Tampere University of Applied Sciences

Drone in Particulate Matter Measurement

Particles behavior under the influence of the propellers of a drone

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ABSTRACT

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Particulate matter is fine solid particle or liquid droplets found in the air that is not visible to the bare eye. It is widely known to have a serious effect on both human health and the environment. Thus, air quality monitoring is necessary for studying and understanding of particles sources, behavior and concentration in order to minimise the impacts. Recently, Unmanned Aerial Vehicles (UAVs) has risen as a new method that is believed to overcome a variety of limitations that current methods hold Among other things, it makes it easy to access any complex area, is convenient in collecting data of vertical atmosphere, is simple to handle and is available at low-cost. However, there are still some issues in using UAV in aerosols measurement that need to be experimented and studied further.

The aim of the research is experiment and analysis on performance, practicality as well as obstacles of applying a drone in measuring air quality and concentration of fine dust specifically in impact of propellers on PM concentration results. In addition, the study also focuses on distribution of air-borne particles at different altitudes and behaviour of different size particles under impacts of wind. The experiment was done using 2 particulate meters: Trotec PC220 and DustTrak under impact of flying drone Phantom 4 PRO. Trotec is hung above drone while DustTrak is placed 2.3 m away to study the propeller's impacts at different distance. The results are collected in indoor environment and it shows significant impacts of propellers on PM concentration in surrounding environment even when the sensor is placed 2.3 m away. The wind speed is lower and lower as it goes further away above the drone and PM concentration also decrease proportionally. However, further study in different environments such as outdoor, industrial site with more constant ambient concentration is needed for deeper understand on mechanism of the impact of the propeller.

Key words: drone, propellers, particulate matter.

CONTENTS

ABBREVIATIONS AND TERMS

AQG	Air Quality Guideline
NASA	National Aeronautics and Space Administration
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
UAVs	Unmanned Aerial Vehicles
TAMK	Tampere University of Applied Sciences
WHO	World Health Organization

1 INTRODUCTION

According to World Health Organization, around 7 million deaths are caused by air pollution around the globe and one out of every nine deaths is linked to poor air quality. Air pollution affects all people at all ages, socioeconomic groups and all different geographic regions through a simple but dispensable action as breathing. However, the severe level might be different by locations due to disparate pollutants emission in each city or countries. For instant, pollutants concentration has been observed to be remarkably higher in Africa, Asia and Middle East than in the rest of the World (WHO, 2016). Polluting compounds is emitted daily in significant amount from various sources but mostly from anthropogenic activities. One of the most essential pollutants that are produced by human activities other than gaseous compounds is particulate matter. Not only affect human health, particulate matter also plays a vital role in global warming, change in cloud formation or radiation balance of the Earth (Amaral, S et al 2015).

Therefore, maintaining ambient air quality at appropriate level has been a real challenge that mankind needs to tackle, especially with today's drastic development of various industries. In order to maintain and control air quality, understanding of particle behaviour, sources, concentration as well as composition is fundamental. In respond, diverse methods and devices with different mechanisms to measure mass concentration and number of particles of each size have been invented (Amaral, S et al 2015). However, the current methods are considered insufficient in dealing with large polluted area or area with physical barriers. For instant, at air quality monitoring sites, particulate matter measuring sensor is fixed, therefore data is gathered with low spatial resolution and thus inaccuracy increase as distance increase, especially in some specific circumstances such as busy intersection or power plant. Vehicle-based sampling system has overcome the physical barriers of monitoring sites, improving significantly in spatial resolution and also establishing source-characterizing ability. Yet in complex topography area such as public road network, construction site or industrial factory, these applications still find difficult to get access over the area. Furthermore, both monitoring site and vehicle-based sampling system are not able to collect data as it comes to vertical atmosphere, which makes it difficult to study and monitor air quality such as at high apartment building outdoor and indoor (Gu, Q. Michanowicz, D & Jia, C. 2018). According to San Francisco Planning Department, it has been observed that air quality does not always improve as it gets higher comparing to ground level, especially for buildings located nearby roadways. From another study, pollutants concentration including black carbon and particulate matter has been measured to be highest at 3^{th} – 5^{th} floor, up to 1.5 times higher than concentration at 0 – 2^{nd} floor (Jung, K et al 2011). Therefore, studying behaviour, concentration and composition of particles in vertical atmosphere is as essential as on the ground level for the health of citizens living in both high-rise and low-rise buildings.

Recently, Unmanned Aerial Vehicles (UAVs) has been introduced as a new method in measuring air quality, which is expected to be a solution for all limitations regarding physical barriers and vertical atmospheric measurement that exist in monitoring sites and vehicle-based sampling system. Previously, balloons, aircrafts and also satellites remote sensing were tested and applied; however, they are expensive and not suitable using in urban area. Together these reasons encourage the application of drone (Small Unmanned Aerial Vehicles) with attached sensor onboard in air monitoring. Beside low-cost advantage, drone is small and flexible enough to provide high spatial resolution data in lower troposphere, urbanized or rural area as well as all types of complex topography area in both horizonal and vertical dimensions (Gu, Q. Michanowicz, D & Jia, C. 2018). Soon enough, it has become the most attractive platform in air quality research as it widens the accessibility to various areas, brings in new study approaches, available at low-cost, simple operation and easy in transportation (Gnawali, N. 2018).

However, despite of its potential in the field, various studies has shown some difficulties in adjusting optimal sensor-drone combination and set-up. In some situations, sensor can present as electromagnetic interference to GPS system of drone and cause flight failure. Also, wind that is produced by drone propellers can mix up the air, blow away or attract more particles, which influences the overall results of air quality measurement. (Gnawali, N. 2018)

2 AIMS

In this thesis, behaviour and concentration of particles under influence of drone propellers is studied. Optimal distance between sensor and drone, at which effect of the wind from propellers is minimized will be concluded based on indoor experiments. Difference in settling time between PM_{10} and $PM_{2.5}$ is also analysed.

The experiment is conducted using two particulate matter sensor Trotec PC220 and DustTrak together with drone Phantom 4 Pro and anemometer LabQuest 1. Besides, study also focus on relation and similarity between results from Trotec PC220 sensor and DustTrak sensor (both are particulate matter measuring devices using mechanism of light scattering intensity).

3 PARTCULATE MATTER

3.1 Definition

Airborne particulate matter (PM), or aerosol is used to refer to fine solid particle or liquid droplets found in the air with size range from only few nanometres (as small as a virus) to 100 micrometres (as the thickness of human hair). The size, properties and pollutants level of particles varies greatly at different locations, times and especially from different sources. Particles can be released from natural sources such as forest fires but mainly from human activities like traffic, manufacturing industries or coal power plants. Particles with diameter from 2.5 µm – 10 µm (PM_{10}) usually consists of insoluble crust-derived minerals, sea salt or organic matters such as bacteria and fungi. On the other hand, $PM_{2.5}$ (particles with diameter smaller than 2.5 µm) is mainly released as product of combustion. In addition, reactions between gaseous pollutants in the atmosphere can also generate secondary particles such as sulphates and nitrogen which are found mostly as fine PM ($PM_{2.5}$). (Adams, K et al. 2015)

3.2 Health and environmental effects

Majority of health effects from particulate matters to human are caused by PM_{10} and $PM_{2.5}$ which is classified as inhalable particles. Smaller the particles are, the deeper they can penetrate into human lunges, thoracic region and therefore damage more severe to respirational system. Severe level of health effect is different between short-term exposure (hours, days) and long-term exposure (months, years) (WHO. 2013). No serious consequence has been observed from short-term exposure except for sensitive group children, elderlies and patients with respirational and cardiorespiratory diseases. With high concentration especially of $PM_{2.5}$, even with short-term exposure can cause ischemic stroke, arrhythmias or increase mortality (Kloog, I et al 2013) and delirium risk in surgical day (Che, L. Li,Y & Gan, C. 2017).

Long-term exposure to PM can cause diverse health effects including asthma, respiratory infection, lung cancer, various cardiovascular issues and significant increase of mortality risk (Kloog, I et al 2013). Every 10 µg/m^3 of $PM_{2.5}$ associates with escalation of cardiopulmonary mortality risk by 6-13%. The study also shows 3% of cardiopulmonary and 5% of lung cancer deaths are indicated as relation to PM globally. According to results from project Improving Knowledge and Communication for Decision-making on Air Pollution and Health in Europe (Aphekom), it has been indicated by using traditional health impact assessment method that increase of 20 months average life expectancy in the most polluted cities is achievable if $PM_{2.5}$ concentration is lowered to WHO Air quality guideline (AQG) annual level. Furthermore, permanent health damage in lung growth and function has been observed in children. (WHO. 2013)

Besides concentration of particulate matters, composition of various chemical compounds and their proportion in the atmosphere also contribute significantly to toxic level of PM to human health. Particles that are released from combustion from both mobile and stationary sources are determined to be more hazardous as well as more consistent damage than from other sources. For instant, PAHs – organic carbons which are produced during industrial fuel combustion process are known to be carcinogens and directly toxic to the cells. (WHO. 2013)

Apart from health, aerosols also influence significantly to climate as they scatter, reflect and absorb the sunlight. Particles with lighter colour or translucent tend to reflect most of the sunlight to surrounding environment as well as back to space, which helps to cool down the Earth surface. On the other hand, particles with darker surface like carbon and mineral dust absorb the radiation and warming up the atmosphere (Myhre, G. 2013). In addition, particulate matter plays a vital role in cloud formation as nuclei of water droplet. In non-polluted area, aerosols appear naturally as sea salt or sulphates with low concentration, which leads to larger droplets and darker clouds. In polluted area, aerosols concentration is high with various compositions, droplets are divided in smaller ones, which form bright white clouds that reflect sun radiation and therefore cool down the atmosphere (NASA. Aerosols and clouds. 2010). Despite of cooling effect, scientists believe warming effect of black carbon that are emitted from industrial combustion as well as other absorbing aerosols is dominant process (NASA. Aerosols and Incoming Sunlight. 2010).

4 DEVICES

4.1 Trotec PC 220

Trotec PC220 is a portable mobile device mainly for testing indoor air quality, measuring air particles and logging different kind of climate data. The core part of the device is the ergonomic laser particle counter, which allows to determine air particle purity with 6 different particle size ranging from 0.3µm to 10µm, humidity and temperature among others such as gas detection. The device has a built-in digital camera supported photo and video function which helps in documenting the recorded measurements. The device's internal memory can store up to 5000 measurement records, which later can be moved to a computer for further analysis by USB interface.

The particle counter is able to detect and differ 6 different particle sizes: 0.3 µm, 0.5 µm, 1.0 µm, 2.5 µm, 5.0 µm, 10.0 µm, while particulate mass conversion and indication is limited to PM2.5 and PM10 only.

PICTURE 1. Device Trotec PC220 (Tran, A. 2019)

4.2 DustTrak 8520 Aerosol Dust Monitor

DustTrak 8520 Aerosol Dust Monitor is - similarly to the Trotec - a portable mobile device for measuring real-time mass concentration. It is used both indoor eg. clean office settings and outdoor in industrial areas to detect airborne contaminations such as dust or smoke. The device can work in quick measurement mode or in advanced logging mode for uninterrupted longer samplings. The device is able to store 31 thousand of measurement records, which is 21 days of logging (if logging rate is 1 log / minute). Using the analog output the data may be moved to a computer for further analysis.

The DustTrak monitor detects and measures 3 different particle sizes: PM10, PM2.5 and PM1.0, while counting of different size of particles is not supported.

