Accuracy improvement to low-cost air quality monitoring devices to enable their use in traffic management

Master by Research Thesis

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Abbreviation and Terminology

Low-cost sensor is a term used in this thesis to refer to sensors that cost 10's of British pounds or platforms (or kits or nodes) that cost 100's of British pounds.

Particulate matter (PM) is a pollutant of air made up of a mixture of particles of liquid and liquid that float freely in air. There are various origins, size and composition of particles. The aerodynamic diameter conveniently summarizes the three properties of PM. In addition, particles are described and sampled with respect to their concentration of mass ($\mu g/m^3$) in terms of their diameter (aerodynamic), commonly referred to simply as the particles size. It is also important to take into account parameters such as the surface area and number concentration.

The size fractions that are most commonly used include:

• **Total suspended particulates (TSP)** consisting of all airborne particles.

• **PM10** which is the term used in describing particles whose aerodynamic diameter is less than10 μm.

• **PM2.5** which is the term used in describing particles whose diameter does not exceed 2.5 μm.

In most cases, the mass concentration of PM10 is used indicator for describing particulate matter. The coarse fraction is made up of particles whose aerodynamic diameter range from 2.5 μm to 10 μm.

On the other hand, **ultrafine particles** are a term that refer to PM whose aerodynamic diameter is <0.1 μm.

Black smoke (BS) is a term that is commonly used in describing as well as indicating the “blackness” of aerosols (usually in the form of surrogate for soot). This is associated with a method of monitoring commonly used in the measuring of black smoke (BS). Usually, the optical method is adopted in monitoring. It is possible to convert the optical density into gravimetric TSP units by the use of calibration curve. However, such a conversion is dependent on the black particles' constituent found in the particulates that are suspended, making them to vary with respect to time as well as different types of monitoring site. It should be noted that this method has no existing validated international standard.

Black Carbon (BC) is in some cases used as a surrogate for soot. In this case, the optical method used in monitoring is commonly referred to as the aethalometer. This is a method that is used for comparing the light transmission via a particulates' loaded filter with transmission through a section of the filter which is unloaded.

Abstract

In the wake of the industrial revolution, air quality monitoring became the primary interest of the international health organizations and other related institutions, due to the increase in air pollution level which led to:

- increase number of deaths caused by the air contaminant
- economic loss due to crops damaging
- Global Warming

Source from: google.com/search?q=air+pollution&rlz 2010

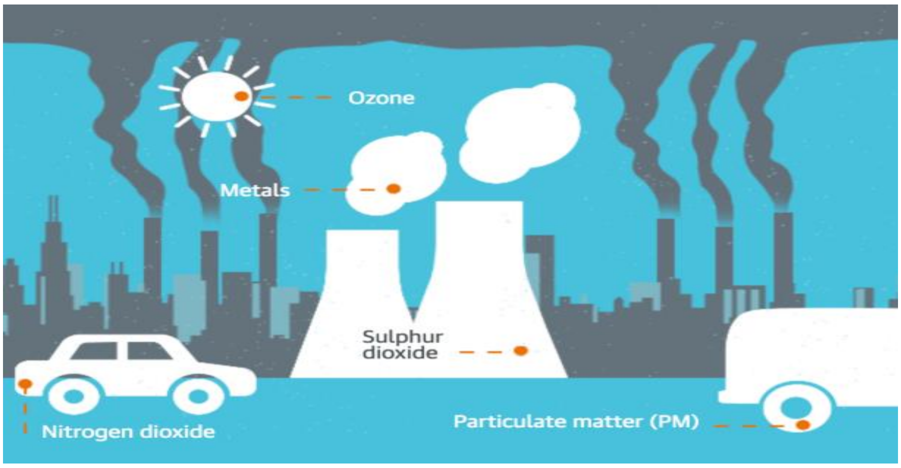
Air quality monitoring is a technology used to detect air contaminant level and collect precise data to enable the concerned institutions to take action in reducing air pollution. This aspect became the subject of technical improvement as part of EU reporting regulation, air annual status report (ASR), annual progress report (APR). Since the cost of the currently used methods is a significant high which are approximately £120 to 150K for each device in Kirklees area, a reliable and cheaper method is required to replace this conventional method that will be addressed in more details further in this thesis.

Air pollution elements can be defined in three types:

1- Solid particles such as particle matter PM10 and PM 2.5 etc. sources mainly from vehicle emission, factories process, dust, spores, volcanic ash also brakes and tyre friction.

2- Liquid droplets from contaminant steam condensation

3- Gases from power stations and vehicle emissions such as NO, SO2, CO, and O3, etc.



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This thesis mainly focusses on of the following pollution elements PM10 and PM2.5 as these elements have a very significant impact on human health.

Chapter 1: Introduction

1.1 Background

In the last few decades, there has been considerable improvement in the ambient air monitoring in most countries across the global. However, various evidence has revealed that the air pollution exposure affects health adversely. In particular, exposure to Particulate Matter (PM) and other pollutants has been reported is linked with increases in cardiovascular as well as respiratory disease, in addition to mortality across the global. In recent years, researchers have carried out studies with a view to quantifying the effects of health that come about as a result of ambient air pollution. According to WHO (2018), exposure to ambient air pollution over a longer period has resulted to a loss of more than 6 million healthy lives.

WHO updated its AQG in the 1990s with a view to providing detailed information regarding the manner in which human health is adversely affected by the exposure to various air pollutants (WHO, 2018). These guidelines were aimed at providing a basis for the protection of people's health from the effect of air pollution. In particular, the intention of these WHO guidelines was to provide guidance and information for authorities in making risk management decisions. These guidelines have been used by the European Union (EU) as a basis for setting binding air quality target values and limiting values for each EU member state for several pollutants, including OJ L 163 (1999), OJ L 313 (2000) and OJ L 067 (2002).

Particulate matter that is airborne contain organic substances and inorganic substances in a complex mixture. Composition and mass in urban environments are usually categorized into coarse particles and fine particles. The barrier between these two sizes of particles has a range of 2.5 µm and 1 µm. By convention, the limit of fine particles and coarse particles, for measurement purposes, is usually fixed at 2.5 μm in aerodynamic diameter (Gakidou, 2016). The smaller particles consist of combustion particles, metal vapours and recondensed organic vapours, and secondarily formed aerosols (conversion from gas to particle). On the other hand, the larger particles consist of fugitive dust from industries and roads as well as earth crust materials. However, the fine faction is made up of hydrogen ion (acidity) and PM's mutagenic activity, as well as the presence of some coarse acid droplets in fog. Although the fine mode (particles ranging from 100 nm to2.5 μm) usually makes up the most mass, the highest proportion of particles is found in minute particles not exceeding 100 nm. With reference to the volume-mass relationship, the contribution of ultrafine particles to the mass is a few percentages, while contributing to more than 90% of the number at the same time.

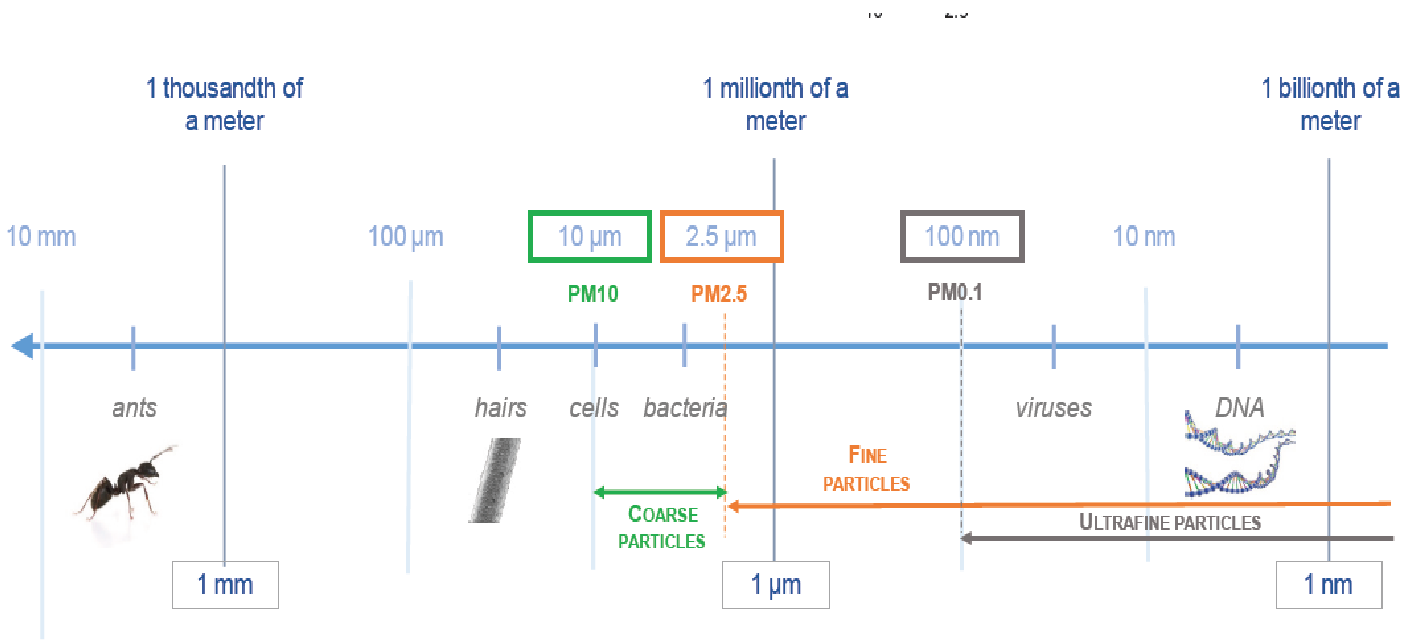


Figure 1: Relative size of ultrafine particles, PM10 and PM2.5 (Source: assets publishing service, 2020)

The pollution of particulate air is made up of suspended particles in air of mixture of liquid, solid or liquid and solid. The particles that are suspended have various in origin, composition as well as size. According to Gakidou (2016), particles may be categorized conveniently based on their aerodynamic properties due to the fact that such properties:

i) dictate the particles removal from the air and their transport;

ii) dictate their own disposition inside the respiratory system;

iii) are related to sources of particles and their chemical composition. The aerodynamic diameter, also referred to as the particle size, is used as a basis for sampling and describing particles.

The suspended particles' size varies over four orders of magnitude in the atmosphere, ranging from tens of micrometres (biggest) to unit nanometres (smallest). The coarse fractions or mode (the largest particles) are produced mechanically through the breaking up of larger solid particles. The particles can be made up of dust from mining operations, unpaved roads, uncovered soil or agricultural processes. Road dust and air turbulence is produced by traffic and the air turbulence usually stirs up the produced road dust. Besides, it is possible to produce large particles closer to coasts by the evaporation of sea spray. This large size range consists of plant and insect parts, mould spores, and pollen grains. To break the particles into smaller sizes, the amount of energy required increases with decrease in the size of these particles, thus effectively establishing a lower limit for the coarse particles production with size of approximately 1 µm.

On the other hand, the formation of fine fractions or mode (smaller particles) often originate from gases. In this case, the smallest particles (not exceeding 0.1 µm) are formed by nucleation. This involves the process of condensation of low-vapour-pressure substance through chemical reaction or through high atmospheric temperature vaporization for the formation of new particles (nuclei). According to Stone (2002), there are four major classes sources that have low enough equilibrium pressure for the formation of nuclei mode particles for the yielding of PM, and these include sulphates and nitrates, elemental carbon, organic carbon, and heavy metals (vaporized during combustion). The growth of the particles in the particular mode or range of nucleation is by either the processes of coagulation or condensation. Coagulation is the combination of at least two particles for the formation of a larger particle whereas condensation involves condensation of molecules of vapour or gas on the already existing particles' surfaces. Condensation is highly suitable for large surface areas while coagulation is highly suitable for large number of particles (Gakidou, 2016). As such, the efficiency and suitability of both condensation and coagulation decrease with increase in the size of the particle, and this results in an upper limit in such a way that the growth of particles by these processes does not exceed approximately 1 μm. therefore, the particles usually accumulate at a range between 0.1 μm and 1 μm, and this is commonly referred to as accumulation range.

The production of particles with a sub-micrometre size may be carried out through condensation of organic compounds or vaporized metals in combustion processes involving high temperatures. Alternatively, the production can be achieved through condensation involving gases obtained via conversion in the atmospheric reactions to substances that have low vapour and pressure (that is, low-vapour-pressure substances) (Gakidou, 2016). A case in point, the oxidation of sulphur dioxide for the formation of sulphuric acid in the atmosphere, and the sulphuric acid can then be form ammonium sulphate through neutralization by ammonia. Another example is the oxidization of nitrogen dioxide to nitric acid. The nitric acid then reacts with ammonia for the formation of ammonium nitrate. These particles which are produced in the intermediate reaction of atmospheric gases are commonly referred to as secondary particles.

A few years ago, a comprehensive report on phenomelogy of PM was compiled in Europe (OECD, 2016). Organic matter and sulphate are two of the major contributors to the average annual $PM_{2.5}$ and PM_{10} mass concentration, with exception of kerbside side in which mineral dust is also a major PM_{10} contributor. However, nitrogen is also a major contributor of $PM_{2.5}$ and PM_{10} in case PM_{10}> 50 μg/m^3. On the other hand, black carbon contributes PM2.5 ranging between 5% and 10% in all sites, while contributing somewhat less to PM_{10}, including in sites with natural background. In addition, the contribution of black carbon at some of the kerbside sites increases in to 15-20%.

Numerous terms have been used in the description of particulate matter owing to its complexity as well as the importance of the size of the particle in the determination of exposure and human dose. Some of these descriptions are defined and derived from analytic and/or sampling method. Other descriptions are in reference to the deposition site within the respiratory tract, including “thoracic particles” that deposit in the lower respiratory tract, “inhalable particles”, passing into the upper airways (mouth), as well as “respirable particles” penetrating to the lung’s gas-exchange region (Hendriks, 2013). However, there are other terms, including PM_{10} that have both sampling and physiological connotations.

1.2 Aim and objectives of Research Programme

To investigate the outdoor low-cost monitoring air quality systems to enable their use in traffic management mainly in the United Kingdom.

The following objectives to be achieved:

OBJ 1: research and study the causes of air pollution in the polluted areas.

OBJ 2: study the conventional air quality monitoring methods and analyse their advantages and disadvantages in term of traffic, and varying temperature.

OBJ 3: research and develop a desired lower cost monitoring technology that able to detect the required air contamination of the following: PM2.5 and PM10.

OBJ 4: Analysis and validate data collected from the new technology with National Physic Laboratory NPL and ensure the accuracy requirements.

OBJ 5: research a potential real-time and high accuracy monitoring methodology that covers the entire targeted areas to obtain a comprehensive valuable monitoring network.

Chapter Two: Literature Review

2.1 Introduction

Previous results of measurements carried out in recent years in suburban Birmingham revealed some distributions of the number, volume and surface area of the particles based on their size. Most of the particles, as shown in the figure, are quite small, <0.1 μm, while the volume of most of the particles (and consequently most of the mass) are for the particles which are not as tiny, that is >0.1 μm. Composition and mass in the urban environments are usually categorized into two groups, including fine particles and coarse particles. These two categories have a boundary that range from 1 μm to 2.5 μm. Moreover, the limit between fine particles and coarse particles is usually fixed at 2.5μm (that is, PM2.5) by convention for measurement purposes. Figure 2 shows the fine fractions and coarse fractions. Figure 3 shows the heterogenic composition of particulate matter, and it shows the electron microscopic images of samples of particulate matter that were collected at two Australian monitoring sites.

Fine particles are made up of aerosols which are secondarily formed, combustion fuels and re-condensed metal and organic vapours. Moreover, the fine particles consist mostly of the hydrogen ion (acidity) as well as mutagenic activity of particulate matter, while coarse fraction mostly consists of contaminants like the bacterial toxins. Secondary inorganic ions (including ammonia, sulphates and nitrates), carbonaceous materials (including both elemental carbon and organic carbon), heavy metals, crustal materials and water are among the key chemical species that contribute the most to the mass of fine PM. Figure 4 shows the size distribution of various components of PM10. Table 1 shows an overview of various characteristics of coarse and fine particulate matter. In some instances, it is necessary to farther divided fine particles into separate modes

• **The accumulation mode** which consist of particles that do not usually grow into the coarse mode and ranges between 0.1 μm and 1 μm.

