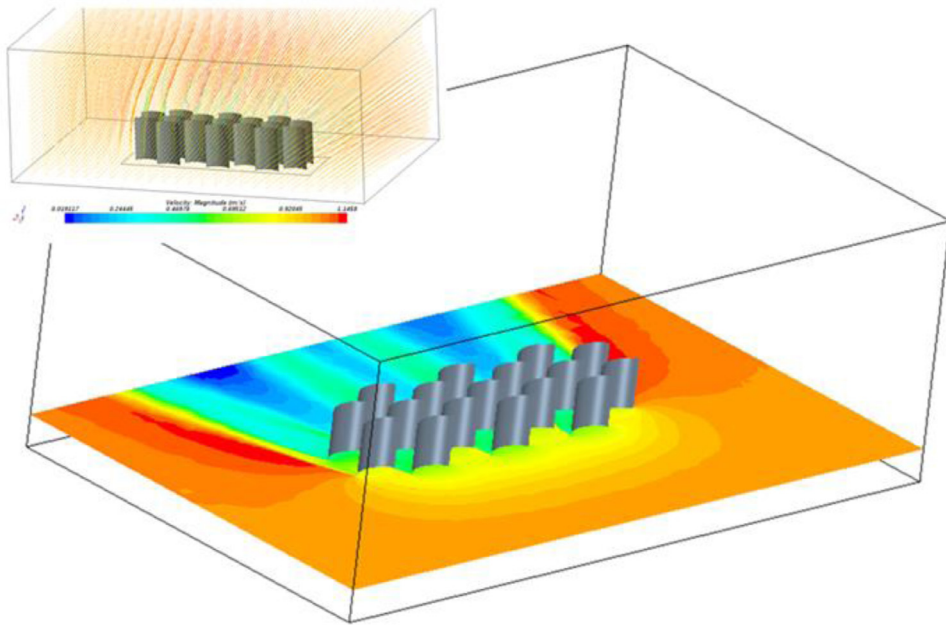


**Fig. 2.** Left - formation an evenly spread network of fine water drops on the surface of the knitted fabric used in this work. Right - The separator developed in this work consists of a frame, an inclined open channel and a knitted fabric screen (Essede 3 Dea, Germany).

waste burning site, domestic fires site). The selected site is located in the port area and is a traffic site representative of anthropogenic emissions (cars, trucks and two stroke motorcycles). The instrumentation was positioned on top of a pylon at 4 m height above the Boulevard de la Marina, a major road in Cotonou. Intense social life is observed along the Boulevard de la Marina and related data may be very useful to estimate inhalation exposure to  $PM_{2.5}$  and  $PM_{1}$ .

The monitoring equipment continuously measures the following data:

- Air temperature ( $\pm 0.2$  °C), relative humidity ( $\pm 2\%$  RH) and absolute pressure ( $\pm 0.4$  hPa)
- Wind speed ( $\pm 0.3$  m/s) and direction ( $\pm 2$  °)
- Rainfall ( $\pm 5\%$ )
- Total radiation ( $\pm 2\%$ )
- $PM_{10}$ ,  $PM_4$ ,  $PM_{2.5}$  and  $PM_1$  ( $\pm 0.1\%$  of reading or  $0.001$  mg/m<sup>3</sup>)



**Fig. 3.** CFD simulation of polluted air flowing through a field particle separator field (CFD = Computational Fluid Dynamics).