PICTURE 2. Device DustTrak (Tran, A. 2019)

4.3 Drone Phantom 4 PRO

Phantom 4 Pro is an unmanned aerial vehicles (UAVs) released in 2016 as part of the Phantom series developed by Chinese technology company called DJI. This drone has a three-axis stabilized camera with a 1-inch 20 MP CMOS sensor, which makes it possible to capture high quality still images as well as videos. The maximum image resolution is 5472 × 3078 (aspect ratio 16:9) and the maximum video bitrate is 100 Megabit / sec with the support of many different file format such as JPEG, DNG, MP4 or MOV.

The UAV has an advance obstacle avoidance system with five directional sensors, besides GPS/GLONASS satellite positioning system which supports better positioning. It has an impressive 72 km / hour maximum speed, operation is possible up to 6000 meters above sea level and resistance of wind up to 10 meters / sec speed. Depending on these factors, the maximum flight time is approximately 30 minutes.

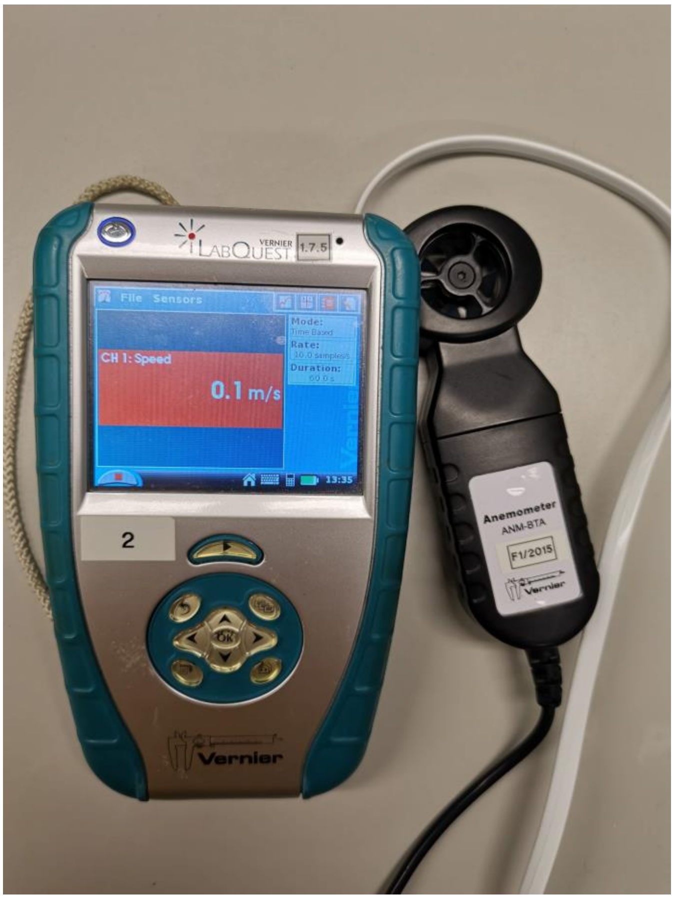
PICTURE 3. Drone Phantom 4 PRO (Tran, A. 2019)

4.4 LabQuest 1

LabQuest1 is a portable computer interface for different type of sensors. This touch screen enabled mobile device unifying the usage of connected sensors and helps the user the to easily control and log measurements. The 320 x 240 pixels colour graphic LED display is easy to read even in bright conditions, which enhances outdoor usage.

The device has 6 sensor ports with already built-in air temperature sensor, microphone and sound sensor. The maximum measurement rate is 100 thousand samples / second. It has multiple interfaces to connect to other devices: USB Standard-A port USB mini-AB port DC power jack.

The LabQuest Graphing and Analysis Application which runs on the device, gives real time graphing capabilities and analytical features.



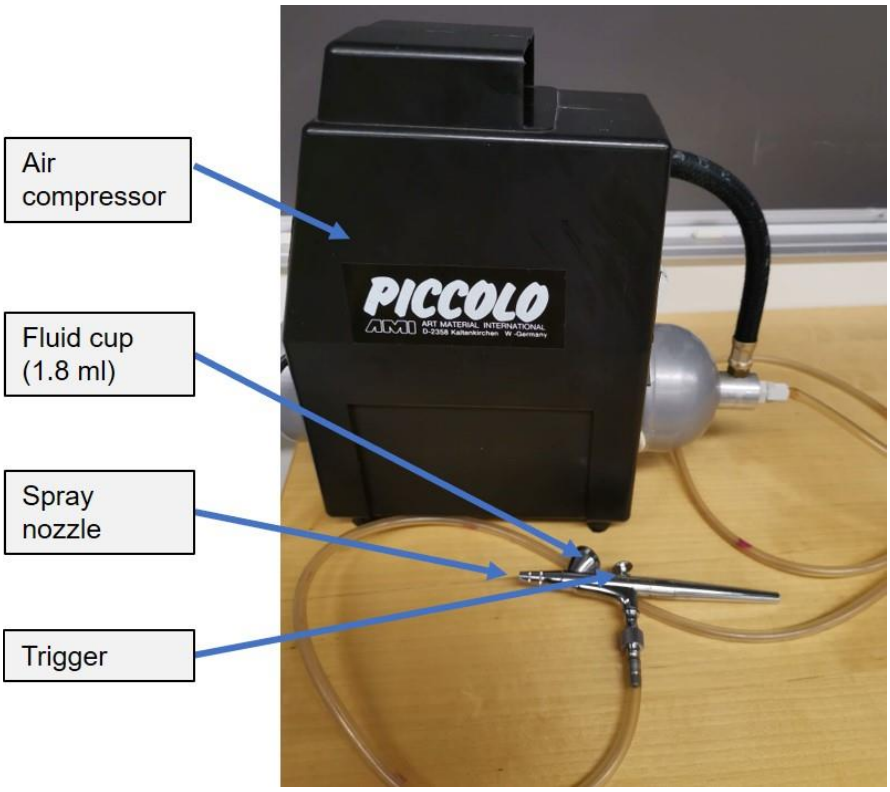
PICTURE 4. Device LabQuest 1 (Tran, A. 2019)

5 EXPERIMENT

5.1 Artificial particles distribution

Due to all the experiments are carried out in the indoor environment, particulate matter concentration is concerned to be insufficient to show clear results under influence of drone or in comparison activities. Therefore, additional source of particles is essential requirement for later analysis and successfully delivery of experiment purposes.

Particles solution is created from clay and Calcium Carbonate ($CaCO_3$) and water with amount of 2 g, 2 g and 200 ml respectively. Calcium Carbonate particles size widely ranges from extremely small as 1 µm and 2 µm to remarkably bigger as 45 µm (Malvern. 2015). Besides, clay is known to be the finest particles in soil as their size have been studied to be smaller than 2 µm (Kolay, K. Kumar,S & Tiwari, D. 2013). As result, mixture of clay and Calcium Carbonate provide us diverse size of particles with sufficient amount.



PICTURE 5. Airbrush spray (Tran, A. 2019)

All ingredients are put in a Florence flash and mixed until evenly dispersed. However, since both clay and Calcium Carbonate are water insoluble, regularly mixing and especially before every spraying time is required. Then mixture is poured into fluid cup of airbrush spray with capacity of 1.8 ml (picture 5). Each cup with full capacity is sprayed in approximately 1 minute.

5.2 Pollution mapping

The experiment is done in Physics laboratory with dimension of 7 m * 8 m approximately and it locates on the second floor of building E in the main campus of Tampere University of Applied Science. The room is divided into 56 small squares with dimensions of 1 m * 1 m as can be seen in the figure 1 below. Due to possible toxic level of PM concentration can be reached during procedure, participants are required to wear protection mask to protect respirational system.

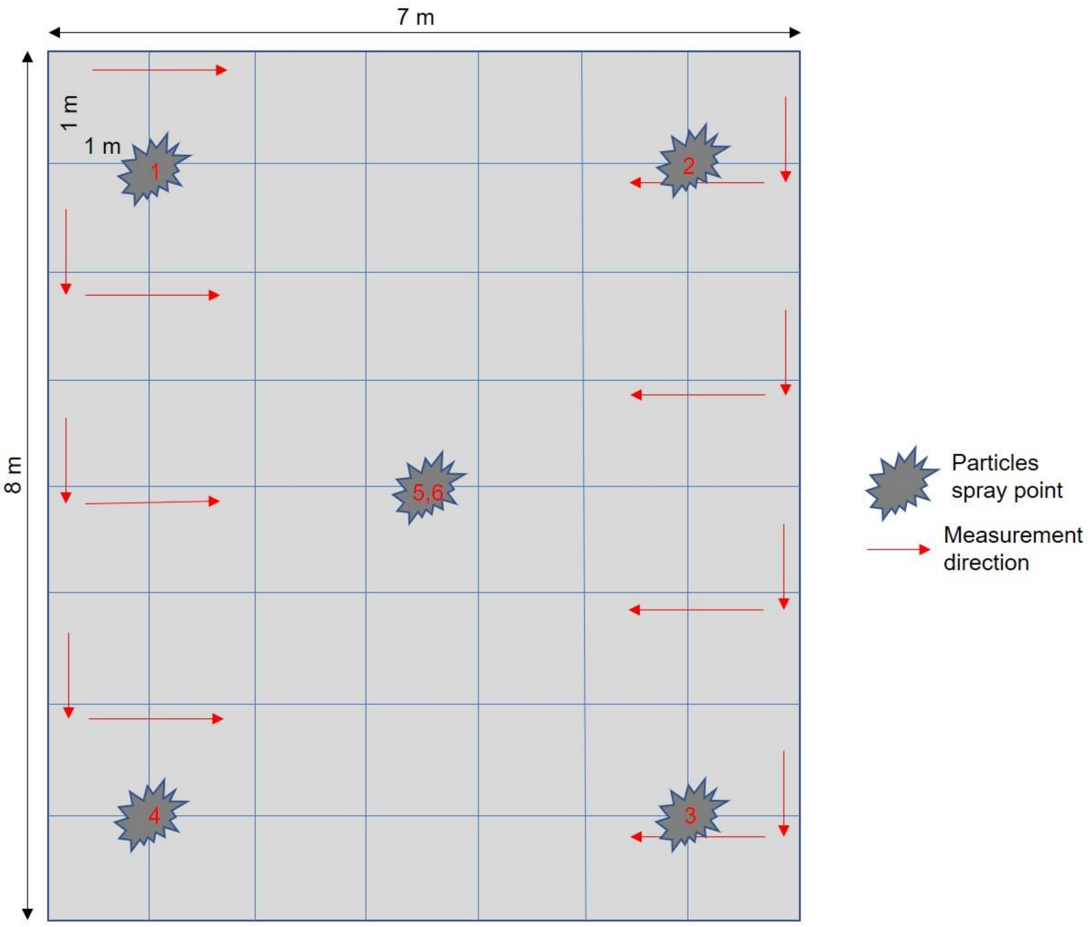
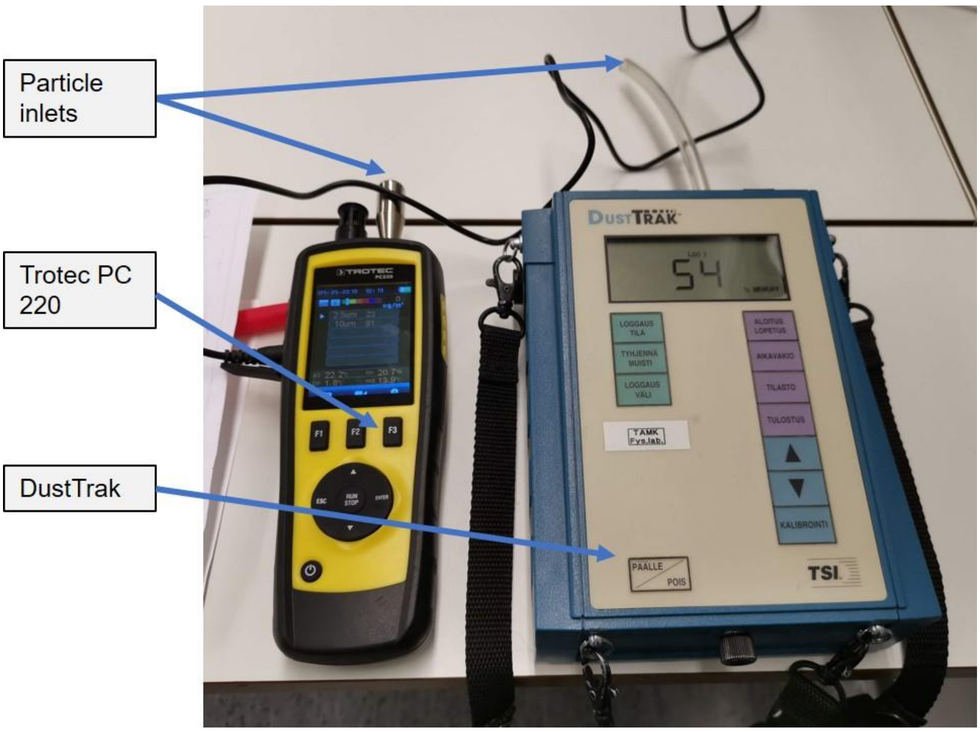


FIGURE 1. Grid map physics laboratory, particle spray point and measurement direction.