• Ultrafine particles, is a common term used in a number of studies, is made up of Aitkin particles and nucleation modes. The process of coagulation is involved in the growth of Aitkin- and Nucleation- mode particles (that is, a pair of particles combining to form a single particle) or by condensation before “accumulating” in this size range.

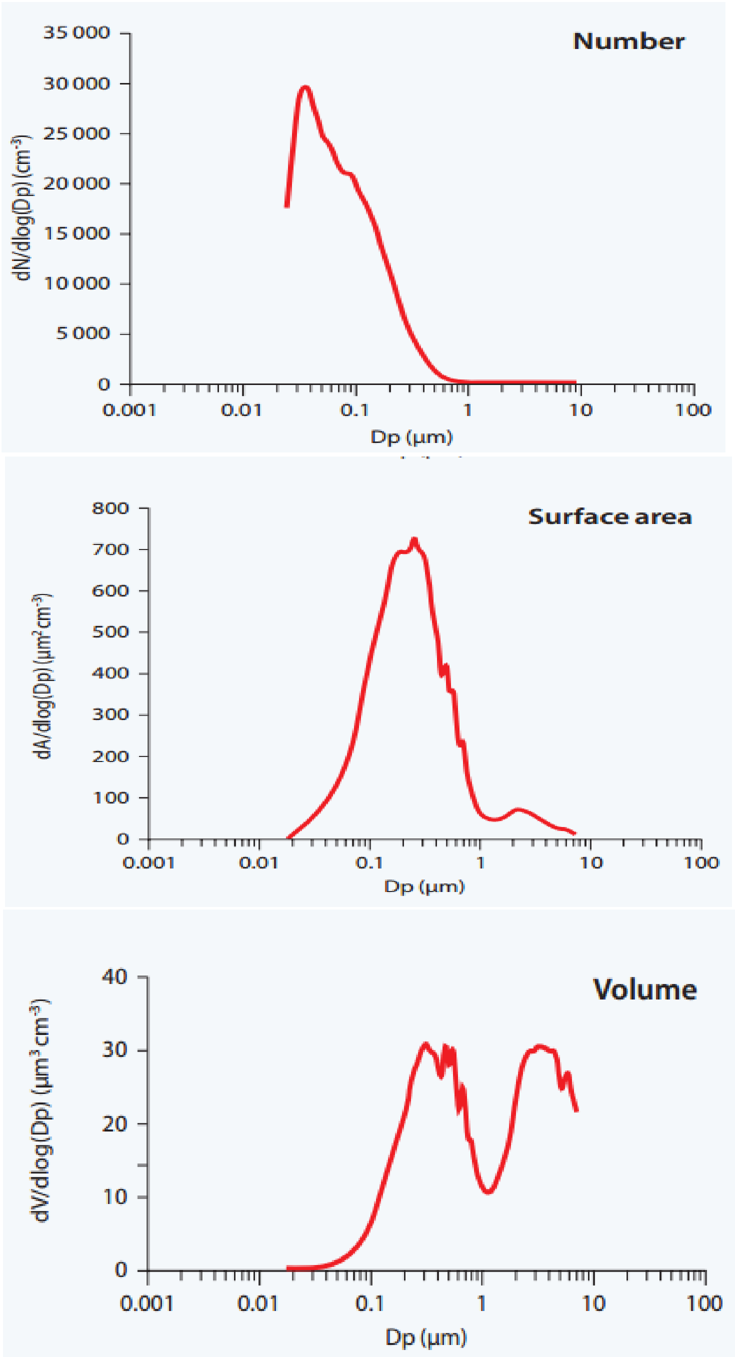


Figure 2: Particle size distribution measured in Birmingham, England (assets publishing service, 2018)

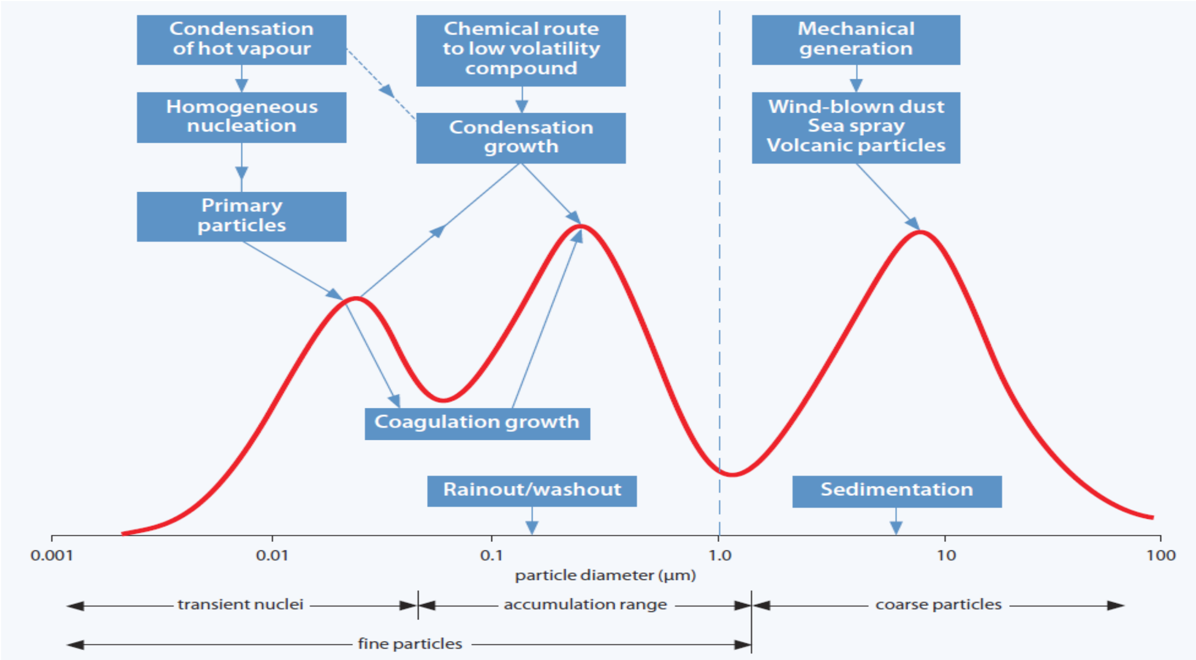


Figure 3: the PM size distribution in ambient air

(Source: http://www.euro.who.int/pubrequest, 2018)

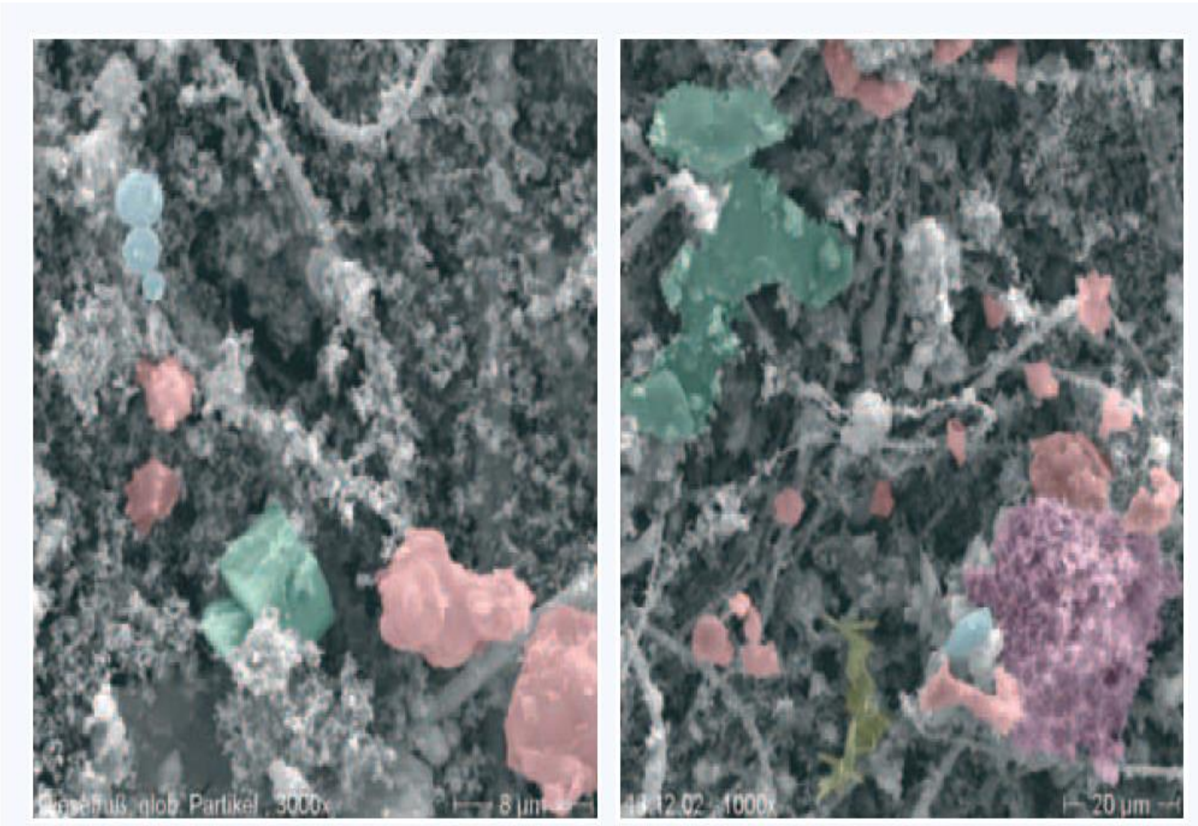


Figure 4: Sampled EM PM10 images at two Austrian traffic monitoring sites (Source: http://www.euro.who.int/pubrequest, 2018)

Table 1: Comparison of fine- and coarse-mode particles

(Source: www.euro.who.int/pubrequest, 2018)

	Fine (< 2.5 µm)		Coarse (2.5–10 µm)
	Ultrafine (< 0.1 µm)	Accumulation (0.1–1 µm)	
Formation processes	Combustion, high-temperature processes and atmospheric reactions		Break-up of large solids/droplets
Formation	Nucleation Condensation Coagulation	Condensation Coagulation Reaction of gases in or on particles Evaporation of fog and cloud droplets in which gases have dissolved and reacted	Mechanical disruption (crushing, grinding, abrasion of surfaces) Evaporation of sprays Suspension of dusts Reactions of gases in or on particles
Composition	Sulfate Elemental carbon Metal compounds Organic compounds with very low saturation vapour pressure at ambient temperature	Sulfate, nitrate, ammonium and hydrogen ions Elemental carbon Large variety of organic compounds Metals: compounds of lead, cadmium, vanadium, nickel copper, zinc, manganese, iron, etc. Particle-bound water	Suspended soil or street dust Fly ash from uncontrolled combustion of coal, oil and wood Nitrates/chlorides from nitric acid/ hydrochloric acid Oxides of crustal elements (silicon, aluminium, titanium, iron) Calcium carbonate, sodium chloride, sea salt Pollen, moulds, fungal spores Plant and animal fragments Tyre, brake pad and road wear debris
Solubility	Probably less soluble than accumulation mode	Often soluble, hygroscopic and deliquescent	Largely insoluble and nonhygroscopic
Sources	Combustion Atmospheric transformation of sulfur dioxide and some organic compounds High-temperature processes	Combustion of coal, oil, gasoline, diesel fuel, wood Atmospheric transformation products of nitrogen oxides, sulfur dioxide and organic carbon, including biogenic organic species such as terpenes High-temperature processes, smelters, steel mills, etc.	Resuspension of industrial dust and soil tracked onto roads and streets Suspension from disturbed soil (e.g. farming, mining, unpaved roads) Construction and demolition Uncontrolled coal and oil combustion Ocean spray Biological sources
Atmospheric half-life	Minutes to hours	Days to weeks	Minutes to days
Removal processes	Grows into accumulation mode Diffuses to raindrops	Forms cloud droplets and is deposited in rain Dry deposition	Dry deposition by fallout Scavenging by falling rain drops

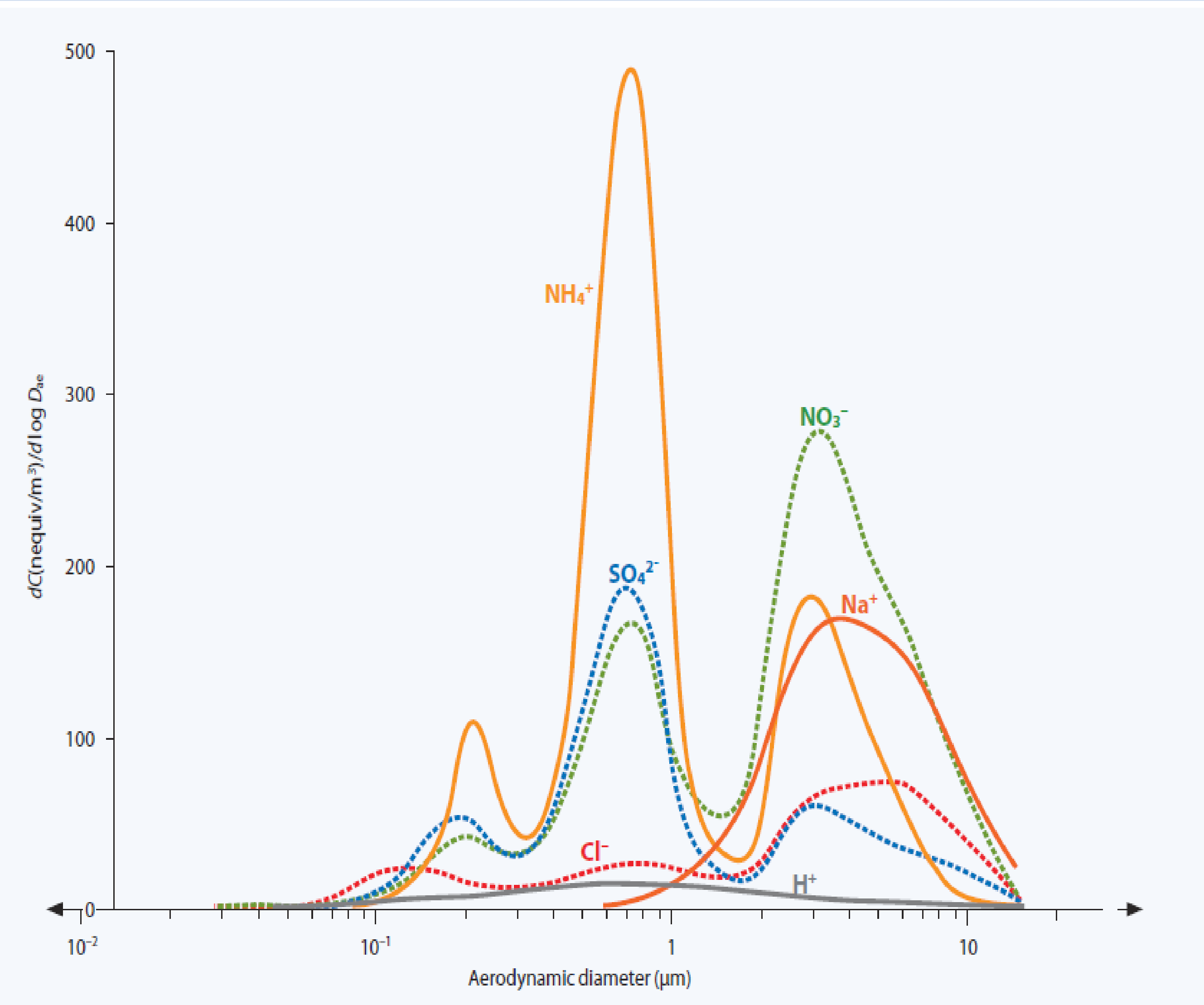


Figure 5: Aerodynamic parameter of PM10’s of the main chemical components

(Source: http://www.euro.who.int/pubrequest, 2018)

Road transport is among the major sources of air pollution affecting the human life quality in addition to the natural environment, thus the need for drastic actions for reduction of harmful particulate matter and gases. More efforts have been over the years focused on developing a number of different applications that are applicable in ITS, not just for reducing energy consumption and reducing emissions from activities related or transportation or improving traffic flow, but also to monitor pollution of air (Ferreira, 2014; Allegrini, 2008). There are various solutions air pollution that are already in existence, such as static measurement stations' networks, which are not only characterized by reliability but also high accuracy in addition to the ability of measuring various air pollutants. Installing these systems has continued to face severe limitations owing to the high-cost purchase and maintenance (Hasenfratz, 2015). Penza (2012) mentioned that as far as profitability is concerned, it is possible to use vehicles that have been equipped with measurement devices as mobile air pollution monitoring laboratories that have high temporal and spatial resolution.