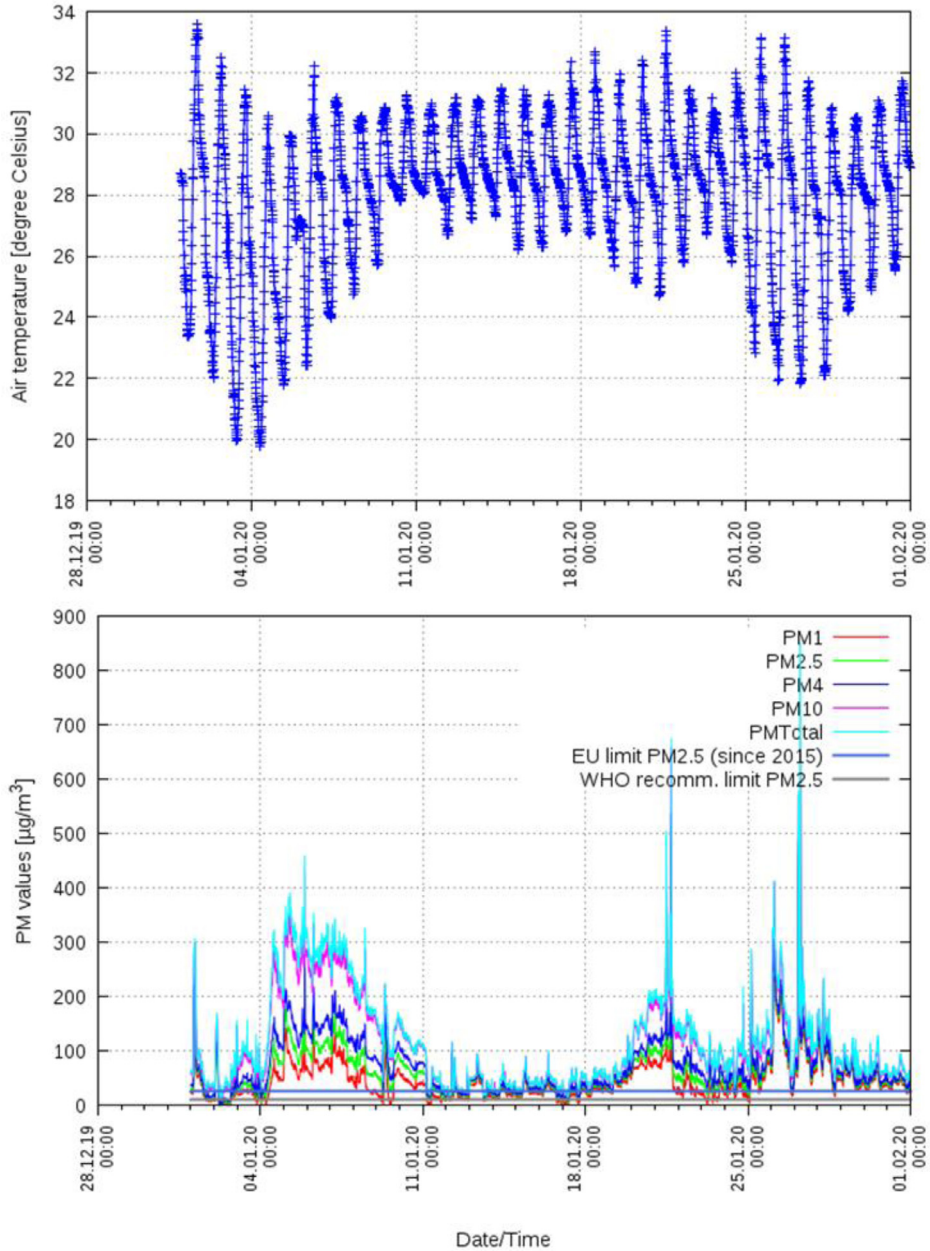


**Fig. 4.** Four separator units have been constructed and two stacks of 2 m height and 2 m width (each one consisting of two units) have been installed nearby the monitoring equipment on the roof a building located from the German Embassy in Cotonou.

Relative humidity values are calculated from measured temperature and dew-point temperature values. The pyranometer (SKS 1110, Driesen + Kern GmbH, Germany) used for radiation measurements includes a cosine correcting head and silicon photoelectric cell. The aerosol monitor (Environmental DustTrak DRX, Model 8543, TSI, Germany) is a continuous, real-time light-scattering laser photometer that simultaneously measures size-segregated mass fraction concentrations corresponding to PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>. It is housed inside a rated environmental enclosure (Environmental Enclosure 854,030, TSI, Germany). The sensors are connected to a data logger (DK 8040, Driesen Kern GmbH, Germany) equipped with SD card drive (local data storage) and a GPRS modem for wireless data transfer to a FTP server located in Karlsruhe. The temporal resolution of data recording is 15 min. A photovoltaic power supply consisting of a 12 V battery (36 h autonomy), a 12 V charge controller (Sun Saver – 20 L, Morningstar Corporation, USA) and two solar panels (2 × 90 W, 180 W in total), makes the monitoring equipment energy self-sufficient. Excess power is used to charge the battery which overtakes power supply at night or by cloudy days.