Particles are spread around the room using airbrush spray at four corners and middle of the room from 2.5 m high approximately. There are 6 sprays in total consuming 6 full fluid cup of prepared mixture; 1 spray at each corner and 2 in the middle following order marked in figure 1. Particulate matter concentration in analysed every square with both devices Trotec PC220 and DustTrak at 1 m high closely to each other (picture 6) and at the same time. After particles are distributed evenly around the room, no more spray is made so that settling time of particles can be studied.

Measurement starts at the top left corner of the room after 10 minutes since the first spray, continues with the direction as can be seen in figure 1 and finishes at the bottom left corner of the room after 30 minutes since the first spray. Data collected from each square is average value of 15 seconds measurement. Particulate matter concentrations are also measured before and 1 hour after spraying at 4 corners and middle of the room to study roughly efficiency of airbrush spray in particle distribution and settling time of distributed particles.

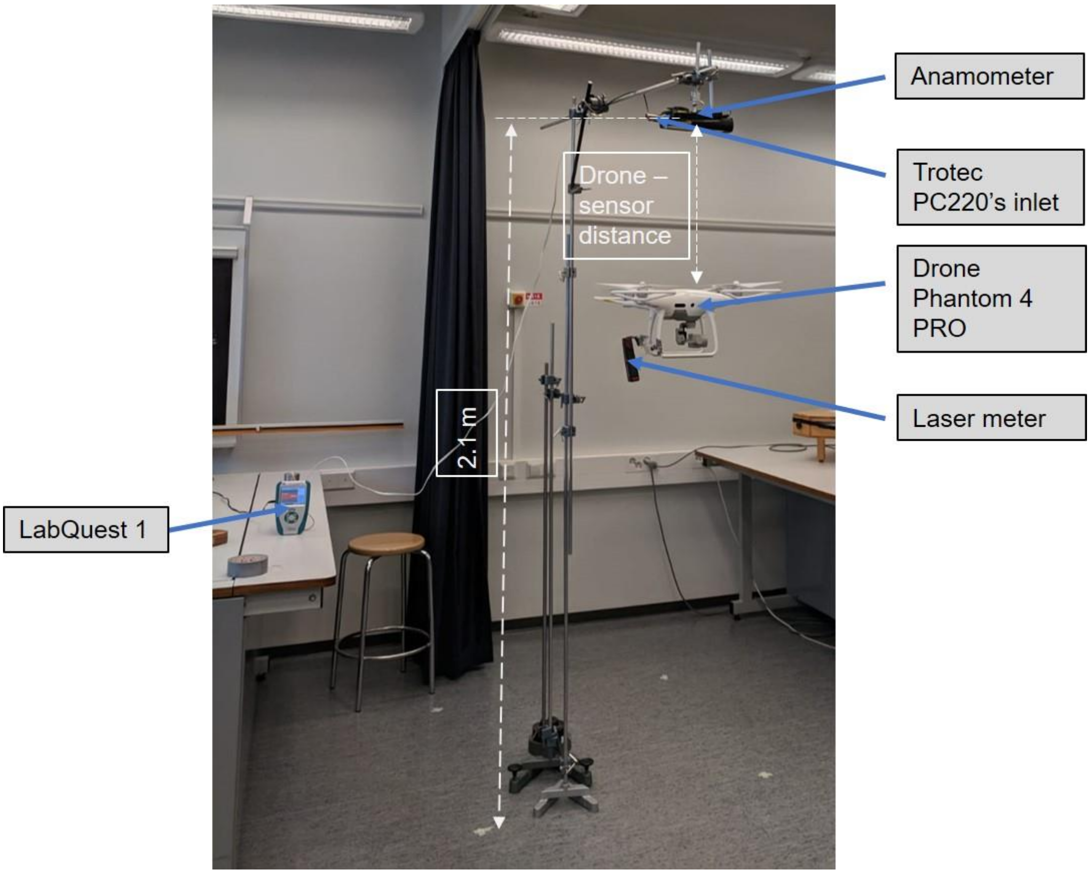


PICTURE 6. Relative position of DustTrak and Trotec PC220 during measurement (Tran, A. 2019)

5.3 Particulate matter concentration under influence of drone's propeller.

The experiment is done in the same physics laboratory in which pollution mapping was carried out. Trotec PC220 and anemometer are hung at 2.1 m high from the ground in the middle of the room and right above a flying drone (Phantom 4 PRO) to measure wind speed and particulate matter concentration in vertical dimension (picture 7). DustTrak is set at the same high as Trotec but 2.3 m away from the drone to study influence of propellers on particles distribution at further distance.

Altitude of drone is controlled using laser meter that has instant data transfer to phone which is attached to landing gear. Experiment was carried out at 7 different drone-sensor distance: 10 cm, 15 cm, 20 cm, 25 cm, 30, cm, 40 cm and 50 cm. At each distance, PM concentration is measured 4 to 5 times, each time is 20 seconds.



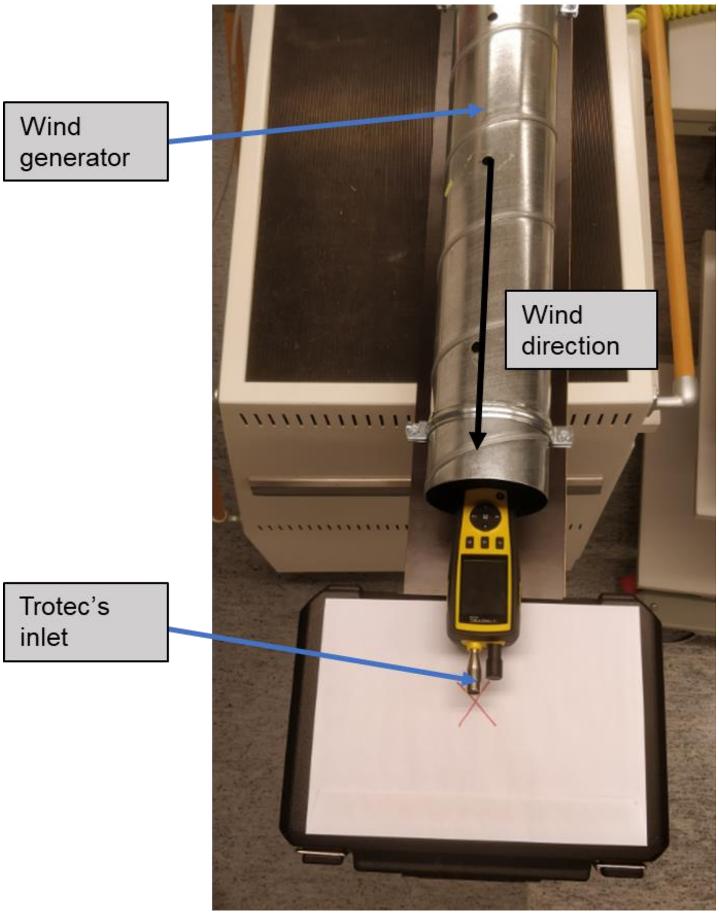
PICTURE 7. Experiment set up (Gubaydullina, A. 2019)

Based on results from pollution mapping experiment, settling time of particles generated by airbrush spray is short with drastic concentration decrease in the first 30 minutes and nearly full settlement after 1 hour. On the other hand, in order to study propellers' effect on particles behaviour at different distance, exact same surrounding condition and especially particles concentration need to remain constantly during the whole experiment. Therefore, particles mixture is sprayed before every measurement with exact same amount as one full fluid cup.

5.4 Impacts of wind direction – sensor set-up on PM concentration

In order to support impacts of drone's propellers on PM concentration research, behaviour of different size particles under influence of various wind speed as well as particle collection ability of Trotec in different sensor-wind direction set-ups are studied. PM concentration is measured in 5 different wind speed: no-wind, 1 m/s, 2 m/s, 3 m/s and 5 m/s. With each wind speed, measurement is repeated 3 times according to 3 different angle sensor-wind direction set-ups as can be seen in picture 8 and 9. In each condition, PM concentration is detected repeatedly 8 times for better evaluation of variation.

Measurement is done in in-door environment without any artificial dust spray beforehand. In this experiment, not only concentration of PM_{10} and $PM_{2.5}$ is recorded but also concentration of smaller size particles like PM_1 and $PM_{0.3}$ are also focused and recorded separately for different behaviour study.



PICTURE 8. Trotec's inlet in the same direction to wind speed (Tran, A. 2019)

a)

b)

PICTURE 9. a) perpendicular to wind direction, b) opposite to wind direction

6 RESULTS

6.1 Pollution mapping

PM concentration observed in physics laboratory before and after artificial particles distribution one hour are indicated to be relatively similar with value ranging from 2 µg/m^3 to 3 µg/m^3. Thus, it can be concluded that particles generated from prepared solutions and distributed by airbrush from 2.5 m high accomplish fully settlement in 1 hour.

Before implementing mapping experiment, particles were distributed at 5 points around the room using about 11 ml of prepared solution in total. PM concentration was measured at 56 squares in total around the room by both DustTrak and Trotec PC220 devices, recorded data were processed by excel resulting in colour map below: figure 2 and figure 3 for PM_{10} and figure 4 for $PM_{2.5}$. During measurement, Trotec was signalling beeping sound when toxic level of Pm concentration is met at few squares around top left corner. The whole measuring process from first square to last square is 20 minutes approximately.