It is becoming more evident that development of portable devices that are cost-effective that are mountable on roads sides with a view to supporting wider applications interest in intelligent transportation systems (ITS) is a challenge in the field of research. For example, sensing units mounted on the roads for public transportation that are meant for displaying real-time pollutants level as well as high-resolution maps generation for the pollution of air in urban. (Al-Ali et al., 2010; Elen, 2013; Velasco, 2016; Keifer & Benrendt, 2016; Ioakimidis & Rycerski, 2016). The combination the latest low-cost sensors market development with available information and communication technologies has made it possible to design and implement portable, inexpensive and compact sensor units for the creation of profiles of concentration of aerosols that have detailed temporal and spatial resolution in addition to deploying networks of the devices in the form of mobile agents who operates simultaneously under analysis of scheme of big data with a view to developing applications and providing additional services in the intelligent transportation systems (ITS) context (Park et al., 2011; Choi, He, & Barbesant, 2012; Hu et al., 2012). The need for quantifying the low-cost sensors' performance in the actual condition has been emphasized by various researchers (Al-Ali et al., 2010; Elen, 2013; Velasco, 2016; Keifer & Benrendt, 2016; Ioakimidis & Rycerski, 2016). To that end, various experiments have been conducted with a view to examining the consistency, durability and stability of the sensing units, by the use of hourly data for the concentrations of particulate matter (Mukherjee, Stanton, &

Graham, 2017). The focus of this present study on outdoor low-cost monitoring air quality to enable their use in traffic management mainly in the UK, especially PM, whose exposure causes chronic and acute health problems to human.

One of the most important parts of the pollution of air monitoring system have been introduced in this thesis, in addition to describing the testing of the sensing unit in the fields as proposed by the use of measurements taken nearby road connected with computer that has an instrument of reading calibration as the comparison making item as well as showcasing its precision on specifying the concentrations of the PM on one minute resolution in an experiment carried out on the area. It should be noted that this thesis is focused on investigating low-cost measurements system for mapping ambient concentration PM in the ambient air after being calibrated on-field.

2.2 Monitoring PM2.5 and PM10 concentrations

There has been a lot of focus, in recent years, to develop low-cost portable sensors with the ability of providing reliable data that relate to emissions by traffic, especially in cities and urban areas, by the use of latest analysis of big data advancement as well as the technology of wireless sensor network communicating with sensor node infrastructures (Yi et al., 2015). Mobile measurements have been designed in such a way that they can be used in multiple spots in addition to being tested in various applications including automobiles, public transport, bicycles, and pedestrian wearables, among others, with a view to introducing inexpensive air mapping solutions (Kuhlbusch, Quincey & Fuller, 2014).

According to Kuhlbusch, Quincey and Fuller (2014), trials conducted on the roads using specified experimental instruments have showed results that have been adopted as benchmark for the footprint of real-time vehicles emissions. Methodologies of these nature have been adopted for a number of different objectives, including personal exposure assessment by the provision of equipment to the object of the study (Rakowska & Wong, 2014), mapping of air pollutions' spatial variation (Van Poppel et al., 2013), or developing and validating models of air quality (De Nazelle & Seto, 2013).

A study by Smith and Li (2016) addressed the possibility of the use of mobile measurements in constructing high spatial resolution maps of air pollution. In recent years, techniques of mobile monitoring have also been receiving increasing attention in the participatory crowdsourcing and sensing methods (Thompson, 2016; Leonardi et al., 2014), therefore setting the filed for the investigation of the relationship between human health and air quality for urban citizen science. Jafari et al. (2015) reported that sensing projects based within communities are increasingly advocating for low-cost sensor instrument for both mobile and large-scale deployment.

Roadside measurements have been providing instantaneous pollutant concentration ratios from passing vehicles on the roadway in which the station has been installed. In addition, mobile sensing makes it possible to monitor emissions linked with spatio-temporal ratio resolution which is tuneable for matching levels of emission with specific vehicle (Deville et al., 2016). The sensing approximation is currently used in roughly estimating value of concentration of particulate matter, mostly obtained from tires, exhausts, fuel combustion and secondary particles generated under particular operating conditions at specific location in the atmosphere and are reliant on the radical changes of the recently developed low-cost sensing components with a view to producing more trustworthy heavy traffic's quantitative model (Mar´c et al., 2015). It is therefore developing better emission factor models for capturing the particulate matter footprint from different sources is a challenging task, only on the basis of inexpensive mobile sensing instruments. In addition, there is the need for designing of mobile systems to deal with background pollution levels and unstable weather that hinder the evaluation of actual emissions of vehicles.

2.3 Industrial emissions trends in the United Kingdom

Industrial emissions of various gases to the atmosphere have significantly decrease since 1990. For instance, there has been 74% reduction of industrial emissions of nitrogen oxide to air, 97% reduction of sulphur dioxide emissions, and 73% reduction in the emissions of volatile organic compound (NAEI, 2018). However, significant contribution is still made by industrial emissions to total emissions in the United Kingdom, including 65% of sulphur oxide, 53% of volatile organic compounds, 35% of nitrogen oxide, and 27% of particulate matter in 2018 (NAEI, 2018). Projected emissions estimate to 2030 put forward the need for more action from the industrial sector with a view to meeting the emission reduction targets in the United Kingdom.

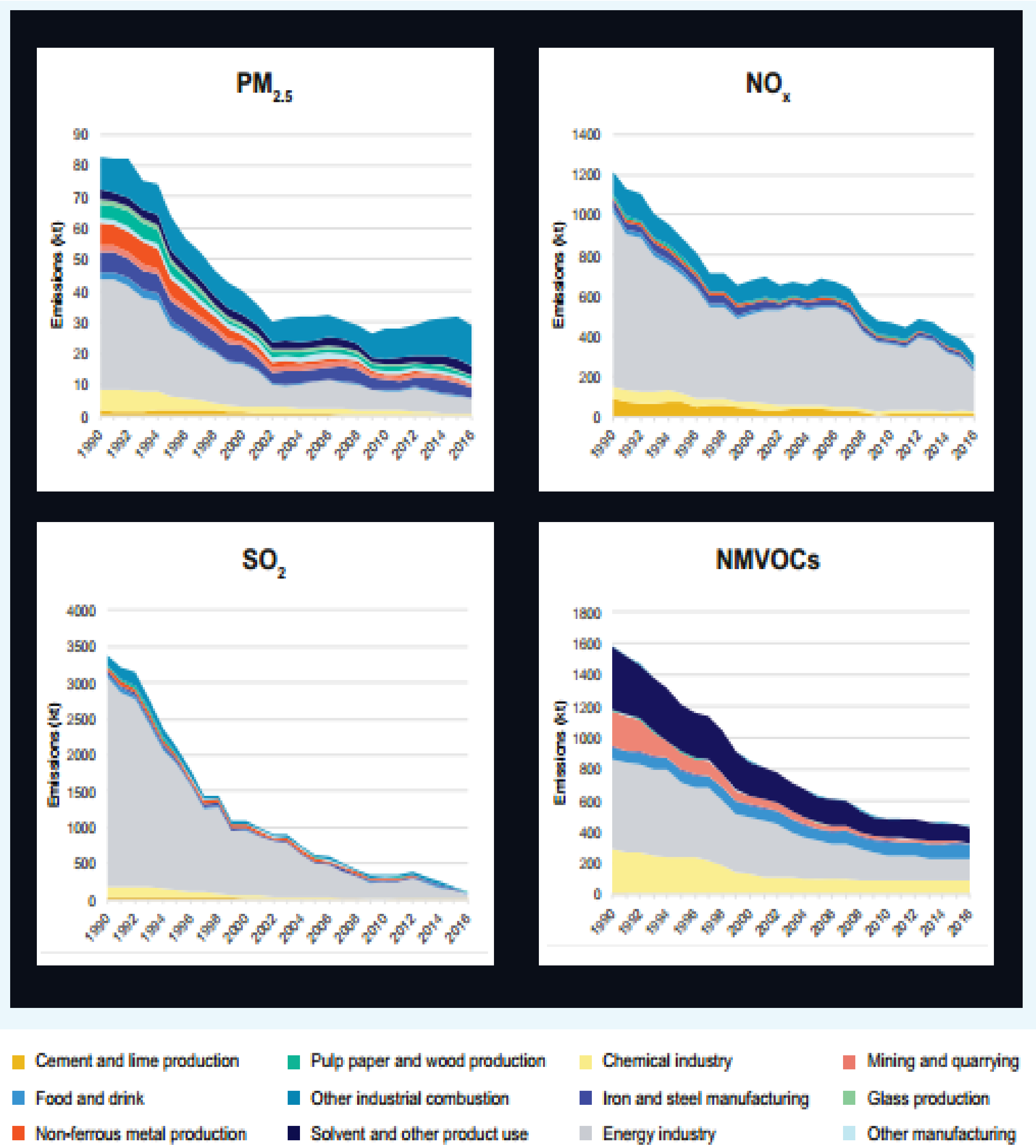


Figure 6: Industrial emissions trends in the United Kingdom (Source: assets publishing service, 2018)

The focus of the Industrial Emissions Directive in the United Kingdom has been placed on the activities that are most polluting to the air. There is the need to control emissions from smaller industrial plants, large buildings, offices, hospitals and schools. The table below shows the baseline emissions of five major pollutants in 2005 in addition to the commitments to reduce them within 2020 to 2030.

Table 2: five key pollutants baseline emissions in 2005

(Source: http://naei.beis.gov.uk/)

Pollutant	**2020 gap to ceiling (kt)**	**2020 CAS impact (kt)**	**2030 gap to ceiling (kt)**	**2030 CAS impact (kt)**
SO_2	-190	Around 5	4	35 to 55
NO_x	-36	Around 10	95	75 to 150
NMVOCS	-23	Around 20	83	50 to 95
NH_3	14	Around 25	35	Up to 65
PM2.5	14	Around 15	31	Up to 40

Based on the table above, it is likely that the emissions ceiling for $PM_{2.5}$ and NH_3 will be exceeded in 2020 and the emissions ceiling for all the five pollutants will be exceeded in 2030 if no action is taken. However, the policies already set out in the United Kingdom should be able to ensure that all the emission ceilings are met.

2.4 Effects of PM and impact on climate change

PM Airborne impact does not affect human health only in fact, it has significant effects on the environment climate change. The following subsections offer an overview demonstrating the importance of decreasing the levels of particulate matter, as well as the linkages between various impact areas.

2.4.1 Health effects

The duration of exposure and the size of the particles are key determining effects factors of the potential adverse on health. PM_{10} has the ability of breaking through the lungs, thus posing a risk to health. However, $PM_{2.5}$ is associated with a very strong evidence for effects on human health because they are fine particles. Ultrafine PM poses even greater risk to health as they can not only penetrate deeper into lung tissue. the impact on health include irritation to throat and nose, chest tightness, shortness of breath, and coughing, as well as irritation of the eyes. Individuals with existing cardiovascular and respiratory conditions, children and the elderly people are particularly at risk of the effects of particulate matter when the levels of air pollution are elevated. This also results in increase in hospital admissions and deaths because of such causes. According to Gakidou (2016), the United Kingdom experienced widespread high levels of particulate matter pollution of air ($PM_{2.5}$ at urban background sites up to 83µg/m^3) in a number of days in March and April 2014. Gakidou (2016) reported that the widespread high levels of particulate matter pollution of air were associated with approximately 1,570 emergence cardiovascular and respiratory admissions in hospital and about 600 deaths. Long term exposure to particulate matter reduces life expectance, possibly due to contribution to development and progression of respiratory and cardiovascular diseases, in addition to exacerbation of symptoms to individual already suffering from these diseases.

Longer exposure to PM also increases the risk of lung cancer, and particulate outdoor air pollution is carcinogenic to humans as classified by IARC, that is IARC Group 1. The PM has consistently shown adverse effect on health at exposures that the urban population are currently experiencing. Moreover, there is strong correlation between exposures to high PM concentrations and increased morbidity and mortality, both over time and daily. Although air pollution is not the sole cause of death in most of these cases, it is considered as one of the major contributing factors. Cohort studies have revealed that the risk associated with living in locations that have elevated levels of particulate matter over long period of time is of greater magnitude in comparison to that observed from studies focusing on the effects of variations in daily exposure. The PHE Public Health Outcomes Framework (PHOF) health indicator on the air pollution estimated the percentage of adult mortality that is associated with exposure to PM air pollution (especially $PM_{2.5}$) over a long period of time in local authorities' areas in the United Kingdom. It was found it ranges from at most 3% in areas with least pollution to more than 7% in some of the London boroughs. Thompson, (2016) reported that the average for the United Kingdom was 5.1% in 2016.

According to the COMEAP (2010), results have shown that PM makes significant contribution towards various causes of human mortality. During pollution episodes, there is the occurrence of less severe effects of exposure to particles over a shorter period of time, and these include worsening of asthma symptoms as well as generally not feeling well, resulting to lower activity level.

According to COMEAP (2010), the best estimate of the effect of the exposure to PM on chronic health was a 6% increase in the rates of deaths for every concentration of 10 $\mu g\ m^{-3}$ of $PM_{2.5}$. However, no fully safe levels of particle exposure have been identified yet. However, the conclusions under consideration are relating to particulate matter measured based on mass rather than various sources or components of particulate matter. Currently, the particles' properties have not been understood clearly yet, and they are most responsible for the toxic effects. According to WHO (2018), particulate matter is a mixture of numerous components which may differ from each other based on their toxicity, although the available data are not sufficient to confidently separate their effects on health. Due to the lack of opposing evidence, it has been recommended that the coefficient should equally apply to every component of $PM_{2.5}$, and this includes PM measured as nitrate and sulphate. However, this does not in any way imply that every component of $PM_{2.5}$ have the toxicity, rather than that, at present, there is no evidence to quantify various components of $PM_{2.5}$ differently in a manner that is likely to gain wide consensus. Moreover, as more mitigation measures are introduced and the emergence of new resources and technologies, it is highly likely that there will be variation in the constituents of particulate matter as time goes. An improvement in the understanding of the composition and the behaviour of particulate matter will better the understanding of its health impacts.

The most susceptible individuals to the health effects of particulate matter are those who suffer first from the morbidity and mortality, thus the increase in day to day concentration of particulate matter is likely to result in the daily mortality and morbidity. However, if the PM concentration remains at a high level, the most susceptible guys in the previous day will already have experienced the health effects. On the other hand, if none of the new individuals have joined the other most susceptible individuals, then there will be a decrease in the number of individuals at risk, thus consequently decreasing the effects found, including hospital admissions, morbidity, mortality, and symptom exacerbation. In case new members have entirely filled up the group of individuals who are susceptible to health effects the most, then the effect of the actual air pollutants' concentration is likely to be the same as that of the previous day, and such an effect is related directly to the absolute concentration rather than the change in concentration.

On the other hand, in case the group of every person who is susceptible is yet to be filled up, then it is likely that the acute effect will be significantly smaller and be associated to the change in concentration and only partially to the absolute concentration. However, the actual situation may fall in between these two extremes, implying that group of every susceptible person is once again filled up with some lag time as illustrated in the figure below.