#### **Particle separator prototype: design and construction**

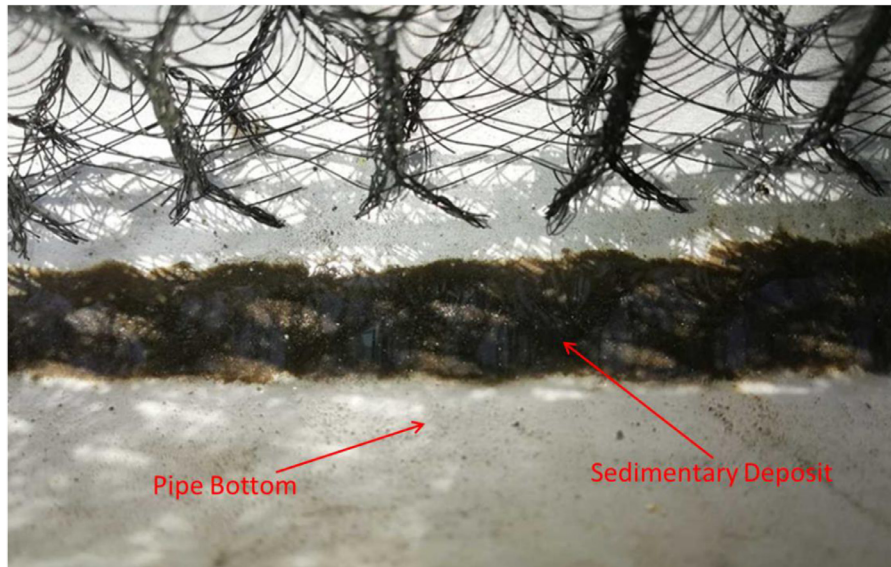
Since inhalation exposure to PM<sub>2.5</sub> and PM<sub>1</sub> presents a considerable risk for inhabitants and especially for children, both emission reduction and efficient large scale dust separation are urgent necessities in South West Africa. Concepts for dust separators - also referred to as “dust catchers” - to capture PM<sub>2.5</sub> from air have been mostly developed for the treatment of indoor air [20,21]. These systems require electricity, air transport by forced convection and high maintenance. In South



**Fig. 5.** Air temperatures and particulate matter concentrations measured at the sample site with the described monitoring equipment in Cotonou during January 2020.

West Africa, life mostly takes place on the street and typical houses do not have windows but holes covered by grills to take sunlight. One of the objectives of this work was to develop and install a low cost, modular pilot scale dust separator for the efficient reduction of aerosol concentration in public places (e.g. markets, schools, universities, hospitals) by contacting outdoor air with wetted knitted fabrics. The proposed Technology should be regarded as an immediate solution for the acute high air pollution in South West Africa. The separation units are intended to be used for enhancing the air quality in public places with high human density with a particular focus on protecting children from air pollution.

In the last decade, knitted fabrics steadily gained attention in the field of environmental engineering with application ranging from fog catcher to bionic approaches for heat production and storage [22,23]. The key concept of the proposed dust separator relies on removing particles from polluted air by efficient wetting. The separator (Fig. 2, right) consists of a frame, an inclined open channel and a knitted fabric screen (Essedea 3 Dea, Germany) that builds up an evenly spread network of fine water drops when wetted by water spraying (Fig. 2, left). Polluted air transported by wind, flows through



**Fig. 6.** After three days of operation, a black sedimentary deposit was observed on the bottom of the guiding pipe confirming the removal of particulate matter from the air.

the textile where particulate matter is separated from the air at the liquid-gas interface. For this purpose, nozzles spray water on the surface of the knitted fabrics (Fig. 4). Water drops move down by gravity and undergo coalescence before reaching the bottom of the knitted fabric screen. They finally fall down in the open channel and the collected water is directed through the foot of the separator to a tank as shown on Fig. 2 (right).