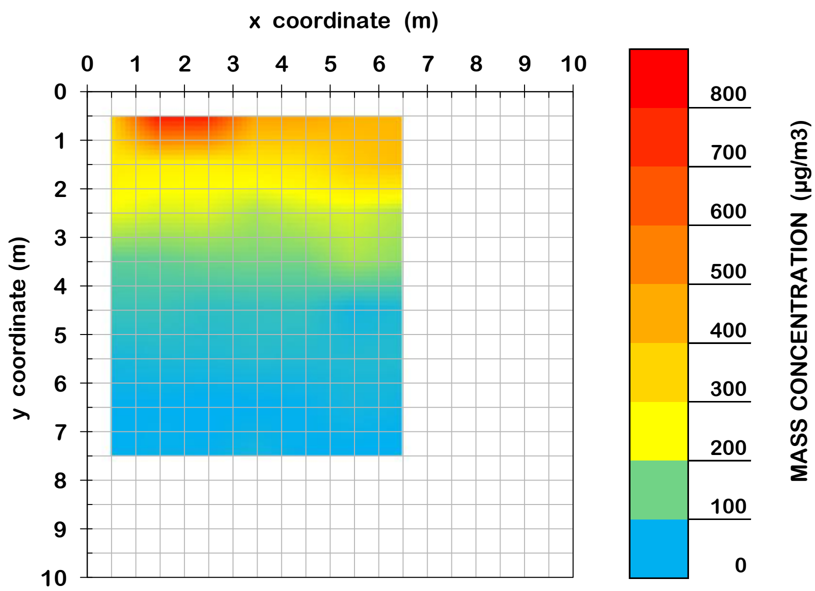


FIGURE 2. Colour grid map by Trotec PC220 (PM_{10} concentration)

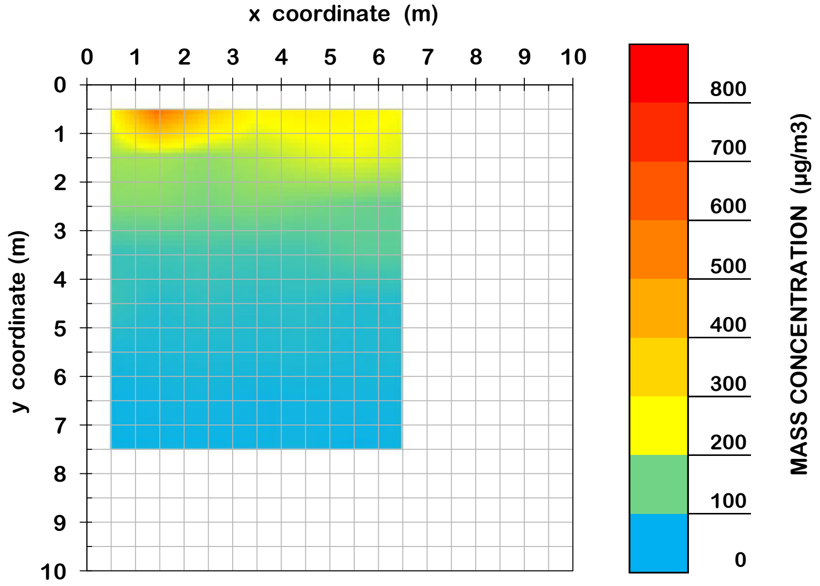


FIGURE 3. Colour grid map by DustTrak (PM_{10} concentration)

Figure 2 and 3 illustrate relatively similar condition despite slightly distinctive in shade between the map produced by DustTrak and the one by Trotec. With same colour scale, DustTrak map start displaying green colour indicating concentration below 200 µg/m^3 after the first meter and blue colour indicating below 100 µg/m^3 after 3.5 m. On the other hand, in Trotec map, green is displayed after 2.5 m and blue is after 4 m. PM concentration is observed to be extremely high in the first half of the room, especially in the left corner where it reaches up to 700 µg/m^3 and then gradually reduces toward the second half of the room with concentration range majorly below 100 µg/m^3. Difference of PM concentration between first half and second half of the room is explained by settlement of particles during measurement period as the first data and last data is 20 minutes from each other. The most polluted square presented in red colour is done after 10 minutes from particles distribution and the final square (right bottom square) is measured after 30 minutes.

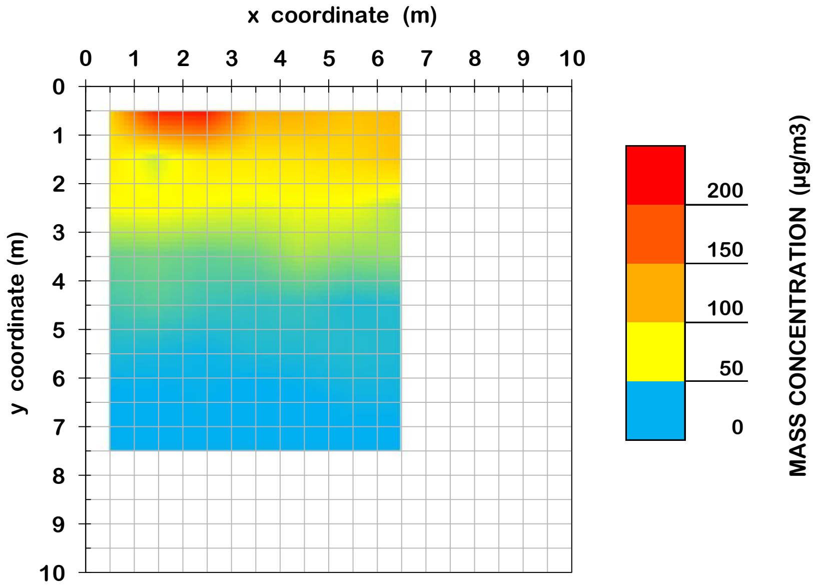


FIGURE 4. Colour grid map by Trotec PC220 ($PM_{2.5}$ concentration)

Figure 4 visualizes concentration of $PM_{2.5}$ in laboratory during measurement period. Similar to PM_{10}, concentration of $PM_{2.5}$ is also observed to be highest in the top left corner of the room (up to 200 µg/m^3) and then decrease gradually as coming toward the second half of the room with major of squares are displayed in blue (below 50 µg/m^3).

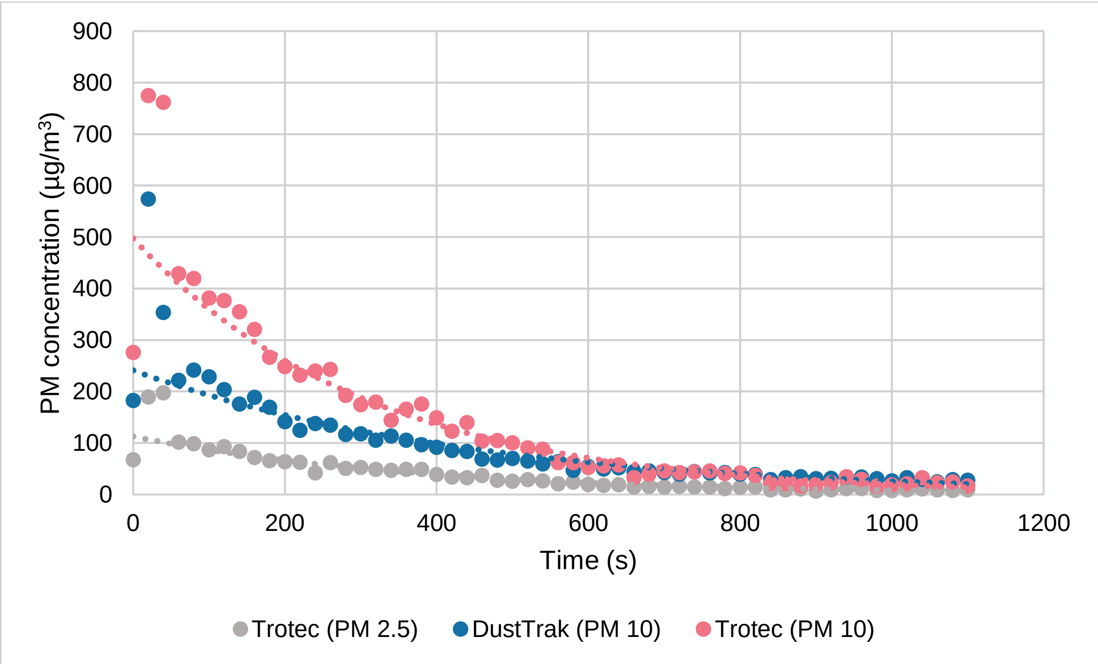


FIGURE 5. Trending of PM mass concentration in time

The trend of decreasing is easily observed in all 3 types of data: $PM_{2.5}$, PM_{10} collected by Trotec as well as PM_{10} collected by DustTrak, which indicates partial settlement of particles after time. Mass concentration of $PM_{2.5}$ compared to PM_{10} decreases remarkably slower, reaching 50% after 8.5 minutes approximately. Although both trendlines present mass concentration of PM_{10} in the room during experiment, trendline generated from Trotec is significantly different from trendline generated from DustTrak with essentially higher concentration and visible steeper slope that indicate shorter settling time. By Trotec, mass concentration of PM_{10} decrease by 50% after 6.5 minutes approximately. While by DustTrak, 50% is reached after almost 8 minutes.

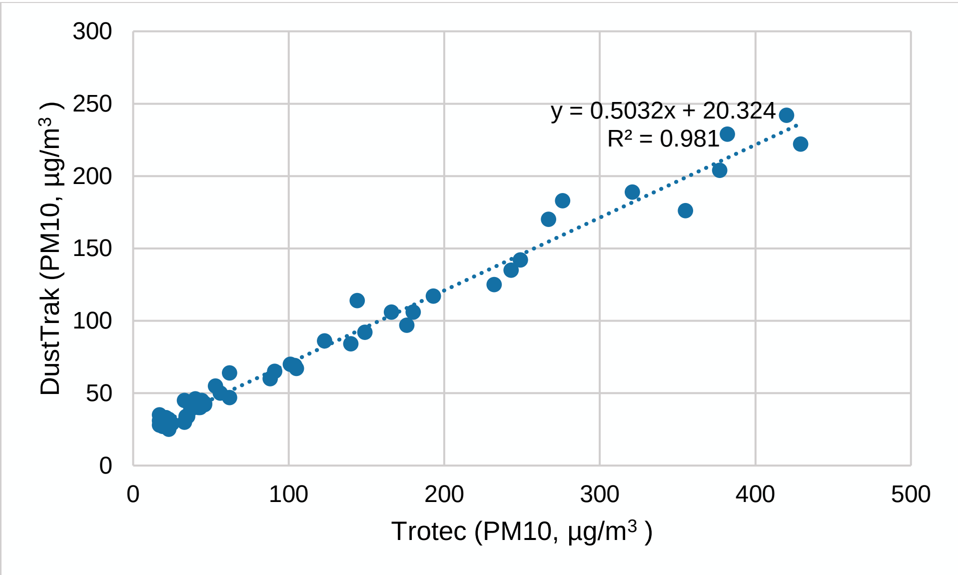


FIGURE 6. Relation between data observed from Trotec and DustTrak

Due to significant difference in value of measured mass concentration between DustTrak and Trotec, it is essential to find out their relation to proceed with further experiment. Figure 6 illustrate relation between data collected from Trotec and data from DustTrak. From graph, mass concentration generated by DustTrak can be calculated based on mass concentration generated by Trotec using equation $y = 0.5032x + 20.324$ with coefficient of determination equal 0.981.

6.2 Particulate matter concentration under influence of drone's propeller.

6.2.1 Wind speed

Wind speed generated vertically above the drone by propellers was measured at 7 distances in total and results are presented in the table below.

TABLE 1. Wind speed generated above the drone vertically by propellers

Distance (cm)	10	15	20	25	30	40	50
Wind speed (m/s)	3	2.7	2.1	1.3	1.3	0.9	0.6

Table 1 presents wind speed obtained from the experiment, only 1 wind speed is recorded at 1 distance. However, wind speed was not always constant due to fluctuation of flying drone. Error is observed to be 0.1 m/s to exceptionally high as 0.7 m/s in some cases, recorded value is the most common and constant value observed throughout each measurement.