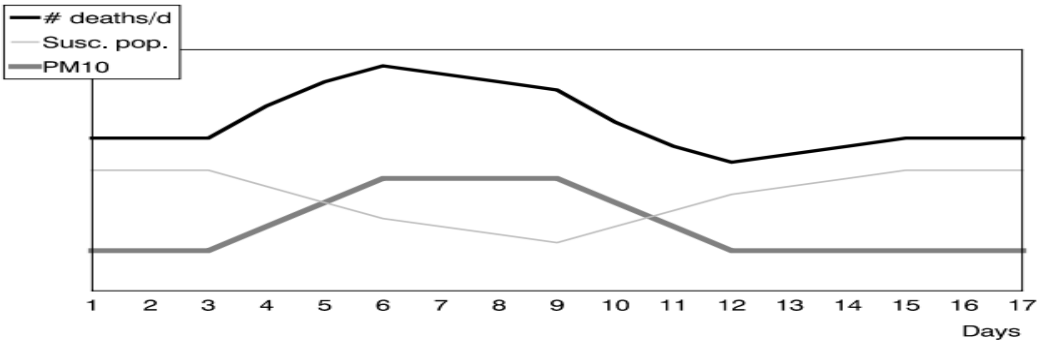


Figure 7: interrelation between the number of deaths, PM10 and susceptible population (assets publishing service, 2018)

2.4.2 Ecosystem impacts of PM in the United Kingdom

Both $PM_{2.5}$ and PM10 have impact on ecosystems, both directly and indirectly. As far as direct effects are concerned, aerosols are deliquescent and hygroscopic, and can occur as a liquid on transpiring leaves. According to Burkhardt (2010), aerosols deposited on the surface of leaf make it possible for the efficient bi-directional transport of solutes and water between the surface of the leaf and the interior of the leaf. With large accumulation of particulates on leaves, there may be regional tree dieback owing to the affected drought tolerance of the trees. However, aerosols also have indirect effect through the modification of exposure of plant to sunlight. Researchers and observers have both showed that efficiency of photosynthesis is significantly increased under the conditions of diffuse light.

Man-made aerosols usually have indirect effect on ecosystem because of the part they play as air pollutants' long-range vectors. The formation of ammonium nitrate and sulphate aerosol occur by oxidation of atmosphere as well as reaction of ammonia with precursor gases such as NO_x and SO_2 (Seinfield & Pandis, 1998), and is made up of a major fine PM component. $PM_{2.5}$ contributes to deposition of nitrogen and sulphur, resulting in the eutrophication and acidification of natural ecosystems. There are two different ways in which surface deposition of $PM_{2.5}$ may occur, and these include wet deposition and dry deposition. Dry deposition a flux driven direct deposition of aerosol to vegetation. This may be in the form of dry particles or in the form of cloud droplets formed by aerosols activation. According to Pruppacher and Klett (2010), particles of aerosol play the role of cloud condensation nuclei and are added into cloud water efficiently at the formation of droplet. The concentration of nitrogen and sulphur in cloud water in upland forests may be much higher than in precipitation. Cape (1993) mentioned that particulate sulphur concentrations in the range ranging between 1µg m^{-3} and 3 µg m^{-3} integrated into cloud water tend to bring about impairment to the foliage through direct cloud droplets deposition. However, there are seemingly no direct effects of direct particles on vegetables rather than in cases in which the leaf surfaces are covered, such as dust from agricultural or industrial activities.

Various reports have been made on the direct deposition estimates of dry particulate sulphate and nitrogen in the United Kingdom by the use of technique commonly referred to as CBED (RoTAP, 2012). CBED is a technique integrating measurements from AGANet with deposition velocities which are specific vegetation. Dry deposition of particulate ammonium, nitrate as well as sulphate annually to the United Kingdom was approximately 8 Gg N-NHx, 7 Gg N-NOy, and 3 Gg sulphur (S), respectively, averaged between 2006 and 2010.

Wet deposition, on the other hand, is a mechanism used in the efficient removal of particulate matter from the atmosphere. Wet deposition uses precipitation to remove atmospheric particulate matter. The cloud droplets growth results in the forming of raindrops which then deposit PM found in the solution to the surface of the earth. Owing to the gas's solubility such as ammonia, nitric acid as well as sulphur dioxide in rainwater, distinguishing the relative contributions of particulates and gases is not possible by measuring concentrations in precipitation. However, atmospheric transport models have successfully been used to show that PM's wash-out is the mechanism which is the most dominant in the wet deposition of nitrogen and sulphur, especially in far off upland regions that have delicate ecosystem. Fine PM is a pollutant of air that has a link to long-range trans-boundary transportation.

The contribution of deposition of nitrogen and sulphur is usually generated by the use of source-receptor matrices. Nyri et al. (2010) reported that the modelling results have revealed that the primary pollutants emissions from sources out of the UK (e.g. international shipping and other countries) contributes 46% of nitrogen disposition and 43% of total sulphur deposition in the United Kingdom in terms of long-range transportation of PM. Therefore, particulate form of sulphur and nitrogen pollutants is a representation of an important link between long-range transport of primary gaseous emissions and eventual deposition in precipitation in the United Kingdom's ecosystems.

The assessment of indirect effects of particulate matter on ecosystem through dry deposition and wet deposition can be done by taking into consideration the impact of total deposition on processes of soil as well as on ecosystems, and this is commonly referred to as "critical load". It is a numeric estimation of a subjection to unitary or multiple pollutants which if not reached results in harmful effects on particular environment's sensitive element do not occur (UBA, 2004).

2.4.3 Effect of change in Climate of PM in the UK

The United Kingdom's report on the Climate Change and Air Quality (AQEG, 2007) provided a thorough overview of interactions between air quality and climate. The report took into consideration particulate matter, Ammonia, NO_x, SO_2 and VOCs are all predecessors of secondary aerosols. Owing to the fact that aerosols are reflective, they tend to scatter solar radiation back to space as well as exerting cooling (negative) radiative forcing effect on climate. Moreover, aerosols have effect on the radioactive properties of clouds. As such, there is likely to be increase in temperature following reductions in secondary aerosols as well as the precursors of secondary aerosols. Previous studies have shown that sulphate aerosol has cooling effects that may partly mask the greenhouse gases' masking effects.

Nevertheless, solar radiation is absorbed by the black carbon, while black carbon aerosols or aerosols mixtures that have larger percentage of black carbon bring to the climate warming radiative forcing effect. Such an impact is normally pointed out in cases in which the black carbon aerosol is found on top of the reflective surfaces such as ice and snow or clouds. In the United Kingdom, the black carbon emissions have significantly reduced over the recent years, but significant increase of emissions has been reported in India and China (AQEG, 2007).

In some cases, aerosols can act indirectly through the modification of the clouds' radiative properties. This is by acting as the nuclei of cloud condensation, increase in the concentration of droplet number while reducing the clouds' average size of the droplet. However, the process has effect on the clouds' ability to scatter radiation. Moreover, there is the reduction of the clouds' precipitation efficiency, consequently increasing their lifetime. Although the magnitude of aerosol is highly uncertain, its overall indirect effect is cooling.

The concentration of methane and carbon dioxide is also significantly affected by air pollutants due to their effects on sinks and sources of ecosystem. They consist of the effect of deposition of nitrogen gas in the increase of the growth of the plant and, consequently, uptake of carbon, as well as the effects that deposition of sulphate has on major natural sources through the reduction of the emissions of methane.

2.4.4 Effects of climate on PM

Over the years, making prediction on the effects of change in climate on regional quality of air has been difficult. Soil dryness, surface temperature and temporal variations are important factors in the understanding of the severity of future summers. Volatile organic compounds are precursors of ozone, making them to affect climate indirectly. Temperature increase during changes in climate brings about variations in the chemistry of ozone formation. This significantly affects water vapour concentration, thus resulting in the decrease in background troposphere's ozone, while increasing more areas facing pollution in areas having higher NO_x concentrations. Moreover, there may also be the increment in the ozone flux to the troposphere from the stratosphere. It has been predicted that there is likely to be higher frequencies of episodes of summer pollution by 2040s similar to hot summer in 2003 which was associated by a significant episode of photochemical smog in south-east of England and other parts of Europe. It was reported that volatile organic compounds emissions from vegetation contributed towards the summer pollution episode of 2003 (Nyri et al., 2010). Thus, temperature increase resulted in the increase in the emissions of isoprene and other biogenic compounds.

Summary of the Chapter

This chapter has been divided into four major sections, including definition of terms, monitoring the PM concentrations, impact of change in climate of PM in the UK, and effects of climate on PM. Particulate matter (PM) is a pollutant of air made up of a mixture of particles of liquid and solid that floats freely in air. There are various origins, size and composition of particles. The aerodynamic diameter conveniently summarizes the three properties of PM. It is also appropriate to take into account parameters such as the surface area and number concentration. Fine particles are made up of aerosols which are secondarily formed, combustion fuels and re-condensed metal and organic vapours. Moreover, the fine particles consist mostly of the hydrogen ion as well as mutagenic activity of particulate matter, while coarse fraction mostly consists of contaminants like the bacterial toxins. Secondary inorganic ions, carbonaceous materials, heavy metals, crustal materials and water are among the key chemical species that contribute the most to the mass of fine PM.

The development of portable devices that are cost-effective that are mountable on vehicles with a view to supporting wider applications interest in intelligent transportation systems (ITS) is a challenge in the field of research. For example, sensing units mounted on vehicles for public transportation that are meant for displaying real-time pollutants level as well as high-resolution maps generation for the pollution of air in urban areas on motorbikes for planning healthier routes as well as capturing fine-grain environmental information or conventional bike for the monitoring of quality of mobile air. The combination the latest low-cost sensors market development with available information and communication technologies has made it possible to design and implement portable, inexpensive and compact sensor units for the creation of profiles of concentration of aerosols that have detailed temporal and spatial resolution in addition to deploying networks of the devices in the form of mobile agents who operates simultaneously under analysis of scheme of big data with a view to developing applications and providing additional services in the intelligent transportation systems (ITS) context. The need for quantifying the low-cost sensors' performance in the actual condition has been emphasized by various researchers (Al-Ali et al., 2010; Elen, 2013; Velasco, 2016; Keifer & Benrendt, 2016; Ioakimidis & Rycerski, 2016). To that end, various experiments have been conducted with a view to examining the consistency, durability and stability of the sensing units, by the use of hourly data for the concentrations of particulate matter.

One of the most important parts of the pollution of air monitoring system have been introduced in this thesis, in addition to describing the testing of the sensing unit in the fields as proposed by the use of measurements taken nearby road connected with computer that has an instrument of reading calibration as the comparison making item as well as showcasing its precision on specifying the concentrations of the PM on one minute resolution in an experiment carried out on the area. It should be noted that this paper is focused on investigating low-cost measurements system for mapping ambient concentration PM in the ambient air after being calibrated on-field.

Roadside measurements have been providing instantaneous pollutant concentration ratios from passing vehicles on the roadway in which the station has been installed. In addition, mobile sensing makes it possible to monitor emissions linked with spatio-temporal ratio resolution which is tuneable for matching levels of emission with specific vehicle (Deville et al., 2016). The sensing approximation is currently used in roughly estimating value of concentration of particulate matter, mostly obtained from tires, exhausts, fuel combustion and secondary particles generated under particular operating conditions at specific location in the atmosphere and are reliant on the radical changes of the recently developed low-cost sensing components with a view to producing more trustworthy heavy traffic's quantitative model (Mar´c et al., 2015). It is therefore developing better emission factor models for capturing the particulate matter footprint from different sources is a challenging task, only on the basis of inexpensive mobile sensing instruments. In addition, there is the need for designing of mobile systems to deal with background pollution levels and unstable weather hindering the examination of actual emissions of vehicles. The following chapter focuses on the adopted research methodology in this research.

Chapter Three: Proposed Low-Cost Air Quality Monitoring System Platform Solution

Most measurements used in the monitoring of PM2.5 and PM10 help in checking compliance with air quality regulations and legislation. The data collected through the measurements are critical in the comprehension of the processes, both physical and chemical, affecting particulate matter, consequently questioning already existing models in addition to supporting the development of models, as well as decisions regarding measures for reducing the concentrations of particulate matter.

This chapter discusses air monitoring and measurement techniques, by focusing on the monitoring PM2.5 and PM10 as well as their components, in addition to highlighting the difficulties of obtaining reliable measurements. Moreover, types of sensors, functionality, cost, characteristics, behaviour and equations relating to particulate matter have been discussed in this chapter.

In the ***Practical section***, all sensors type has been discussed in addition to methods of detecting particle matters PM2.5 and PM10, their advantages and disadvantages, costs and equations. The design selected for the practical is the light scattering sensor method, and its light scattering sensor has been explained as well as the reason why it was chosen.

The design contained the following:

- DN7C3CA006 or DN7C3CA007 PM2.5 DUST SENSOR
- Temperature Humidity Pressure Sensor (SPI or BME280 I2C)
- SDS011 Fine dust sensor Nova Fitness, inclusive of the USB adapter
- Arduino uno connected to DN7C3CA007 as this sensor has analogue output
- Raspberry Pi 3 B+ Ultimate 32GB
- All connected to Raspberry Pi and send data to dashboard online.

Test and measurements were carried out under different conditions, and these included:

i. when fans are closed
ii. when fans open
iii. the steps were repeated by replacing sensors individually with another one from same models.

Moreover, their behaviours were determined by taking into consideration correlation coefficient values.

The prototype model collected and sent data in a near real-time data reading and high accuracy. The collected data were plotted using MATLAB or other software by the use of scatter method in addition to determining correlation coefficients value.

The main considerable issue with this method is how accurate and efficient is its performance due to the following factors:

- sensitivity to other air pollutants
- long term performance
- sensor interferences
- sensitivity to meteorology and environment
- tests should meet with UK criteria certification scheme MCERTS in parallel with European standard EN14662-2
- compare data collected from new prototyped device with the approved machine used by the institutions for calibration and validation
- structure a low-cost monitoring network that covers the targeted area

Also, this technology can only read data at the present time but will not be able to give indications of whether the pollution level is rising or falling in a particular period of time.

3.2 Monitoring methods

3.2.1 Diffusion tubes

Diffusion tubes are convenient and pollutant specific monitoring method for various types of air pollution. The tubes are relatively cheap, small and can be located in the exact place to be monitored. They are useful for observing trends in pollution concentrations because of their suitability for providing longer term measurements. The tubes can either placed on suitably located street furniture (such as lamp post or road sign) or outside of buildings.

Diffusion tubes absorb, in a passive manner, the pollutant that they are exposed to over a given time in a given place. There are no complicated technologies or pumps involved. The tubes are usually exposed for a month (in most cases), released and sent to a laboratory, where analysis is carried out based on the nationally agreed procedures. At the end of the year, the monthly data are adjusted to take into account laboratory accuracies and other possible sources of inaccuracies, before producing a single annual figure. Finally, the obtained figure is used for comparison with the Air Quality Objective and for Review and Assessment.

A diffusion tube is made of plastic whose diameter is 1 cm and a length of 7.5 cm. There is a cap used in sealing each end of the diffusion tube, one may have any colour while the other is usually white. The tube is placed in position after taking off the white cap when monitoring is initiated. The interior of the coloured cap has a metal grid soaked with 'triethanolamine' or TEA. Air is drawn up into the tube via molecular diffusion process once the tube has been set in position.

Once the measuring is completed, usually after a period of one month, the white cap is put back on with a view to preventing more NO2 from getting in. the exposure period is the period of time the tube is left open. The tube is then taken to the laboratory to remove and measure the NO2. The results show the average NO2 in the air for the exposure period (one month) in that location. The diffusion tubes' accuracy is monitored monthly by co-locating diffusion tubes with continuous automatic analysers inlets. Moreover, the diffusion tubes' precision is monitored by co-locating diffusion tubes at various sites in triplicates.

Figure 8: Diffusion tube monitors

(source: opendata Camden, 2018)

Advantages of diffusion tubes

The diffusion tubes are relatively cheap, small and can be located in the exact place to be monitored. They do not require complicated technologies or pumps. They are also convenient and pollutant specific monitoring method for various types of air pollution. They are suitable for providing longer term measurements.

Disadvantages of diffusion tubes

One of the main disadvantages of diffusion tubes is its accuracy of results, which are considered to have accuracy range between -/+20%. Another disadvantage is that the diffusion tube only has one number representing the entire month, thus making it impossible to examine fluctuations on daily or weekly basis. Moreover, diffusion tube samplers are prone to a number of sources of uncertainty which comes about because of the nature of materials of construction, the method of preparation, the absorbent used, the their deployment details in addition to the adopted analytical methods in establishing the absorbed nitrite ion concentration.