The separators are modular units that can be stacked (up to a height of 6 m, Fig. 4). A certain height is required for the supply of clean air to large areas. Prior to construction, the geometry of the separator was developed and optimized at TinniT Technologies GmbH (Karlsruhe, Germany) by means of Computational Fluid Dynamics (CFD) in order to achieve high efficient particle separation. In real applications, large scale particle separation can be implemented as a field of separator shields (each shield consisting of a stack of five separator units) leading to successive leaching of particulate matter.

The distribution of the shields is critical and has to be simulated by CFD (Fig. 3). Since experiments with nanoparticles require particular infrastructures in order to avoid inhalation by the scientific staff. The authors decided to perform CFD simulations to optimize the geometry of the separator by considering both the wind direction and the permeability of the knitted fabrics. Subsequently, four separator units have been constructed and two stacks of 2 m height and 2 m width (each one consisting of two units) have been installed nearby the monitoring equipment on the roof a building located in the residence of the German ambassador in Cotonou (Fig. 4). Maximal height of construction above ground level was approx. 4.20 m and wind direction perpendicular to the separator was 90° (west wind).

## First results

After installation and precise positioning, the monitoring equipment was taken into operation. All sensors work and data are properly transferred to the FTP-server located in Karlsruhe. In the current validation phase, data are available for the scientists from the University of Abomey-Calavi (Benin), the Technical University of Cologne and the Karlsruhe University of Applied Sciences who start to develop methods for the interpretation of these results. Fig. 5 shows the air temperature and PM values measured during January 2020. Overall, particle concentrations of all classes ( $PM_{Total}$ ,  $PM_{10}$ ,  $PM_4$ ,  $PM_{2.5}$  and  $PM_1$ ) are very high in the air sampled at the selected site. These measurements clearly confirm the concentrations reported in the frame of the DACCWA project. The WHO limits for annual mean values are 10  $\mu\text{g}/\text{m}^3$  and 20  $\mu\text{g}/\text{m}^3$  for  $PM_{2.5}$  and  $PM_{10}$  respectively. Furthermore, the limits for 24h-mean values are 25  $\mu\text{g}/\text{m}^3$  and 50  $\mu\text{g}/\text{m}^3$  for  $PM_{2.5}$  and  $PM_{10}$  respectively. The concentrations presented in this work are higher than these recommendations with peaks above 100  $\mu\text{g}/\text{m}^3$ . The values also often exceed the legally binding limit value of the EU Clean Air Policy Package for  $PM_{2.5}$  from January 2015 (25  $\mu\text{g}/\text{m}^3$ ) and are in good agreement with the concentrations measured by Djossou et al. in traffic areas in Abidjan and Cotonou [24]. Furthermore, the data suggest a relationship between air temperature fluctuations and an increase in particulate matter concentration. In this regard, stronger fluctuations seem to correlate with higher PM values. The affirmation needs to be proved and a statistical analysis will be useful to prove that point and also data from a longer period of time. The particle separator was successfully taken into operation, the formation of homogeneous network of water drops was observed in the upper part of the knitter fabric screen. Drops move down and transport a high amount of particulate matter to the open channel. After three days of operation, a black sedimentary deposit was observed on the bottom of the guiding pipe

confirming the removal of particulate matter from the air [Fig. 6]. The scientists from the University of Abomey–Calavi will start the experiments to characterize the system and aim to correlate the separation performance with the data obtained from the monitoring system.

## Conclusion

The progress achieved during this Beninese–German scientific mission is a pioneering step and the authors deeply hope that it will encourage other groups, association but also politicians to follow up and replicate this approach in other places in Benin and in other countries from South Africa. At the end of the validation phase, data will be made available for international scientists and African National Weather Services. The urgency of the situation has been confirmed by the first data measured in January 2020 and international reaction is needed to address this human issue. Furthermore, the developed particle separator seems to work well for the cleaning of outdoor air and the results from the characterization phase will be decisive for the upscaling of the system and public health in Benin. A scientific team from the Université d'Abomey-Calavi will investigate the performance of the separators.

In this regard, effluent water from the separator will be collected and quantified. The corresponding solid matter concentration will be measured and related to the particle matter load. Considering a serial production, the authors estimate the manufacturing costs for one air separator unit between 600 and 800 €.

## Declaration of Competing Interest

The authors declare that they have no conflict of interest.

## Acknowledgement

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