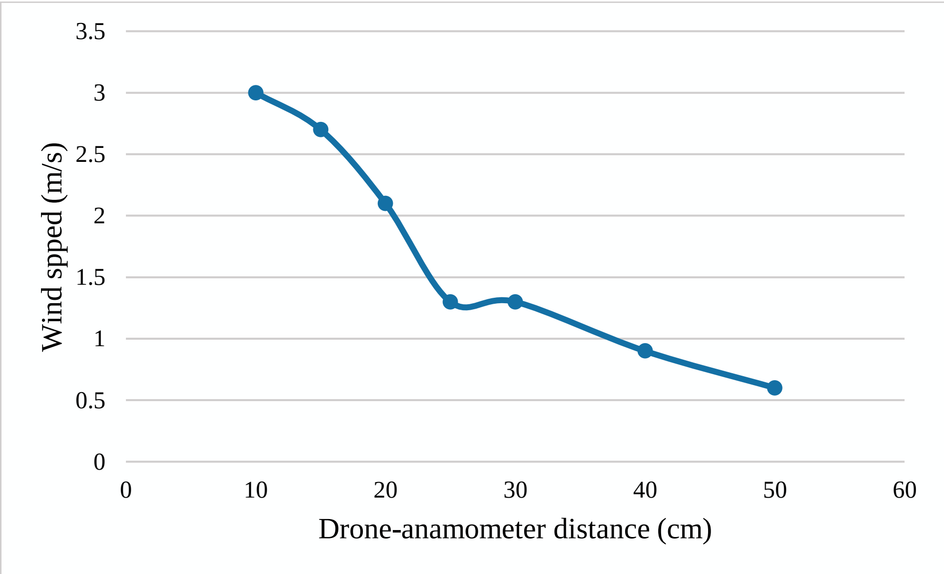


FIGURE 7. Wind speed generated above the drone vertically by propellers

Figure 7 emphasizes clear decline trend of wind speed as it goes further from drone's propellers. Measurement only start from 10 cm in distance and further due to safety reasons. Wind speed drastically reduces from 3 m/s to only 1.3 m/s within only 15 cm (from 10 cm to 25 cm). After that, wind speed is measured to be similar as 1.3 m/s before start reducing again but with slower pace. It reduces only 0.7 m/s within 20 cm (from 30 cm to 50 cm)

6.2.2 Particulate matter concentration

Mass concentration of PM_{10} is measured at 2 different points during drone flight: first point is right above drone's propellers performed by Trotec PC220 and second point is 2.3 m away from drone performed by DustTrak. Both devices are set up 2.1 m above the ground for more comparable results.

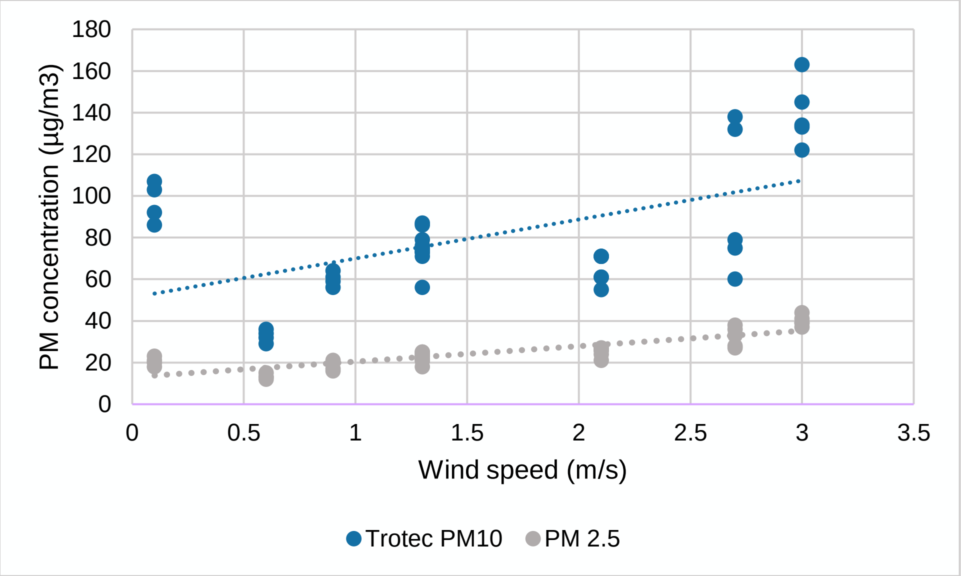


FIGURE 8. Mass concentration of PM_{10} and $PM_{2.5}$ collected by Trotec above drone' s propellers.

From figure 8, mass concentration of PM_{10} shows great variation with remarkable difference between measurements and unclear trend throughout the experiment. $PM_{2.5}$ shows steadier rate of change in mass concentration as it slowly increases following escalation of wind speed. As wind speed rises 2.5 m/s from 0.5 m/s to 3m/s, mass concentration of $PM_{2.5}$ is detected to gain 20 µg/m^3 from 15 µg/m^3 to 35 µg/m^3. PM_{10} mass concentration trendline also indicates clear increase in stronger wind speed from 60 µg/m^3 up to 140 µg/m^3 approximate as wind speed escalates from 0.5 m/s to 3 m/s.

Furthermore, although both PM_{10} and $PM_{2.5}$ is measured 4 to 5 times in each condition, data of $PM_{2.5}$ is unified as can be seen in figure 8 that points in 1 condition almost overlap each other. PM_{10} on the other hand shows great variation in concentration even in the same condition, which can be explained by fluctuation of drone during flight. Based on figure 8, PM_{10} is seen to behave more strongly under impacts of wind than $PM_{2.5}$.

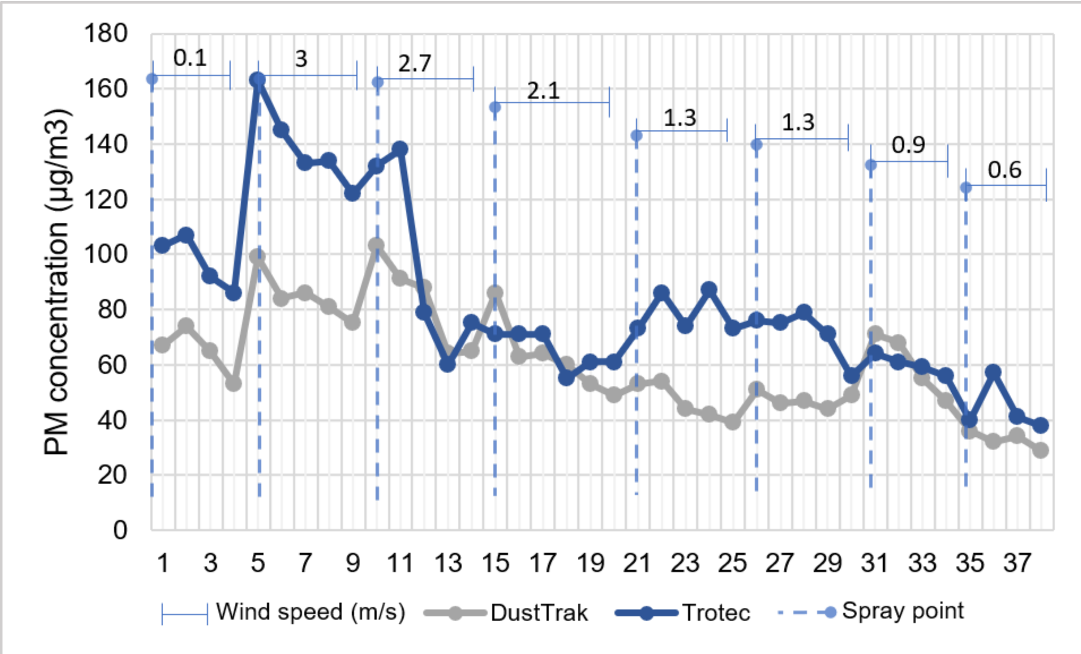


FIGURE 9. Mass concentration of PM_{10} collected by Trotec (above the drone) and DustTrak (2.3 m away from the drone)

Figure 9 presents mass concentration of PM_{10} measured by both Trotec and DustTrak in no drone condition, 10 cm, 15 cm, 20 cm, and further away vertically respectively with 4 to 5 points at each distance. It is easily observed that mass concentration measured by Trotec has surprisingly higher value than ones produced by DustTrak although Trotec is under direct influence of propellers in close distance. Comparing to trendline of Trotec, results from DustTrak give more constant line throughout the measurement, which can be explained by 2.3 m distance between DustTrak and drone resulting less influence from propellers on PM concentration. On the other hand, Trotec is hung right above flying drone, as consequence, PM concentration is heavily affected and results in much greater variation. The most different parts between 2 results are observed to be from point 6 to point 13 when wind affected on Trotec with speed of 2.7- 3 m/s and secondly from point 20 to point 30 when wind speed is 1.3 m/s. The rest of the results are considered to be relatively similar. Despite being in different condition and under impacts of propellers in distinctive ways, both results show clearly intention of decrease as it is further away from the drone vertically.

Beside influence of drone's propellers, results also shows connection with spraying activities as the PM concentration peaks closely after particles distribution, which can be seen at total of 6 out of 8 distributions: 2nd, 5th, 11th, 15th, 22nd and 36th. Although distribution of particles was planned right before every experiment and about 5 to 10 minutes in between each time to keep as constant concentration as possible, results still show undesired variation as influence of the distribution. However, the peaks and variation is observed to be much higher in Trotec than in DustTrak despite of similar distance from spraying points to both sensors.

However, due to Trotec and DustTrak are observed to show somewhat different results in pollution mapping experiment where they are put in same condition and no present of drone's impacts, results that gained during drone flight are not entirely comparable. Therefore, results of DustTrak is converted to Trotec results using relation function calculated in pollution mapping experiment and are showed in table 2 below.

TABLE 2. Mass concentration of PM_{10} collected from Trotec, DustTrak and expected DustTrak data converted from Trotec's results using DustTrak-Trotec relation function: y = 0.5032x + 20.324

Trotec PM_{10}(μg/m^3)	Converted PM_{10}(μg/m^3)	DustTrak PM_{10}(μg/m^3)	Trotec PM_{10}(μg/m^3)	Converted PM_{10}(μg/m^3)	DustTrak PM_{10}(μg/m^3)
103	72.2	67	61	51.0	49
107	74.2	74	73	57.1	53
92	66.6	65	86	63.6	54
86	63.6	53	74	57.6	44
163	102.3	99	87	64.1	42
145	93.3	84	73	57.1	39
133	87.2	86	76	58.6	51
134	87.8	81	75	58.1	46
122	81.7	75	79	60.1	47
132	86.7	103	71	56.1	44
138	89.8	91	56	48.5	49
79	60.1	88	64	52.5	71
60	50.5	64	61	51.0	68
75	58.1	65	59	50.0	55
71	56.1	86	56	48.5	47
71	56.1	63	40	40.5	36
71	56.1	64	57	49.0	32
55	48.0	60	41	41.0	34

After being converted, data in overall show more similarity to results gained from DustTrak. Comparison of DustTrak data and converted data are visualized in figure 10 below.