3.2.2 Automatic monitoring

The automatic monitoring sites provide near real-time data of high quality which can be deployed in analysing patterns in addition to trying to find out more about the pollution characteristics as it varies over time. Such information collected at the automatic monitoring sites is useful in the identification of causes of pollution in addition to highlighting areas where more effort should be focused with a view to reducing air pollution.

Various ways are in existence in which the Defra's Air Quality Objectives are expressed based on the pollutant being measured, and these include hourly average, 8-hour average, daily average and annual average. The averages are calculated by the collected data from a number of automatic air quality monitoring stations.

Each of the pollutants is measured in a different way in the automatic air quality monitoring stations. For instance, to measure **nitrogen dioxide**, nitrogen oxide in the sample of air reacts with the Ozone generated within the automatic monitor to emit chemiluminescence light. The concentration of NO2 is calculated by measuring the resulting chemiluminescence light. On the other hand, **Ozone** can be measured by first passing ultraviolet light through the sample of air. The quantity of absorbed light is compared to a reference sample that does not contain Ozone, and the concentration of ozone is calculated by determining the ratios between the two readings. As far as measurement of **particulates** is concerned, BAM and TEOM are the two main monitors used, although they both reliant on the direct measurement of particles of size. The particulate matter of interest is collected, and the concentration is calculated using the mass of the particles.

Advantages of automatic monitoring

The automatic monitoring analyser provides high quality data revealing the variation of pollution characteristics over time.

Disadvantages of automatic monitoring

The automatic monitoring analyser equipment is expensive not only to purchase but also to maintain. This has called for the making of compromises such as location for logistical purposes.

3.3 Proposed Low-cost Platform Solution Monitoring

The proposed outdoor low-cost monitoring air quality networking implementation is aimed at functioning as an adjustable, portable as well as compact solution for data collecting. It is made up of one board microcontroller that consists of a GPS module, a data-logging extension in addition to an off-the-shelf particulate matter sensor, commonly referred to as Laser PM2.5 Sensor SDS011. The sensor has an inbuilt fan for ensuring the circulation of sample air to an impactor consisting of a laser diode, in which the amount and size of particulate matter (PM) is determined. There is the transformation of scattered light into electrical signals while the signal waveform of the component's digital output, on further analysis, is the concentration of particulate matter, from particles counts whose diameters range between 0.3 μm and 10 μm. In this case, the principle at work is on the basis of the light scattering, in which the particles couples is illuminated by the source of light with the transformation of light that has been scattered into a photo-detector signal whose amplitude is dependent on the wavelength of light, size of the particles, scattering angle and the relative refraction index between the medium and the particle.

The Laser PM2.5 Sensor SDS011 (PM2.5 SDS) allows for the measurement intervals of approximately 1 second because it uses sampling that has 0–5 V pulses with length of 1004 ms. According to (Wang et al., 2015) a laser diode is able to generate only one frequency beam coupled with a wavelength which is typically in components which are similar and falling in the infrared spectrum (with a range between 870 nm and 980 nm). Unlike other low-cost PM sensors that are commercially available that utilize thermal resistors in the generation of heat, thus using natural convection to introduce the particles in the light scattering section, the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) achieved that by the use of the embedded fan generating a negative pressure with a view to conducting particle the flow of the particle via the specified paths (see figure 9). According to the manufacturer, the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) measures particulate matter within a range of 0.0 μg/m^3 to 999.9 μg/m^3, and is associated with a relative error that does not exceed 15% at a temperature of25 ºC and relative humidity of 50%. It should however, be noted that some errors are yielded by the specific sensor when taking the measurements of the concentration of the particulate matter (especially when the concentration of PM2.5 = 999.9 μg/m^3), thus the need to filter out the outlier readings from the presented time series.

The microcontroller is programmed for recording the PM sensor's time stamped reading. The data logger of the proposed outdoor low-cost monitoring air quality networking records measurements every one minute from the sensors. Besides, the logger consists of a real-time clock whose purpose is the addition of a timestamp to every measurement before saving the information in a unique csv file on day-by-day basis. Additionally, the components of auxiliary sensor for humidity, temperature in addition to air pressure were integrated into the system with a view to examining the manner in which the ambient weather conditions affects performance overall, thus excluding any possible alterations on the collected data's quality. Moreover, the DHT22 sensor was used in the measurement of humidity, temperature and pressure, because it is a digital sensor with calibration offering a ±0.5 ºC accuracy for temperature in addition to accuracy of humidity ranging between ±2% and ±5%.

The final assembly, alongside the power circuit, makes it possible for powering from various storage options was placed in a 27 cm by 11 cm by 7 cm polypropylene box weighing 150 g. As far as cost is concerned, the electronic parts can be purchased from online retailer, although more cost-effective variants that are capable of assigning the data logging and power to a movable computer may be made at a relatively cheaper cost.

3.4 System Architecture and Design Specifications of Proposed System

This System contains two main parts:

1. Hardware Part.

   Which is consist of the Temperature, Humidity and Air-Pressure (BME280) Sensor. This sensor is selected based on its ability to detect the three values, accuracy and price. Also, this part includes Nova PM SDS011 and DNAC3CA007 dust sensors. These sensors are selected based on technical factors that clarified on previous section and prices.

   These smart sensors work when connected to smart computer platform such as Raspberry pi that convert, and compute values collected from these sensors based on sensors reference manufacture values which is done through software part.

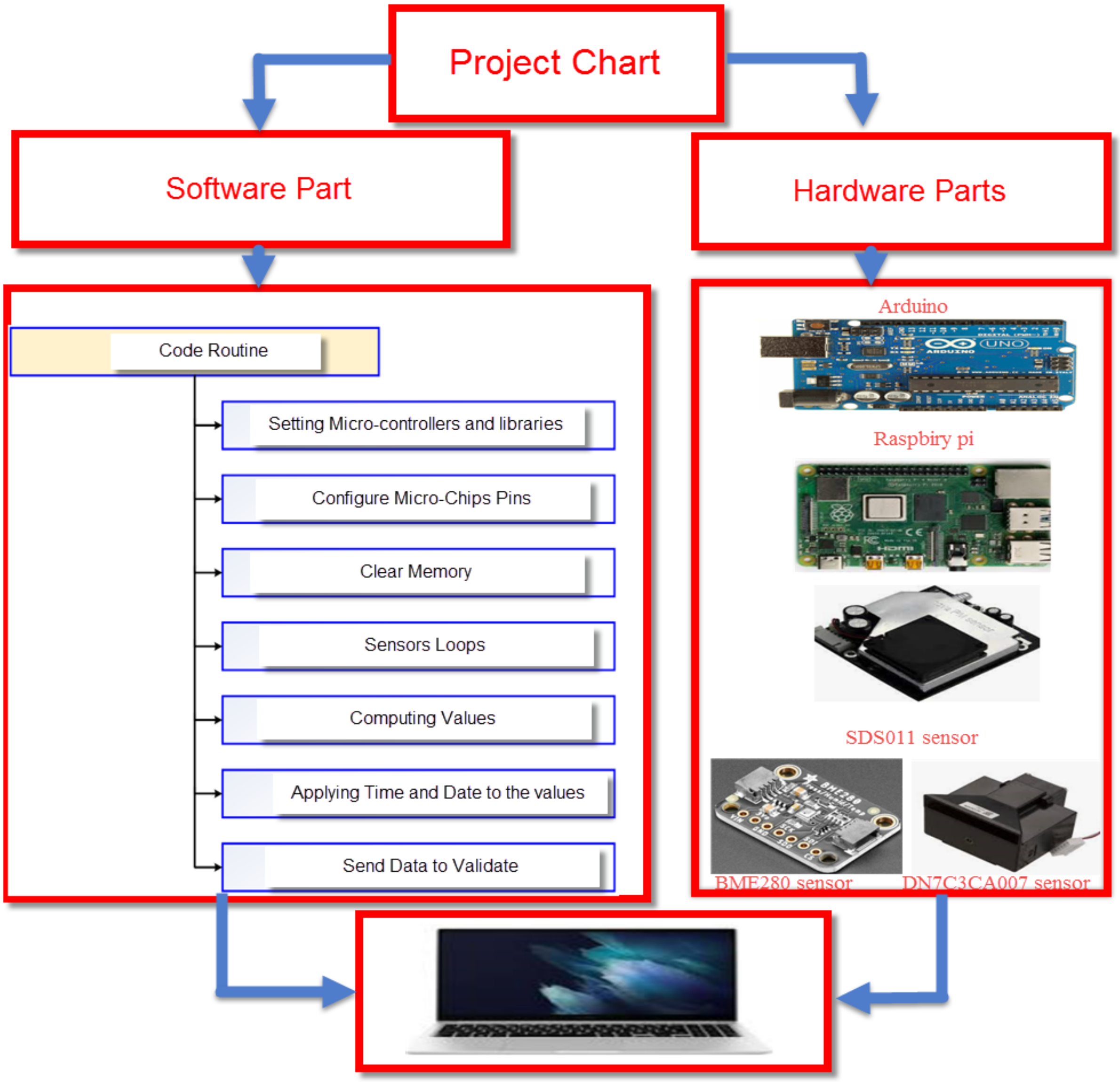
   Since the DNAC3CA007 sensor has analogue output and the Raspberry pi dealing with digital output, an extra smart micro-chip is connected to it (Arduino) that communicate with Raspberry pi to deliver the final values

2. Software part.

Since this system s consist on smart technology such as microcontroller, the design requires also a software code structures that allows the communications between the component also, the potential of calibrate the system when it requires.

All codes structures usually start with define component input and output also, all the associated parameters. Then define the pins voltage values in term to the data sheet and microcontroller specification.

The main-loop contains code main routine eventually, the displaying-loop to deliver the result. More software evidence is attached within appendix section. The chart below illustrates the design structure.



- *Nova PM Sensor SDS011*

The Laser PM2.5 Sensor SDS011 (PM2.5 SDS) sensor is an air quality sensor that was developed recently by Inovafit (figure 9). It is a technology that is closely associated with laser diffraction theory, in which the distribution of particle density is well defied from the distribution patterns of light intensity (SDS011, 2018; Genikomsakis et al., 2018). The sensor is made up of a built-in fan and a digital output (Figure 10), which is capable of measuring the density distribution of the particle in the air ranging between 0.3 and 10 μm. It also contains a software structure that converts the distribution density of particle into particle mass, evidence can be found under appendix section. The table below shows a short technical specification of the sensor.

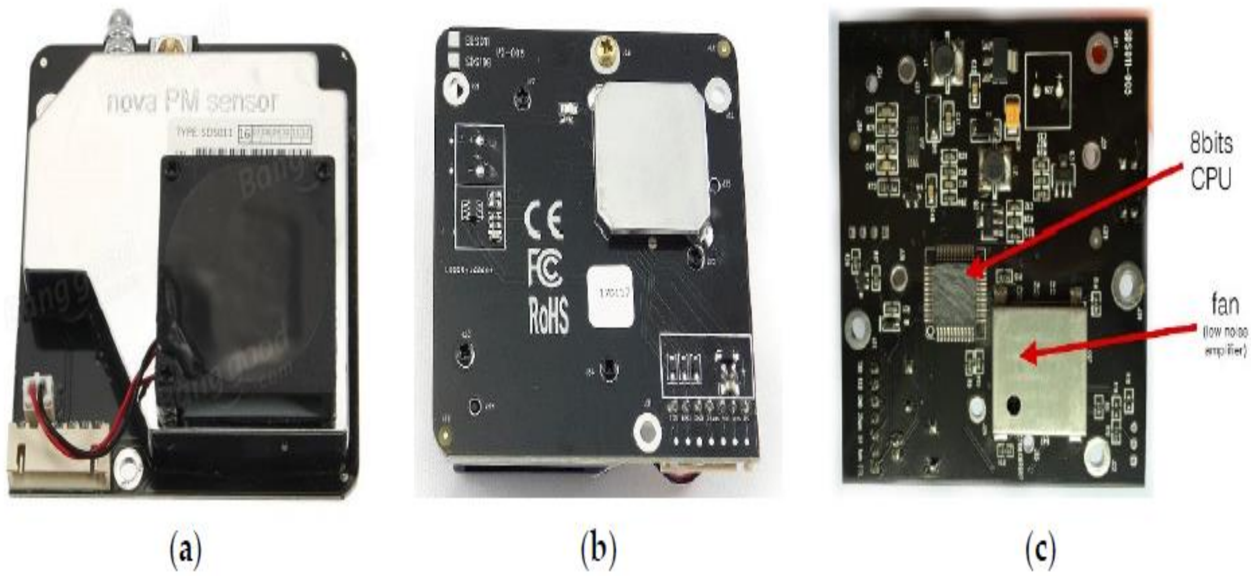


Figure 9: Nova particulate matter (PM) sensor SDS011 showing sensor front (a); sensor back (b); and sensor inside (c) (Source: https://www.researchgate.net/publication/330544166)

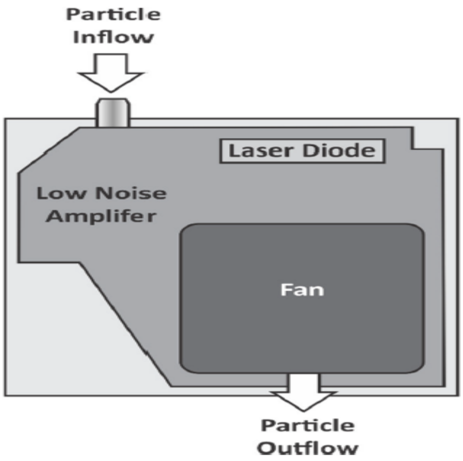


Figure 10: SDS011 sensor layout for measuring the concentrations of particulate matter

(Source: https://www.researchgate.net/publication/330544166)

Table 3: Nova PM Sensor SDS011 Characteristics

(Source: https://www.researchgate.net/publication/330544166)

Item	Specification
Measurement parameters	$PM_{2.5}$, PM_{10}
Measuring range	0.0–999.9 μg/m³
Input voltage	5 V
Related current	70 mA ± 10 mA
Sleep current	< 4 mA (lase and fan sleep)
Response time	1 s
Serial data output frequency	1 Hz (1 time/s)
Minimum resolution of particle	0.3 μm
Counting yield	70% @ 0.3 μm; 98% @ 0. n5 μm
Relative error	Maximum of ± 15% and ±10 μg/m³
Temperature range	Storage environment: −20–+60 °C; work environment: −10–+50 °C
Humidity range	Storage environment: max. 90%; work environment: max. 70%
Air pressure	86 KPa–110 KPa
Product Size	L × W × H = 71 × 70 × 23 mm
Appropriate price	€16/piece
Appropriate weight	50 g
Service life	Up to 8000 h
Certification	CE/FCC/RoHS

- ***DN7C3CA007 PM2.5 Dust Sensor***

DN7C3CA007 is a PM2.5 sensor device which is regarded as the smallest of such sensor devices and has a detection speed of 10 seconds (GP2Y1010AU0F, 2018). It was developed as a sensor for PM whose diameter does not exceed 2.5 µm, which has emerged as one of the most pressing environmental concerns. DN7C3CA007 sensor module is made up of a particle separator that is instrumental in the separation of PM2.5 particles from larger articles, as well as an optical sensor to measure the density of PM2.5 particles within 10 seconds. However, it is also possible to switch the device with a view to detecting much larger particles. Other commercially available PM2.5 sensors that available, including laser-equipped systems that employ the impactor method or the cyclone method, are not only bulky but also need maintenance. DN7C3CA007 PM2.5 dust sensor overcame these drawbacks through its LED based sensor as well as a compact virtual impactor that eliminates need for maintenance. The table below illustrates some of the specifications of DN7C3CA007 PM2.5 dust sensor.