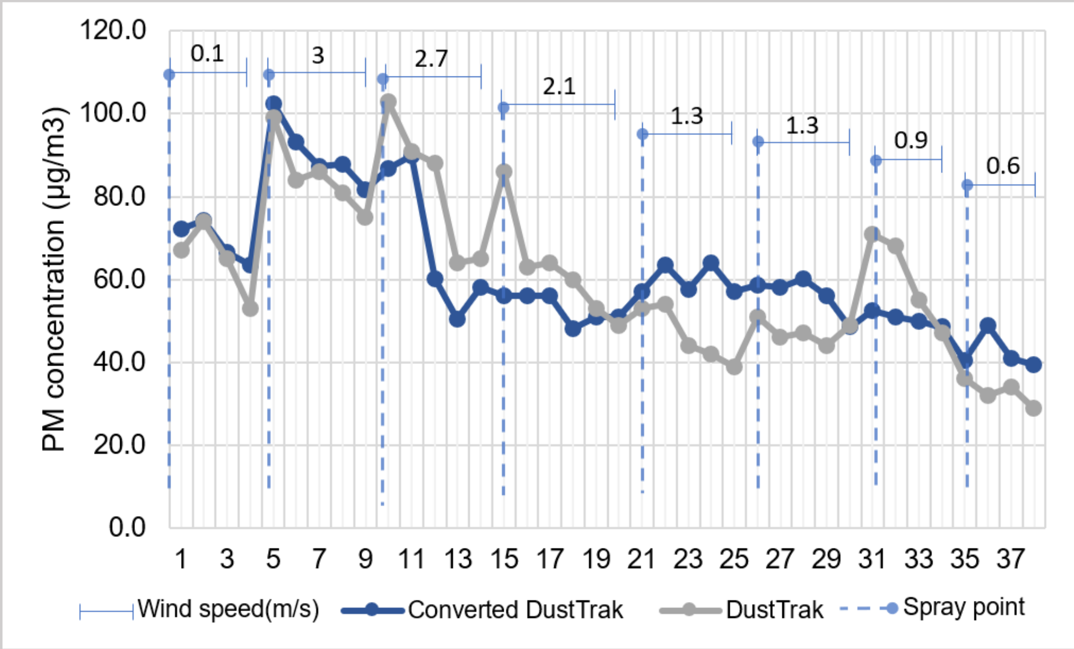


FIGURE 10. Comparison between real data from Trotec during drone flight and data converted from DustTrak's results using Trotec-DustTrak relation function.

In figure 10, converted data from Trotec and data from DustTrak show better correlation with more harmonic variation compared to in figure 9. The 2 data lines are observed to be almost overlapped at the first 4 points, where measurement is done in no drone condition. After 6th point, although the trend is similar, gap between 2 values at 2 according points is still noticeable. The biggest gap is at point 15th as 60 µg/m^3 and second one is point 31st, point 32nd with difference goes up to 40 µg/m^3. From figure 10, both sensors are seen to be affected similarly by propeller's wind even DustTrak was placed 2.3 m away.

6.3 Impacts of wind direction – sensor set-up on PM concentration

PM concentration in this experiment is not measured by µg/m^3 but by number of particles in various sizes under influence of different wind speed. Measurement is carried out in 5 different wind speed, 3 angles of wind direction – sensor each wind speed: opposite wind, perpendicular to wind and same direction to wind. Measurement is repeated 8 times in each condition and each time lasts 20 seconds. According to device, in 20 seconds, volume of air collected is around 0.94L. Results are presented in graphs below.

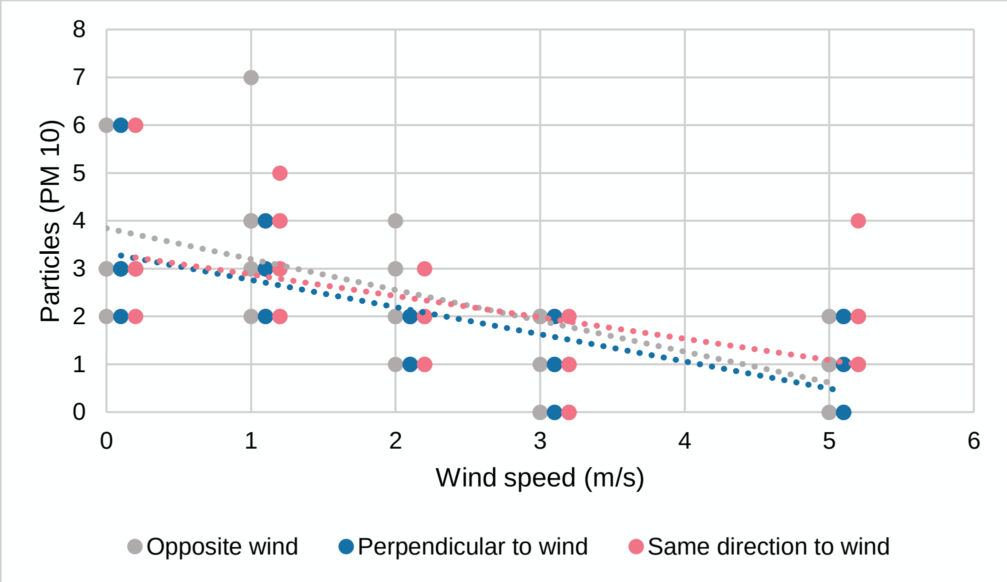


FIGURE 11. PM_{10} particles under impacts of different wind speed.

According to figure 11, number of PM_{10} is measured to be in quite small amount, only few particles were indicated. Particles amount also decreases remarkably as wind get stronger, even get down to 0 or 1 particle only in 5 m/s wind while in no-wind condition, device can detect 4, 5 or even higher particles in same 0.94L of air. As can be seen following trending lines, different angles of sensor-wind direction don't interfere greatly to collected particles amount.

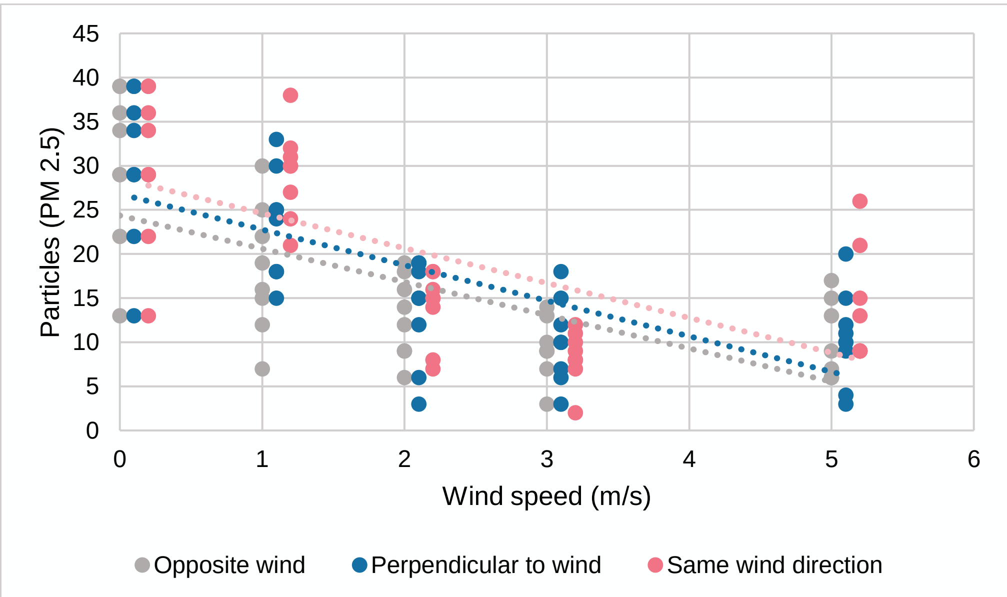


FIGURE 12. $PM_{2.5}$ particles under impacts of different wind speed.

Figure 12 presents amount of $PM_{2.5}$ particles collected in different wind speeds. Comparing to PM_{10}, $PM_{2.5}$ present in higher amount as 40 particles is highest number measured in no-wind condition. However, similar to PM_{10}, $PM_{2.5}$ is also affected greatly by wind as the number of particles decreases more than 60% from no-wind condition to under influence of 5 m/s wind. Different angles of sensor-direction of wind also shows slightly influence on the results. According to trend line, same direction to wind is a bit higher than 2 other set-ups, following is perpendicular set up and opposite to wind shows the least collected particles. All 3 set-up shows constant decrease of particles inversely to wind speed.

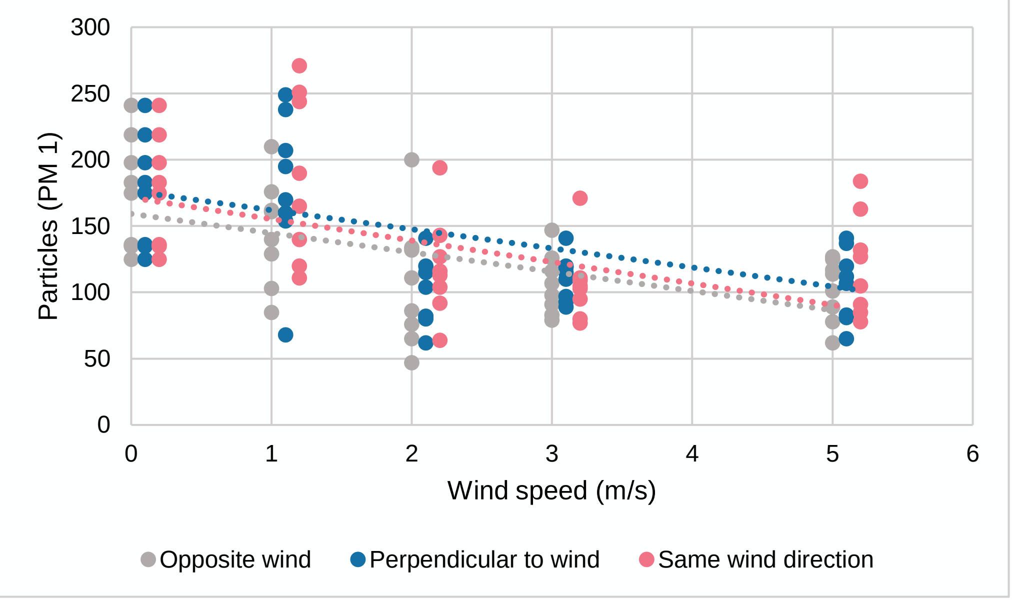


FIGURE 13. PM_1 particles under impacts of different wind speed.

PM_1 particles is collected with much higher amount, about 10 more times than $PM_{2.5}$. Similar to bigger particles, PM_1 also presents at most concentration in no-wind concentration or in 1 m/s wind. As the wind get stronger toward 5 m/s, concentration of particles reduces. However, compared to PM_{10} and $PM_{2.5}$, trend lines of concentration decrease at slower rate. All 3 different sensor-wind direction set-ups give closely identical results.

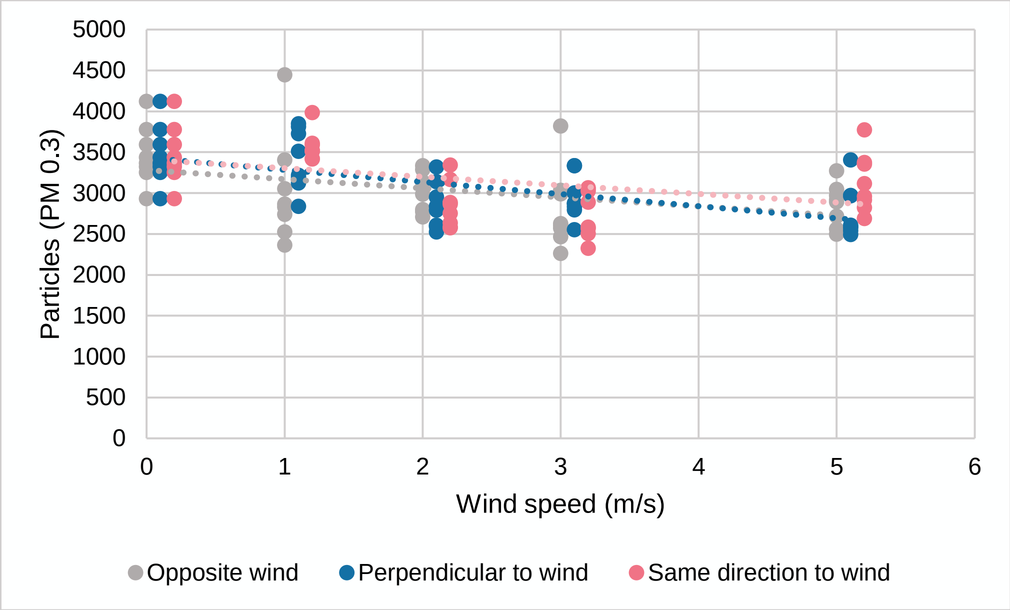


FIGURE 14. $PM_{0.3}$ particles under impacts of different wind speed.

$PM_{0.3}$ is collected at significant amount in just 0.94L of air, up to 4500 particles as highest value. As can be seen clearly from 4 graphs, $PM_{0.3}$ is the least affected by wind as the concentration reduction is insignificant under impacts of different wind speeds. All 3 trend lines from different set-up are closely identical with small slope, presenting small rate of change in particles concentration. Also, number of particles collected in 1 condition are more similar for $PM_{0.3}$ as points are closer to each other, not widely spread like for bigger particles.

7 DISCUSSION

From pollution mapping experiment results, artificial dust distribution using airbrush spray doesn't show effectiveness in maintaining constant particle concentration. Both PM_{10} and $PM_{2.5}$ settle with remarkable rate during only 20 minutes of experiment, which can be seen clearly in colour grid maps. Also, settling rate of artificial particles can be induced by participation of water in aerosols mixture. Existence of water in particles distribution can accidentally cause wet deposition of aerosols, which is much faster than dry deposition (happen purely by gravity) (Hemond, H & Fechner, E. 2015). Furthermore, spraying water together with particles can increase capillary force between particles, thus they form bigger size particles leading to faster settlement (Yang, Z. Guo, Q & Li, J. 2011). However, no measurement was carried out twice at the very same square, therefore, comparison is only possible between different square respectively with assumption of constant PM concentration all over the room at the beginning.

Although both particles meters working under the same operating principles, light scattering detection, and they were placed right next to each other in the same condition, they present different results in every measurement. Which is expected to be systematic errors as Trotec has not been calibrated in PM concentration but only particles counting measurement (Appendix 5).

Congestion of airbrush after few spraying times is also a theory explaining the significant deduction of PM concentration in both pollution mapping and drone experiment. Since congestion can trap bigger particles inside can therefore cause remarkable mass concentration loss.

According to results collected from 3rd experiment: impacts of wind direction – sensor set-up on PM concentration, density of particles in the atmosphere is clearly reversely proportional to wind speed. Stronger the wind, the lower particles sensor can collect. The trend is correct for all sizes of particles from PM_{10} to extremely small like $PM_{0.3}$ despite of different reduction rate. Figure 8, 11, 12, 13 and 14 show that the smaller the particles, the less influence concentration is affected by wind. In figure 8, although in same condition measured at the same time, concentration of $PM_{2.5}$ show remarkably less variation than PM_{10} concentration. In figure 11,12,13 and 14, reduction trend is less and less as it come to smaller particles. Number of particles PM_{10} and $PM_{2.5}$ decrease more than 70,60 % respectively from when wind speed reach to 5 m/s. While concentration of PM_1 and $PM_{0.3}$ reduce less than 50% and 30% respectively under impacts of 5 m/s wind.

In addition, different angles between sensor's inlet and wind direction does not show any significant impacts on PM concentration as none of the angle constantly present highest value or lowest of particles (figure 11, 12, 13, 14). However, with $PM_{2.5}$, the difference of ambient density is noticeable between set-ups: Trotec collect the most particles when it is placed same direction to wind, following is perpendicular and last is opposite direction. Nonetheless, in order to conclude on the effect of different angle set-ups, more measurement need to be done repeatedly more times to indicate any clear trend among variation of data.

As can be seen in figure 7, wind generated by propellers is much weaker as it goes further away from the drone. Wind speed decrease from 3 m/s to 0.6 m/s after 50 cm above the drone.

It was expected that PM concentration would increase as the sensor move further from the drone due to reduction of wind speed and until some point, PM concentration would be stable as the effect of wind is insignificant. However, inconsistency to the 3rd experiment, PM concentration measured under impacts of wind from drone's propellers show the opposite trend, the stronger the wind, the higher the aerosols concentration. Concentration was observed to be exceptionally high under wind speed of 3 m/s and 2.7 m/s, from 2.1 m/s, PM value remain more constantly with small reduction after each time wind speed is lower. Data collected from DustTrak, which is set 2.3 m away from drone also present the same trend of PM concentration. From that, it is can be indicated that even the distance between sensor and drone is up to 2.3 m but in indoor environment, influence is still significant due to wind reflection from walls.

Furthermore, peaks of PM concentration are noticeable after every time of particles spraying. The artificial particles distribution is believed to play a vital role in this scenario due to fast settling time and congestion of airbrush. In further experiment, it is recommended to exclude airbrush and apply other method that is more effective in maintaining ambient concentration instead such as continuous particles pump. Wet particles from a solution also effect greatly on effectiveness of the process dur to faster settling time and possible increase of capillary force between particles, thus, dry particles is expected to perform better and more suitable to experiment requirement.

8 CONCLUSIONS

The main focused experiment of the research results unexpectedly opposite to beforehand prediction. Instead of being reversely proportional to wind speed, PM concentration show clearly decreasing trend as it goes further and wind speed from drone's propellers decrease. Although data collected at 20 cm distance above the drone, meaning 2.1 m/s wind speed is the most similar to concentration gained in no-drone condition. More measurement in more proper conditions should be carried out for more convincible conclusion.

Improvements should be done in next experiment include artificial particles distribution method, particles mixture, larger room or outside environment is recommended to avoid wind reflection. Reference measurement should be planned better for latter analysis and comparison. In this experiment, DustTrak was failed as reference data since it was clearly affected by drone's propellers even at 2.3 m further away.

In conclusion, drone clearly has great effect on PM concentration and thus present not reliable results of situation. From the experiment, 20 cm above drone perform the closest data as in no-drone environment. However, to conclude propellers influence negatively or positively on PM concentration, or at what distance sensor receives the least effect, further experiment with more accurate reference measurement is required.

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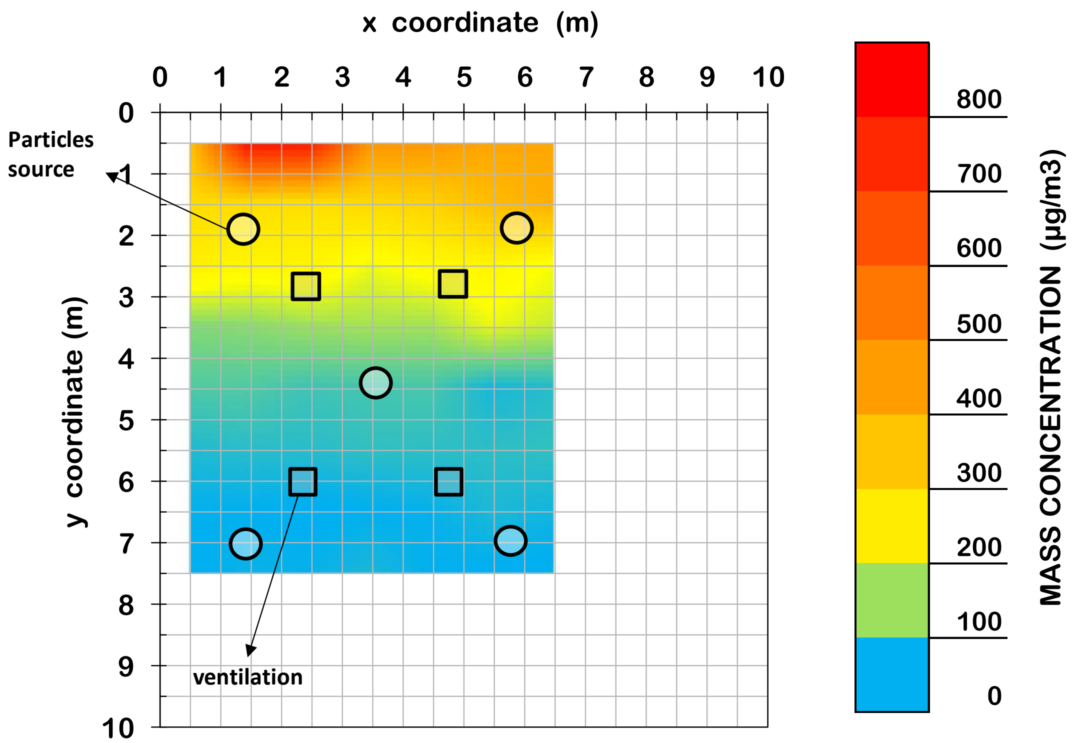
APPENDICES

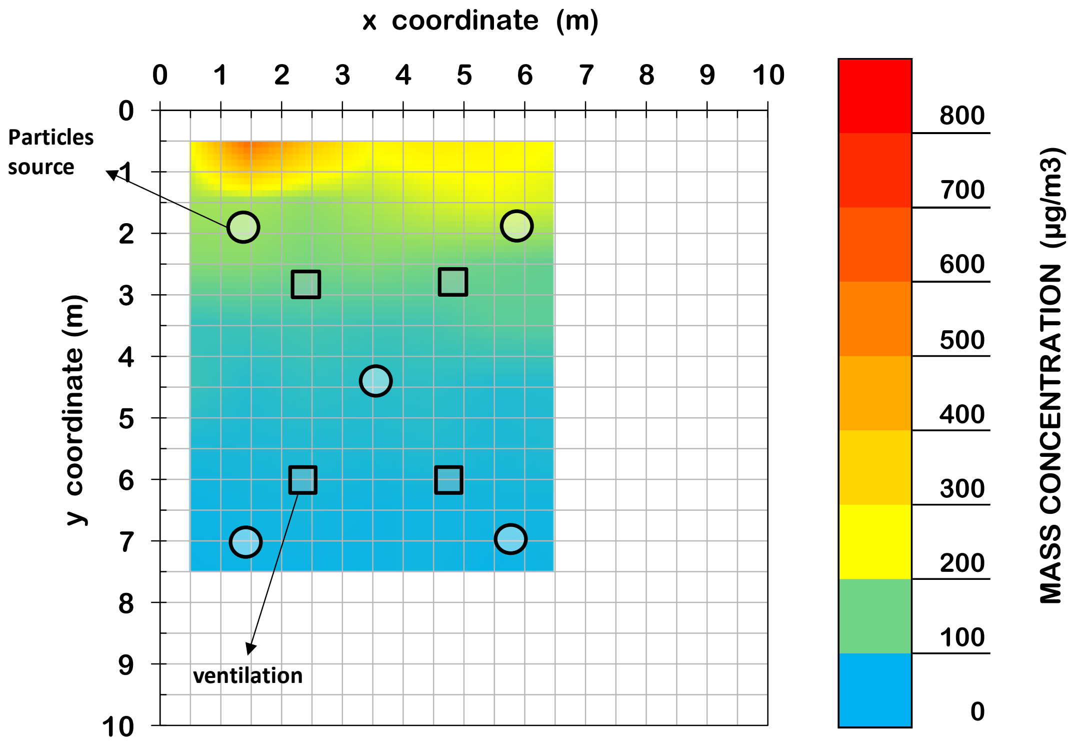
Appendix 1. Colour grid map data sheet (Trotec PM_{10})