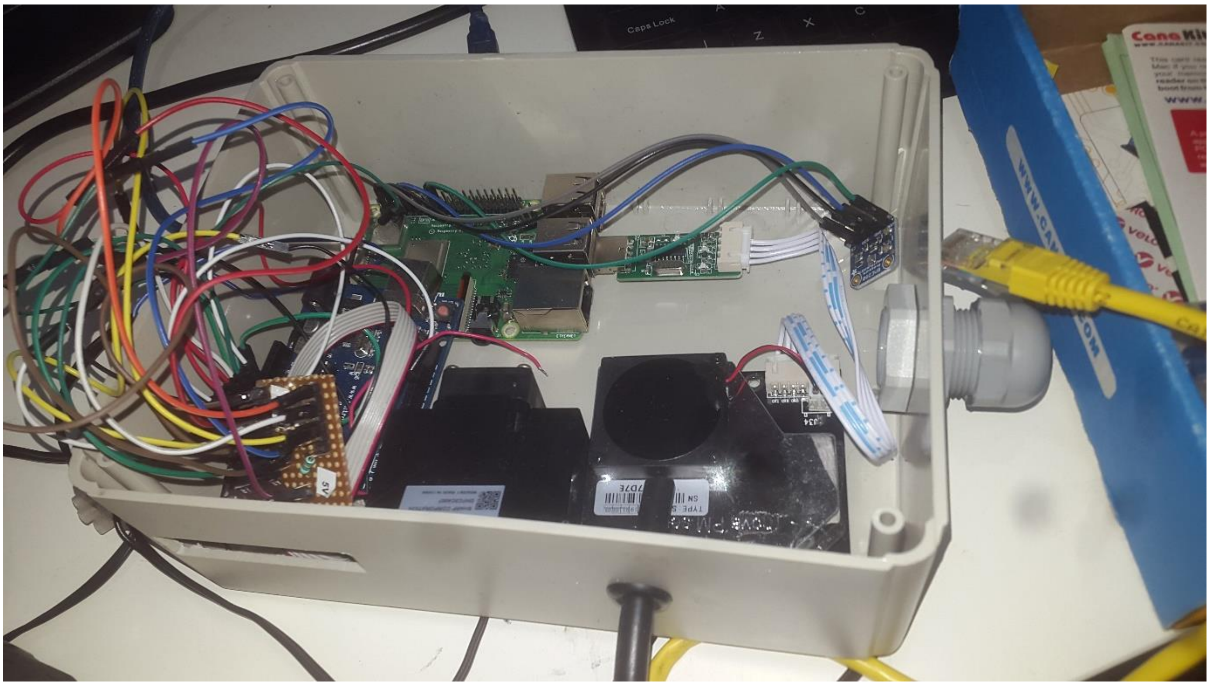
Table 4: specifications of DN7C3CA007 PM2.5 dust sensor

(Source: global sharp)

Model No.	**DN7C3CA007 [Overseas]**	DN7C3CD015 [Japan / Overseas]
Measuring range (μg/m³)	25 to 500	25 to 500
Output type	Analog voltage	Digital PWM
Power supply voltage (Vcc/fan)	DC5 V / DC5 V	DC5 V / DC5 V
Power consumption (mW) (TYP.)	At sensor: 55, At fan: 450	At sensor: 75, At fan: 450
Output voltage range (V)	0 to 5 (MAX.)	Vhigh: Vcc-1.5 (MIN.), Vlow: 1.3 (MAX.)
Operating temperature range (°C)	–10 to +60	–10 to +60
Outline dimensions (mm)	53.0 × 40.0 × 51.0 (excluding protruding parts)	53.0 × 40.0 × 51.0 (excluding protruding parts)

3.6 Comparison Measurement System

DN7C3 CA007 was connected to Arduino, because of its analogue output while raspberry pi deal with digital output, before being connected to raspberry pi. On the other hand, the SDS011 sensors were connected directly to raspberry pi as it has digital output figure 10.5. The filed experiments for calibrating and tuning the prototype were conducted in selected sites in the Kirklees area United Kingdom. The comparison system in the measurement of particulate matter included both DN7C3 CA007 (PM2.5 DN7 sensor) and the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) based on changes in humidity, temperature and pressure see figure below.



combined device

The measurements from the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) was compared with the measurements from DN7C3 CA007 sensor (PM2.5 DN7 sensor). The testing and calibration of the instruments used revealed that they have been calibrated by the use of standards whose accuracies potentially can be traced to the National physical laboratory (NPL) in addition to being verified based on the instrumentation whose accuracy. The data for humidity, pressure and temperature were also available from the laboratory. This experiment set first to take dust level when sensors fans for both the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and DN7C3 CA007 sensor (PM2.5 DN7 sensor) were closed, for which the reading was stable as no dust was going through. The fan was then opened, and the sensors data read to give the actual reading. Each of the sensor's data (PM2.5 SDS and PM2.5 DN7) were plotted in MS Excel file against humidity, pressure and temperature to yield scatter plots. The scatter plots were used in the evaluation of the change and behaviour of the PM under closed fan and open fan under the influence of humidity, pressure and temperature. Moreover, correlation coefficient values were determined in the case of each of the sensors within software structure please refer to appendix MATLAB code. This helped in determining the relationship between the variation of the PM and each of humidity, pressure and temperature.

3.7 Calibration method

A number of methods may be adopted in calibrating the low-cost air monitoring sensors. However, the most widely used calibration methods for calibrating PM data against reference measurement include multi-linear regression model and linear model, including using covariates in the improvement of the quality of calibration. Other calibration methods include the quadratic, logarithmic, exponential, and Kohler theory of particles growing factor, among other supervised learning techniques such as Random Forest (RF), ANN, SVM and SVR. A higher percentage of the multi-linear regression models usually adopt covariates such as humidity, pressure and temperature, among other meteorological parameters, in addition to gaseous interferent cross-sensitivities such as Nitric Monoxide (NO), nitric dioxide ($NO2$) as well as Ozone ($O3$) with a view to improving the low-cost sensor calibration.

3.7.1 Quality assurance/quality control procedures

It is necessary to evaluate data from particular instruments in the based on the calibration and checks adopted when in use in addition to the retrieval of the published data, and such a process also known as QA/QC. All the measurements of PM2.5 follow thorough procedure of ratification and validation before being used. The QA/QC checks are employed with a view to ensuring that the collected data not only represent the actual ambient concentrations of PM2.5 existing in different locations under investigation but is also precise and accurate to meet the set objects, in addition to being reproducible and comparable. As such, the results have to be consistent and comparable with other accepted standards that are already in existence. Moreover, the collected data has to be consistent over time. This is important in case there is the need to undertake long-term trend analysis of the data.

3.7.2 Site audits and Network inter-calibration

A system for network inter-calibration and site audit have been in Kirklees area within the United Kingdom for many years. The network inter-comparison and site audit exercise are primarily aimed at checking and evaluating various key analyser functions through easy to understand set of calibrations and tests; in addition to carrying out instrument calibration within the site by the use of standards that can be traced directly to the QA/QC Unit Calibration Laboratory standards as well as the United Kingdom's national metrology standards.

3.8 Sensors Co-Location and Measurement Site

A number of sensors, including SDS011 sensors, SPI or BME280 I2C Temperature Humidity Pressure Sensor, and DN7C3CA007 PM2.5 DUST SENSOR were co-located in a unit located in Dewsbury within Kirklees area. Road transport is the dominant source of particulate matter emission. All sensors that used were connected to DN7C3CA007 or DN7C3CA007 PM2.5 DUST SENSOR, BME280 I2C Temperature Humidity Pressure Sensor, SDS011 Fine dust sensor Nova Fitness including USB adapter, Raspberry Pi 3 B+ Ultimate 32GB, Arduino uno connected to DN7C3CA007 as this sensor has analogue output, and all connected to Raspberry Pi and send data to dashboard online.

A virtual impactor is responsible for splitting the inlet airflow. To avoid condensation, the inlet air is made to pass through a filter. Before measuring the mass concentration (MCbase), dry air mass is remains for few minutes to be accumulated in the filter. stream (TEOM, 2018). To measure the mass concentration (MC_{ref}), the clean air is sampled for another few minutes on the filter. After 12 minutes, the total mass concentration (MC) is calculated as follows:

$$MC = MC_{base} - MC_{ref} \quad (1)$$

Although FDMS unit is not regarded as a true reference instrument, the calibration and the resulting uncertainties are considerably small in comparison to the SDS011 sensors uncertainties and they are unlikely to have considerable effect on this analysis.

3.8.1 Local station site requirements

After determining the type of location, there are a number of factors that have to be taken into consideration before selecting the actual sites for the sensors, and these include accessibility, provision of infrastructure (such as telephone, electricity), and security against vandalism. It is also important for the monitoring site to be representative of the area surrounding the local station. The following guidelines should be met as a minimum requirement:

- There should be unrestricted flow around the inlet sampling probe with no obstructions affecting the flow of air in the vicinity of the sampler (that is, there should be some meters away from trees, buildings, and balconies, among other obstructions);
- The inlet sampling point should generally be between 1.5 meters and 4 meters (the breathing zone) above the ground. For the evaluation of potential human exposure (e.g. area near heavy traffic), a height of 1.5 meters would be preferred, while a height of 2.5 meters is generally preferred for practical reasons such as for prevention of vandalism. A maximum height of 4 meters is generally acceptable for city background stations, although the specific sitting has to be considered and positions of up to 8 meters may be acceptable and necessary in some sites.

- The position of the inlet probe should not be very close to the vicinity of sources with a view to avoiding drifting air pollution plumes (for instance, not close to the chimneys serving the heating system of the stations).
- The position of the sampler's exhaust should be in such a way that the recirculation of air to the sample inlet is not possible.

3.9 summery

It is important to fully document the site selection procedures at the classification stage in addition to providing the surrounding area's compass point photographs together with a detailed map. This makes it possible to characterize the sites in terms of topography and local sources, among other site characteristics. It is also important to review the sites at regular intervals with repeat photographs and documentation with a view to ensuring the validity of selection criteria over time.

Chapter 4: system integration, experimental Testing and results

4.1 Preparation of Data

PM2.5 and PM10 data that were measured for this study was used from July 2019 to November 2019. During this period, data was captured for different sensors open fan (humidity, temperature, pressure, PM2.5 SDS and PM2.5 DN7 for fan open) and for different sensor fan closed (humidity, temperature, pressure, PM2.5 SDS and PM2.5 DN7 for fan closed).

4.2 Data Analysis

The analysis of the collected data focused on the comparison between different variables related to particulate matter, and this include analysis of measurements used in the monitoring of PM2.5 and PM10 for different sensors when the fan is open for DN7C3CA007 figure 11, and for SDS011 figure 13. Repeating the process when fan is closed for DN7C3CA007 figure 12, and for SDS011 figure 14. and also, for replacing these sensors with identical and different sensors unit when the fan is closed figures 15 to 18

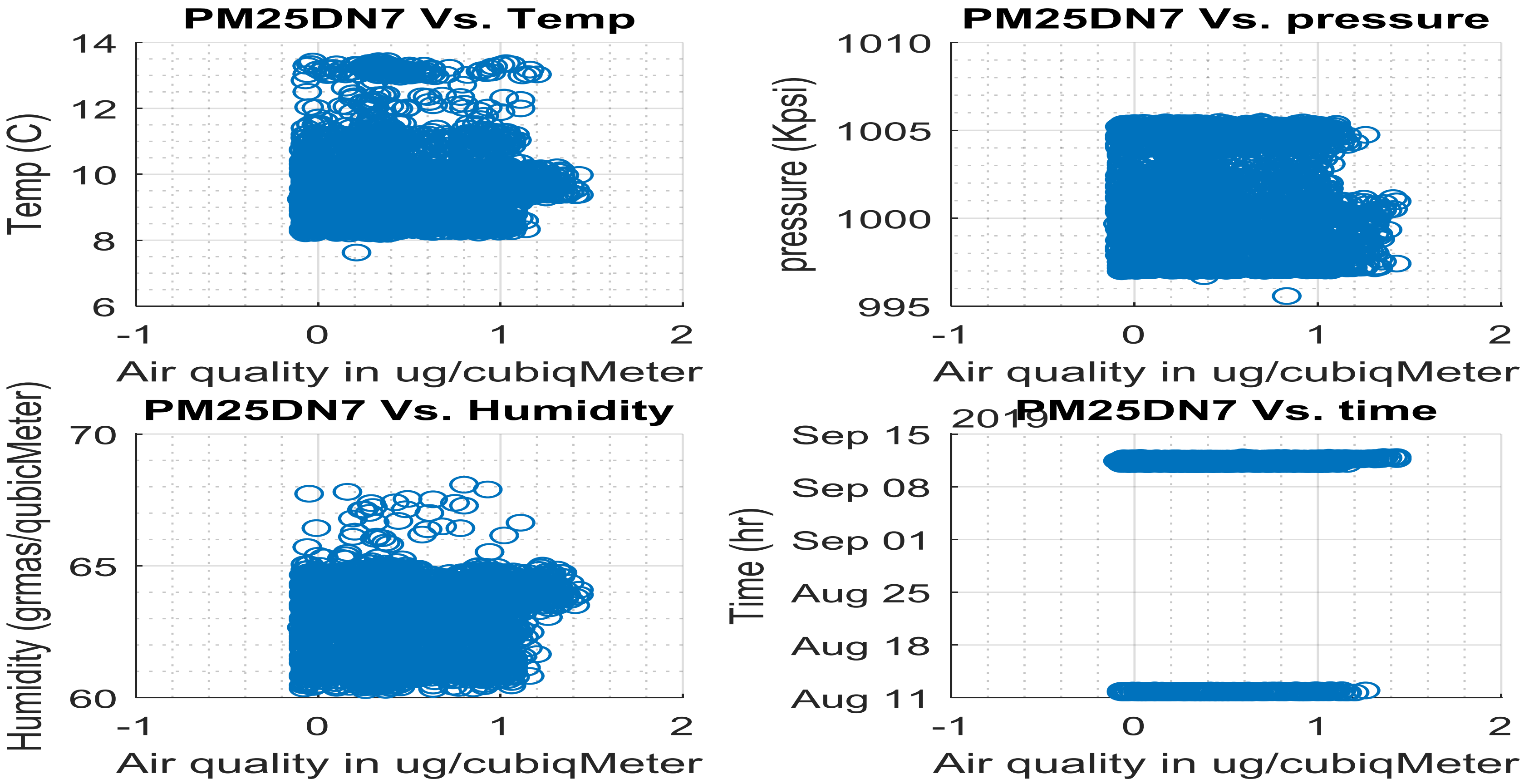


Figure 11: DN7C3CA007 with opened fan

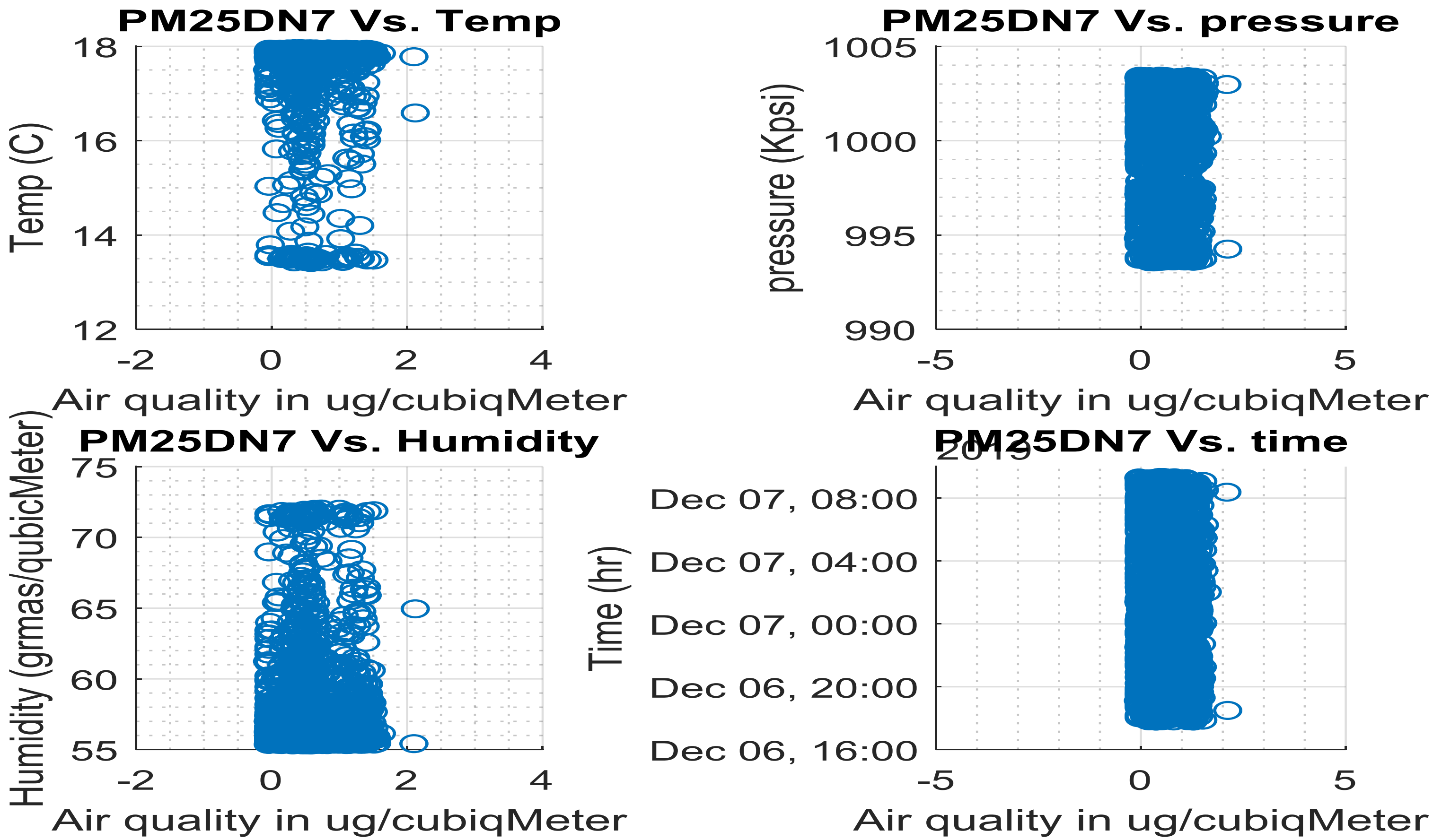


Figure 12: DN7C3CA007 with closed fan

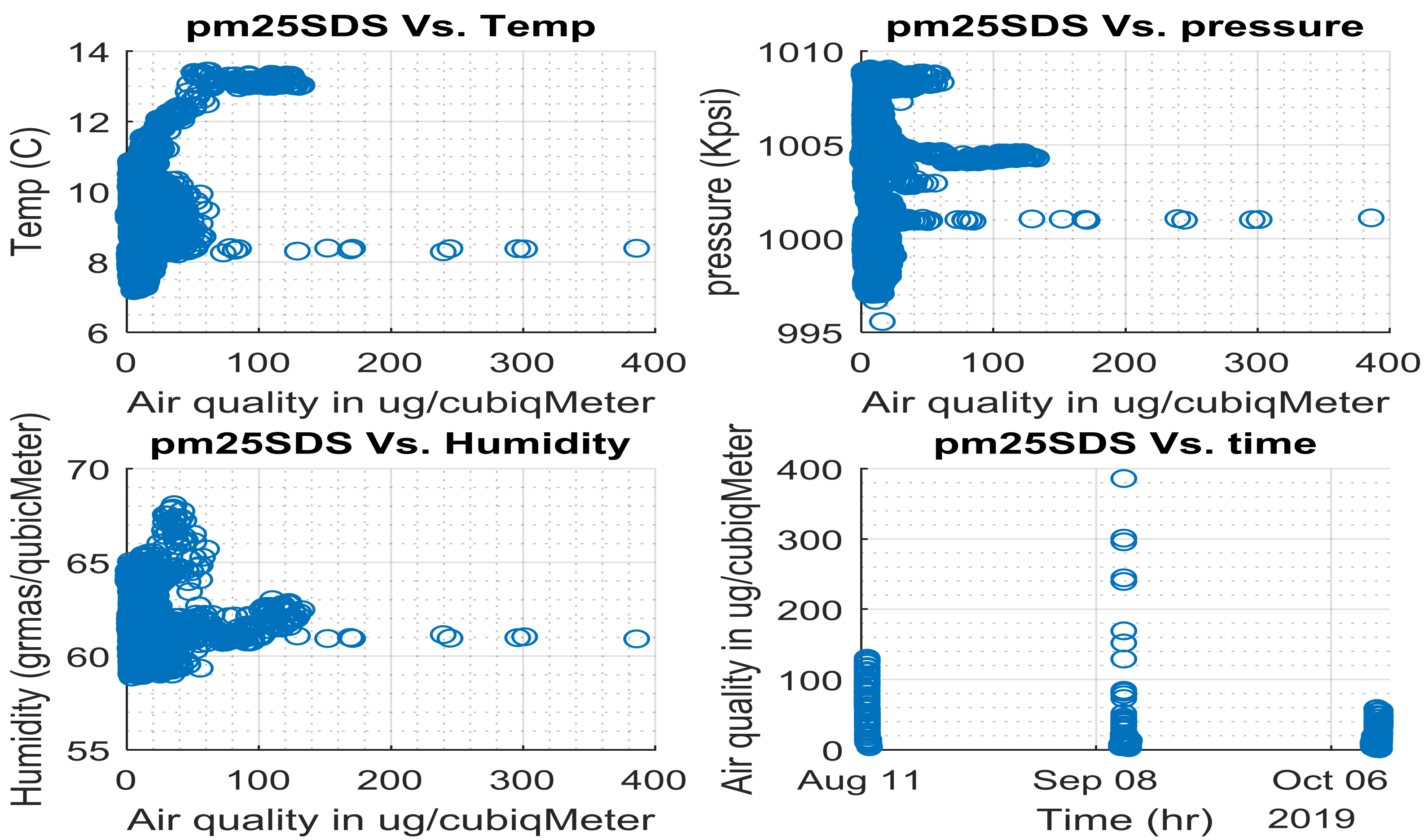


Figure 13: SDS011 with open fan

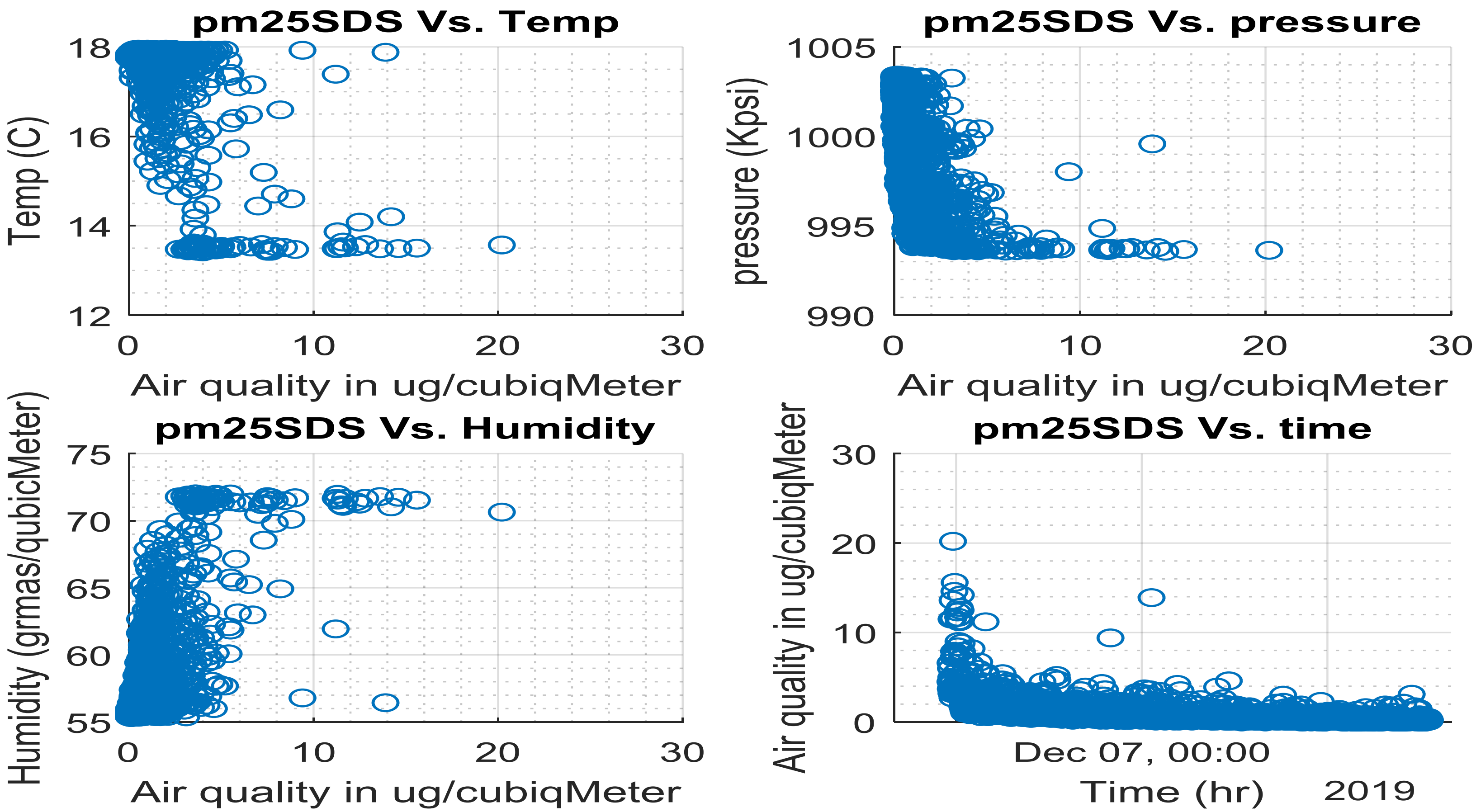


Figure 14: SDS011 with closed fan

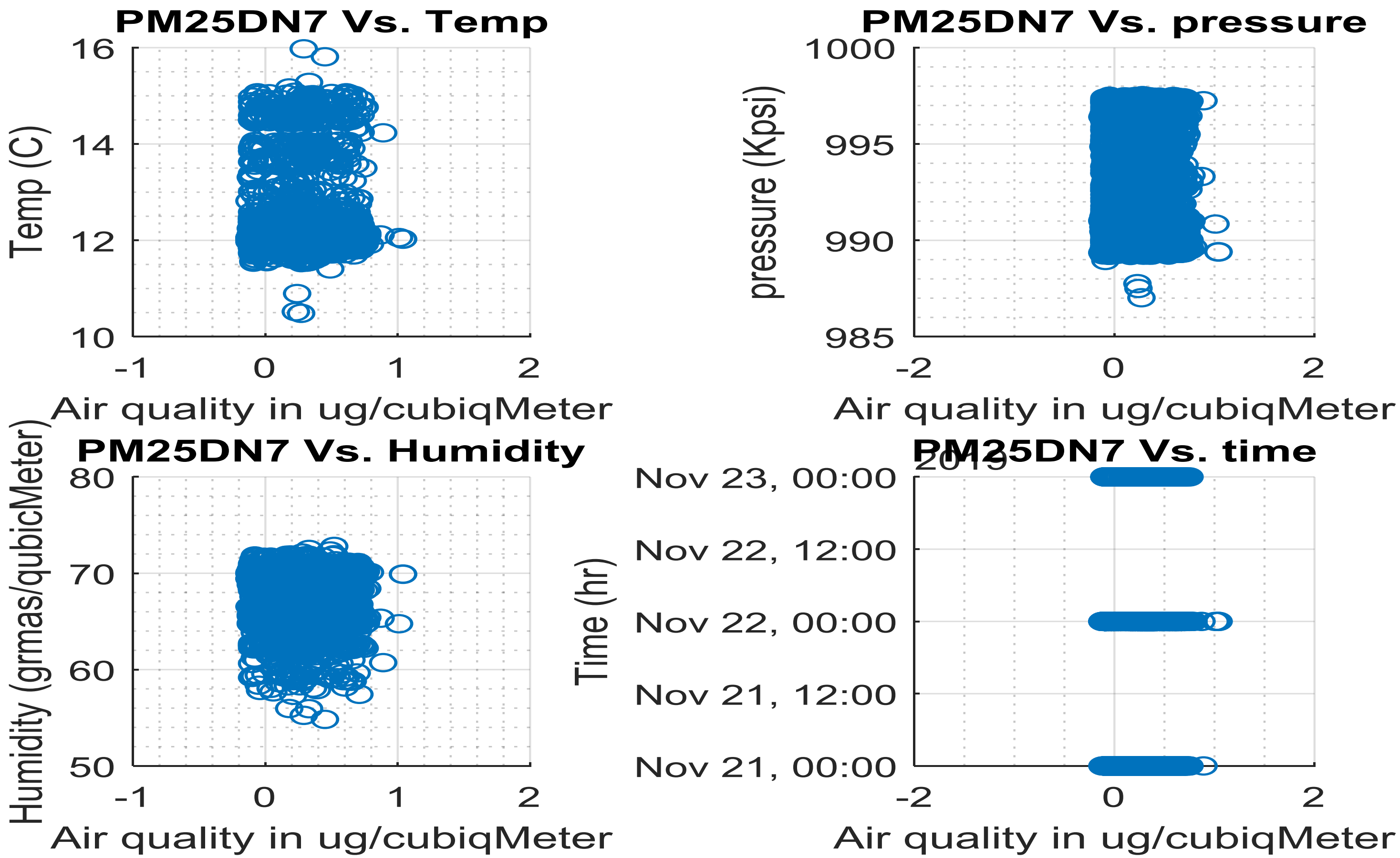
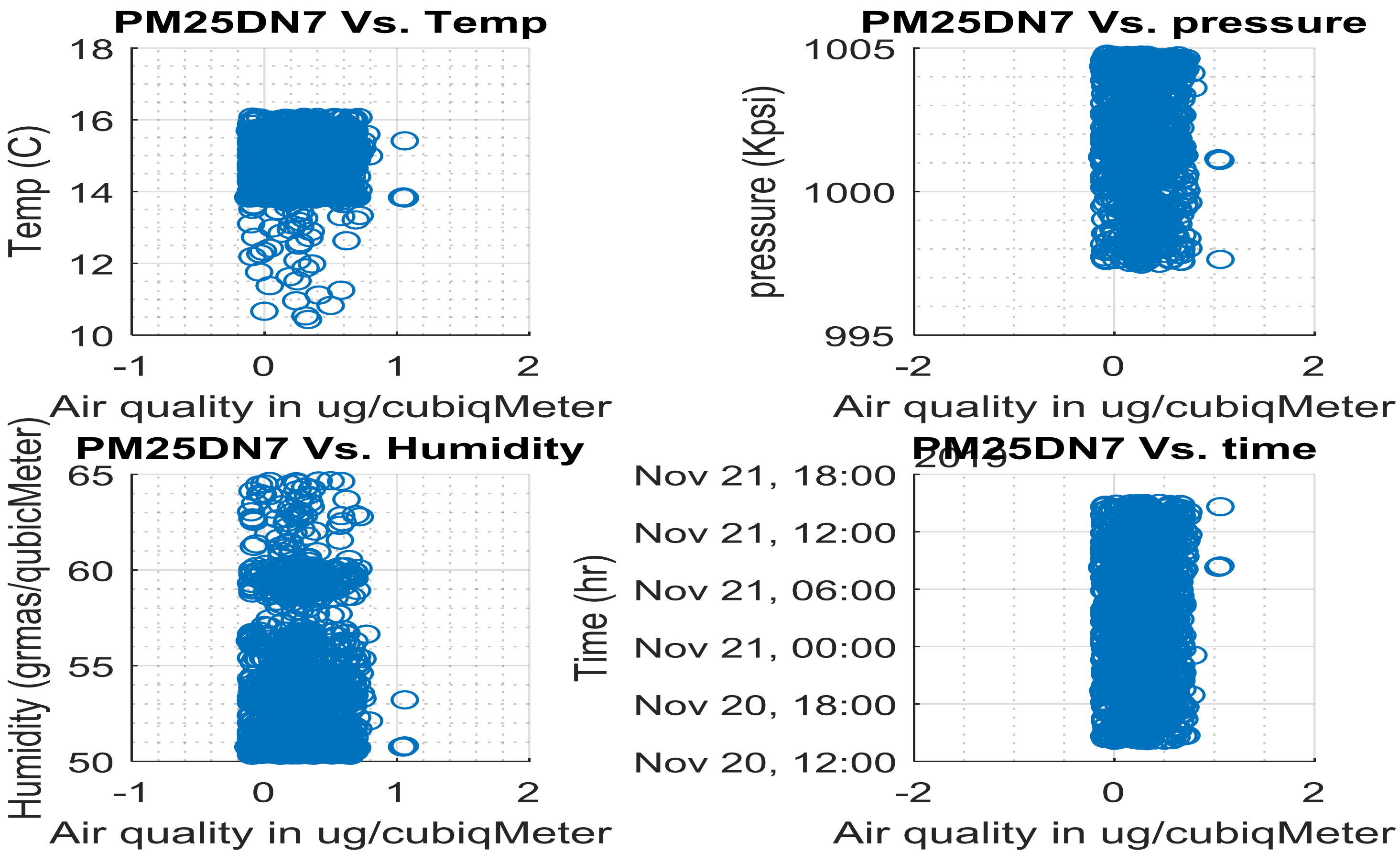