MASS CONCENTRATION (µg/m3)

		1	2	3	4	5	6	7	8	9	10	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**x (m)**
1	**1**	276	775	762	429	420	382	377				
2	**2**	243	240	232	249	267	321	355				
3	**3**	193	175	180	144	166	176	149				
4	**4**	88	91	101	105	104	140	123				
5	**5**	62	62	53	56	58	33	40				
6	**6**	37	42	41	46	44	43	46				
7	**7**	22	21	17	20	23	35	30				
8	**8**	17	25	23	33	21	19	17				
9	**9**											
10	**10**											
	y(m)											

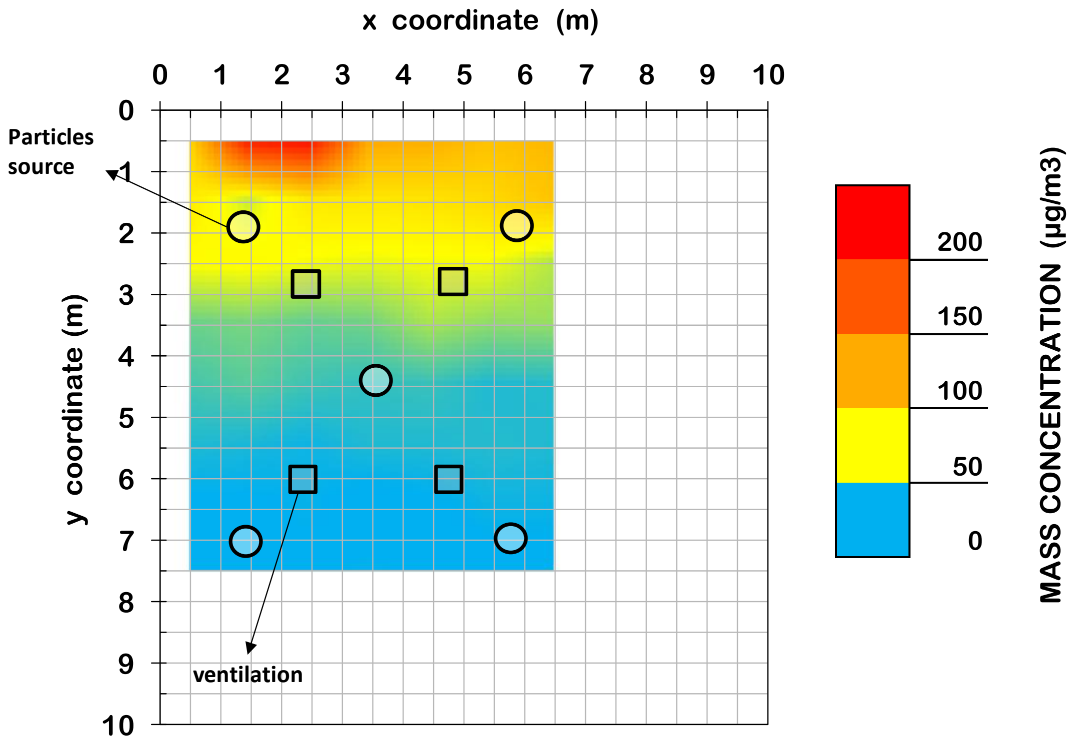
Appendix 2. Colour grid map data sheet (DustTrak PM_{10})



MASS CONCENTRATION (µg/m3)

		1	2	3	4	5	6	7	8	9	10	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**x (m)**
1	**1**	183	574	354	222	242	229	204				
2	**2**	135	138	125	142	170	189	176				
3	**3**	117	118	106	114	106	97	92				
4	**4**	60	65	70	67	69	84	86				
5	**5**	64	47	55	50	52	45	46				
6	**6**	39	40	43	42	45	40	43				
7	**7**	29	33	35	31	32	34	34				
8	**8**	28	29	29	30	33	27	31				
9	**9**											
10	**10**											
	y(m)											

Appendix 3. Colour grid map data sheet (Trotec $PM_{2.5}$)



MASS CONCENTRATION (µg/m3)

		1	2	3	4	5	6	7	8	9	10	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**x (m)**
1	**1**	68	190	198	102	99	87	93				
2	**2**	62	42	63	64	66	72	84				
3	**3**	51	53	49	47	49	49	39				
4	**4**	27	29	26	28	37	33	34				
5	**5**	21	24	20	18	19	15	16				
6	**6**	15	14	12	15	15	16	15				
7	**7**	9	9	11	7	9	12	12				
8	**8**	9	8	9	11	9	8	8				
9	**9**											
10	**10**											
	y(m)											

Appendix 4. DustTrak's calibration document

CERTIFICATE OF CALIBRATION AND TESTING

TSI Instruments Ltd, Stirling Road, Cressex Business Park
High Wycombe Bucks HP12 3ST England
Tel: (Int +44) (UK 0) 1494 459200 Fax: (Int +44) (UK 0) 1494 459700 http://www.tsiinc.co.uk

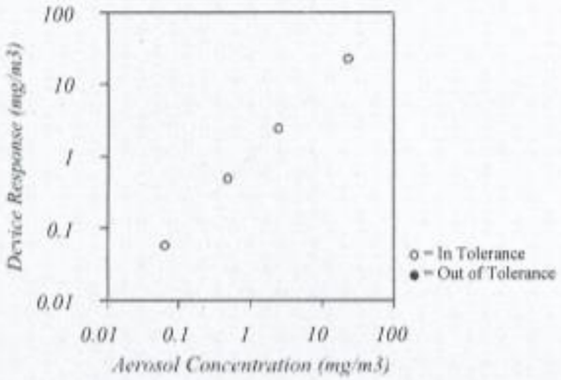
Environment Conditions		
Temperature	20.5	°C
Relative Humidity	47.02	%RH
Barometric Pressure	1017.6	hPa

Model	8520
Serial Number	14210

☒ As Left
☐ As Found

☒ In Tolerance
☐ Out of Tolerance

Concentration Linearity Plot



System ID: DTII02-01

Zero Stability Results

Average:	Minimum:	Maximum:	Time:
0.001 :mg/m³	0.000 :mg/m³	0.002 :mg/m³	2.10 :hrs.

TSI Incorporated does hereby certify that all materials, components, and workmanship used in the manufacture of this equipment are in strict accordance with the applicable specifications agreed upon by TSI and the customer and with all published specifications. All performance and acceptance tests required under this contract were successfully conducted according to required specifications. There is no NIST standard for optical mass measurements. Calibration of this instrument performed by TSI has been done using emery oil and has been nominally adjusted to respirable mass per standard ISO 12103-1, A1 test dust (Arizona dust). Our calibration ratio is greater than 1.2:1

Measurement Variable	System ID	Last Cal.	Cal. Due
Barometric Pressure	E006180	09-05-17	09-05-18
Humidity	E006182	09-05-17	09-05-18
Microbalance	UK WB13D0013	04-01-17	04-01-18
Pressure	E006180	09-05-17	09-05-18
DC Voltage	E003323	09-05-17	09-05-18

Measurement Variable	System ID	Last Cal.	Cal. Due
Temperature	E006182	09-05-17	09-05-18
Photometer	E003336	11-09-17	11-03-18
Flow and Temperature	E006128	16-01-17	16-01-18
DC Voltage	E003322	10-05-17	10-05-18

Calibrated

☐ Final Function Check

22 December, 2017
Date

Werkskalibrierzeugnis
Calibration test report
Certificat d'étalonnage

Hiermit wird bescheinigt, dass dieses Trotec-Erzeugnis in Übereinstimmung mit dem QM-Handbuch der Trotec GmbH & Co. KG nach DIN EN ISO 9001/9002 gefertigt wurde. Die Bestellvorgaben wurden eingehalten. Die Ausführung und Anzeigegenauigkeit der Geräte/Systeme wurde im Rahmen der Trotec Kalibrier- und Qualitätssicherungsmaßnahmen überwacht. Die Kalibrierung des Gerätes erfolgte gemäß ISO 21501-4.

This is to certify that this Trotec product has been made according to the TQM to the Trotec GmbH & Co. KG manual in accordance with DIN EN ISO 9001/9002. Ordering specifications are complied with. Execution of instruments / systems as well as testing of accuracy was carried out following Trotec calibration and quality assurance procedures. Item calibration has been made corresponding to ISO 21501-4.

Par ce document, nous certifions que votre produit Trotec a été fabriqué suivant les normes TQM de Trotec GmbH & Co. KG en concordance avec DIN EN ISO 9001/9002. Les spécifications stipulées dans la commande ont été appliquées. La réalisation des appareils/systèmes ainsi que les tests de précision ont été réalisés dans le cadre des procédés de qualité et d'étalonnage Trotec. L'étalonnage de l'appareil a été réalisé conformément à ISO 21501-4.

Typ/Type/Type: **PC220**

Genauigkeit/Accuracy/Précision:

Particle:	accuracy ±30 %
	counting efficiency 50 % @ 0.3 µm; 100 % for particles >0.45 µm
HCHO:	±5.0 % FS*
CO:	±5.0 % FS*
T:	±0.5 °C (0.9 °F) 10 °C to 40 °C
	±1.0 °C (1.8 °F) others
RH:	±3.0 %RH (40 % to 60 %)
	±3.5 %RH (20 % to 40 % and 60 % to 80 %)
	±5.0 %RH (0 % to 20 % and 80 % to 100 %)

Serien Nr./Serial Nr./N° de série: 1804105[illegible]0

Kalibriereinheit (Referenz)/Calibration unit (Reference)/ Équipement d'étalonnage (référence):

Fabrikat/ brand/Modèle:	LIGHTHOUSE 402999220-1/FLUKE 985
Zertifikat-Nr./Certificate-No./ N° de certificat	175104806
Serien Nr./Serial Nr./N° de série	51000020 / 1210993188
Genauigkeit/Accuracy/Précision:	+/10%um
Kal.-datum/Cal.-date/ Date d'étalonnage	2017-9-30
Standards/Standards/Normes:	JJF1190-2008

*FS = Full Scale

Umgebungsbedingungen/Environmental conditions/ Conditions environnementales:

Temp [°C]: 25,0 ℃

Rel. Hum [%]: 51,0 %RH

Datum/Date/Date: 2018-4-18

Messergebnisse/Measuring results/Résultats: Particle

Nr.	Messbereich/ Range/ Plage de mesure [µm]	Referenz/ Reference/ Référence [n]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [n]	Abweichung/ Deviation/ Écart [% (n)]	Status/ Status/ Résultat
1	0.3	105378	+/-30	102726	-3% (-2652)	Passed
2	0.5	32141	+/-30	31187	-3% (-954)	Passed
3	1.0	4726	+/-30	4497	-5% (-229)	Passed
4	2.5	428	+/-30	452	6% (+24)	Passed
5	5.0	78	+/-30	79	1% (+1)	Passed
6	10	21	+/-30	26	24% (+5)	Passed

Messergebnisse/Measuring results/Résultats: HCHO

Nr.	Messbereich/ Range/ Plage de mesure [PPM]	Referenz/ Reference/ Référence [PPM]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [PPM]	Abweichung/ Deviation/ Écart [%]	Status/ Status/ Résultat
1	0.01-5.00	0.25	+/-0.25	0.21	-0.04	Passed
2	0.01-5.00	0.40	+/-0.25	0.41	+0.01	Passed

Messergebnisse/Measuring results/Résultats: CO

Nr.	Messbereich/ Range/ Plage de mesure [PPM]	Referenz/ Reference/ Référence [PPM]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [PPM]	Abweichung/ Deviation/ Écart [%]	Status/ Status/ Résultat
1	10-1000	420	+/-50	415	-5	Passed