Figure 15: replacing DN7C3CA007 with opened fan

Figure 16: replacing DN7C3CA007 with closed fan



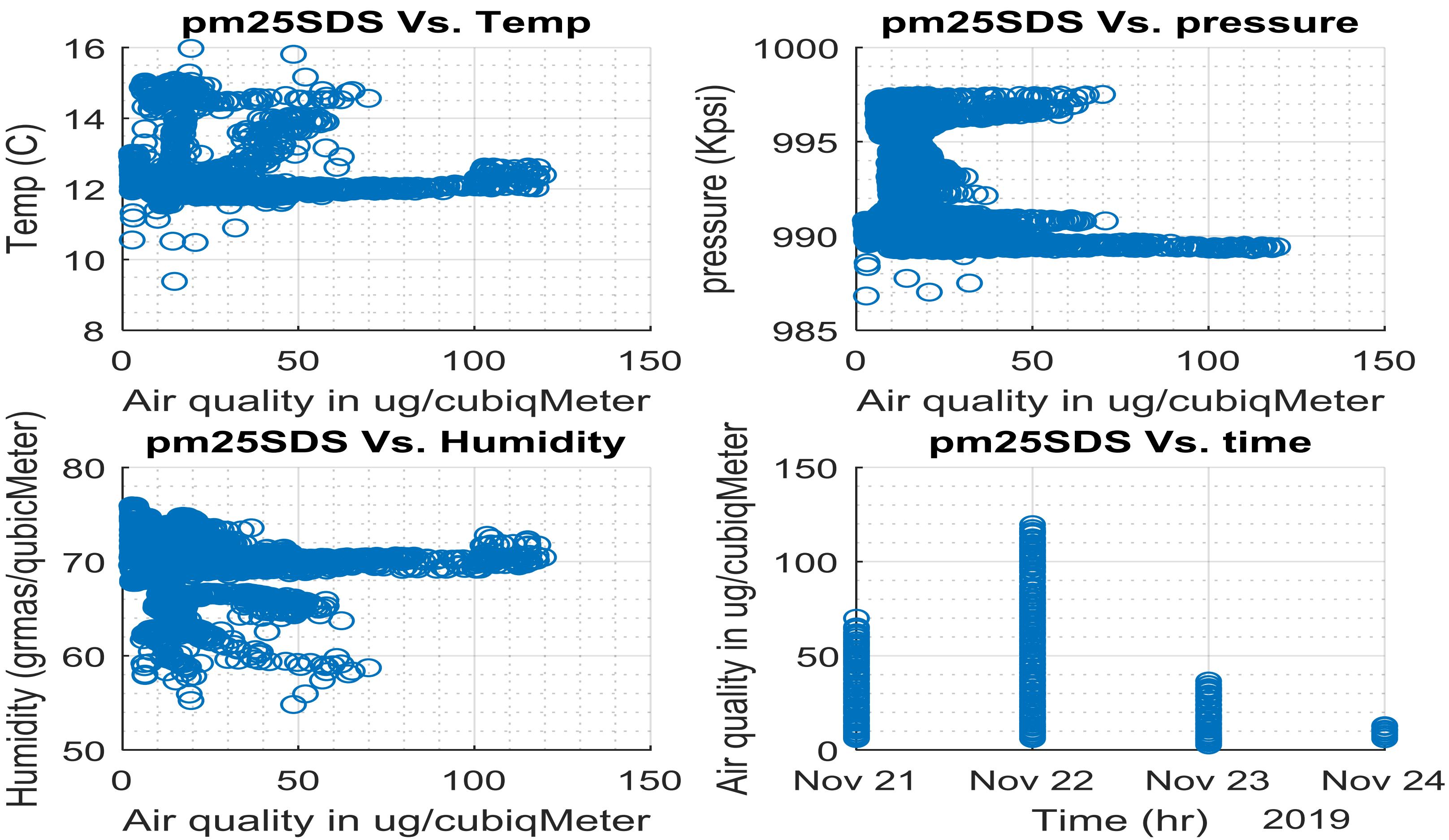


Figure 17: replacing SDS011 with opened fan

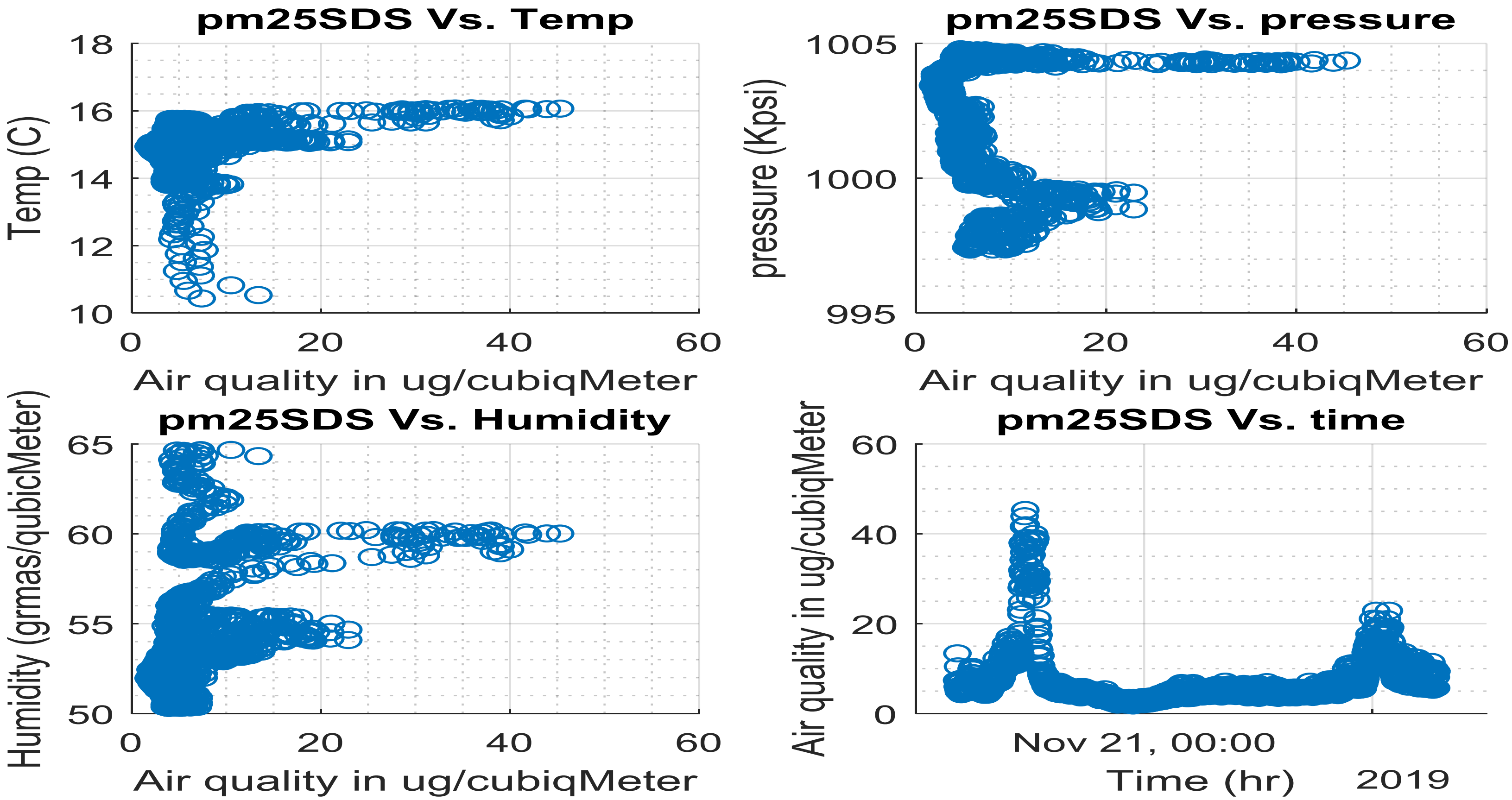


Figure 18: replacing SDS011 with closed fan

The sensors operate best within a certain humidity and temperature tolerances, thus making it important to carry out a ratification process with a view to inspecting the data closely. As far as temperature is concerned, there has to be at least 4 ºC separation between the external dew point and the internal dew point with a view to preventing condensation of moisture on the filter. After exposure to ambient air, the provisional measurements of or the calculation of the daily non-automatic PM2.5 mean from the variation in mass of weight filters. To ratify the data, it is necessary to take into consideration the relevant measurement flow rates, instrument alarms, filter exposure period and diagnostics. Online data updating included checking that each of the instruments operating parameter is not only within specification but also that there is sensible comparison between the resulting measurement and other monitoring data at the nearby locations or at the same measurement sites.

The result of the analysis and the plotting of the day-to-day difference between various measurements of humidity, temperature, pressure, PM2.5 SDS and PM2.5 DN7 from co-located instruments are demonstrated in figure 11 to 18. The results revealed substantial bias towards the concentration of PM2.5. The statistical analysis also revealed strong correlation between various measurements under investigation. For instance, in the case of closed fan, there was strong correlation of 0.704 between humidity and PM2.5 SDS. However, there was a strong negative correlation of -0.799between humidity and pressure as well as a strong negative correlation of -0.884 between humidity and temperature.

4.2.1 Correlation analysis

There was a correlation of 0.704 between PM2.5 SDS and Humidity which was not only significant but also strong and positive. There was a correlation of -0.541 between PM2.5 SDS and Pressure which was not only significant but also strong and negative. There was a correlation of -0.670 between PM2.5 SDS and temperature which was not only significant but also strong and negative. There was a correlation of 0.029 between PM2.5 DN7 and Humidity which was not only significant but also weak and positive. There was a correlation of -0.023 between PM2.5 DN7 and Pressure which was not only significant but also weak and negative. There was a correlation of -0.024 between PM2.5 DN7 and Temperature which was not only significant but also weak and negative.

Table 5: Closed fan correlations

	Humidity	Pressure	Temperature	PM2.5_SDS	PM2.5_DN7
Humidity	1	-.779**	-.884**	.704**	.029
Pressure	-.779**	1	.439**	-.541**	-.023
Temperature	-.884**	.439**	1	-.670**	-.024
PM2.5_SDS	.704**	-.541**	-.670**	1	.018
PM2.5_DN7	.029	-.023	-.024	.018	1

There was a correlation of -0.075 between PM2.5 SDS and Humidity which was not only significant but also weak and negative. There was a correlation of 0.067 between PM2.5 SDS and Pressure which was not only significant but also weak and positive. There was a correlation of 0.346between PM2.5 SDS and temperature which was not only significant but also weak and positive. There was a correlation of 0.070 between PM2.5 DN7 and Humidity which was not only significant but also weak and positive. There was a correlation of -0.044 between PM2.5 DN7 and Pressure which was not only significant but also weak and negative. There was a weak positive correlation of 0.025 between PM2.5 DN7 and Temperature which was not only significant but also weak and positive.

Table 6: Open fan Correlations

	Humidity	Temperature	PM2.5_SDS	PM2.5_DN
Humidity	1	.323**	-.075**	.070**
		.000	.000	.000
	15365	15365	9478	5589
Pressure	-.718**	-.412**	.067**	-.044**
Temperature	.323**	1	.346**	.025
PM2.5_SDS	-.075**	.346**	1	-.020
PM2.5_DN	.070**	.025	-.020	1

There was a correlation of 0.479 between PM2.5 SDS and Humidity which was not only significant but also weak and positive. There was a correlation of -0.016 between PM2.5 SDS and Pressure which was not only significant but also weak and negative. There was a correlation of 0.405 between PM2.5 SDS and temperature which was not only significant but also weak and positive. There was a correlation of 0.013 between PM2.5 DN7 and Humidity which was not only significant but also weak and positive. There was a correlation of -0.020 between PM2.5 DN7 and Pressure which was not only significant but also weak and negative. There was a correlation of 0.048 between PM2.5 DN7 and Temperature which was not only significant but also weak and positive.

Table 7: Different sensors closed fan Correlations

	Humidity	Pressure	Temperature	PM2.5_SDS	PM2.5_DN7
Humidity	1	.466**	.188**	.479**	.013
Pressure	.466**	1	.023	-.016	-.020
Temperature	.188**	.023	1	.405**	.048
PM2.5_SDS	.479**	-.016	.405**	1	.045
PM2.5_DN7	.013	-.020	.048	.045	1

There was a correlation of 0.051 between PM2.5 SDS and Humidity which was not only significant but also weak and positive. There was a correlation of -0.224 between PM2.5 SDS and Pressure which was not only significant but also weak and negative. There was a correlation of -0.008 between PM2.5 SDS and temperature which was not only significant but also weak and negative. There was a correlation of -0.002 between PM2.5 DN7 and Humidity which was not only significant but also weak and negative. There was a correlation of 0.002 between PM2.5 DN7 and Pressure which was not only significant but also weak and positive. There no correlation between PM2.5 DN7 and Temperature.

Table 8: Different sensors open fan Correlations

	Humidity	Pressure	Temperature	PM2.5_SDS	PM2.5_DN7
Humidity	1	-.032**	-.305**	.051**	-.002
Pressure	-.032**	1	.554**	-.224**	.002
Temperature	-.305**	.554**	1	-.008	.000
PM2.5_SDS	.051**	-.224**	-.008	1	-.009
PM2.5_DN7	-.002	.002	.000	-.009	1

From the results of the correlation analysis above, it is evident that there was no significant relationship between each of humidity, pressure and temperature and PM2.5 DN7 both in the case of closed fan and open fan.

4.2.2 Repeatability, reproducibility and stability

The following scatter diagrams (figures19 to 24) illustrates the effects of humidity, temperature as well as pressure on the outputs of the PM SDS and PM DN7 sensors for closed fan and for open fan. Figures 25 and 30 showing the scatter plot of humidity, temperature as well as pressure against PM SDS and PM DN7. for different sensors closed fan and the scatter plot of humidity against PM2.5 SDS for different sensors open fan figures 31 to 42, respectively, had the smallest scatter in the case of PM2.5 SDS sensor. Based on the results of the scatter diagrams, both PM2.5 SDS and PM2.5 DN7 were characterized with high reproducibility, although some part of the data was significantly distant from the ideal relationship. This could have been as a result of high humidity.

It is challenging to measure repeatability PM sensors because of the challenge in the maintenance of constant concentrations of particles. The repeatability of various low-cost PM sensors ware reported to lie between 2 and 28% based on the coefficient of variation (CV) measurement (Wang et al., 2015). At low PM concentrations, the repeatability deteriorated while all the sensors had coefficient of variation ranging between 23% and 26% at~50 μg/m^{3}PM concentration.

As far as reproducibility is concerned, various researches have revealed that there is the need of calibrating the sensors individually, thus making the insufficient raw outputs reproducibility of the sensor evident. After calibration, however, there is improvement of their reproducibility characteristics. The piling up in the sensing zone of the particles may bring about deterioration of sensor reproducibility, and this is considerably less evident in case sensors are exposed to smaller particles than bigger particles.

The response of sensors usually changes with time because of dust accumulation and sensor aging, although the number of days in which a sensor has been used can be considered as a confounding variable the following figures are from the same data in chapter four (figures 11-19) with different plotting methods for extra clarification.

Closed fan

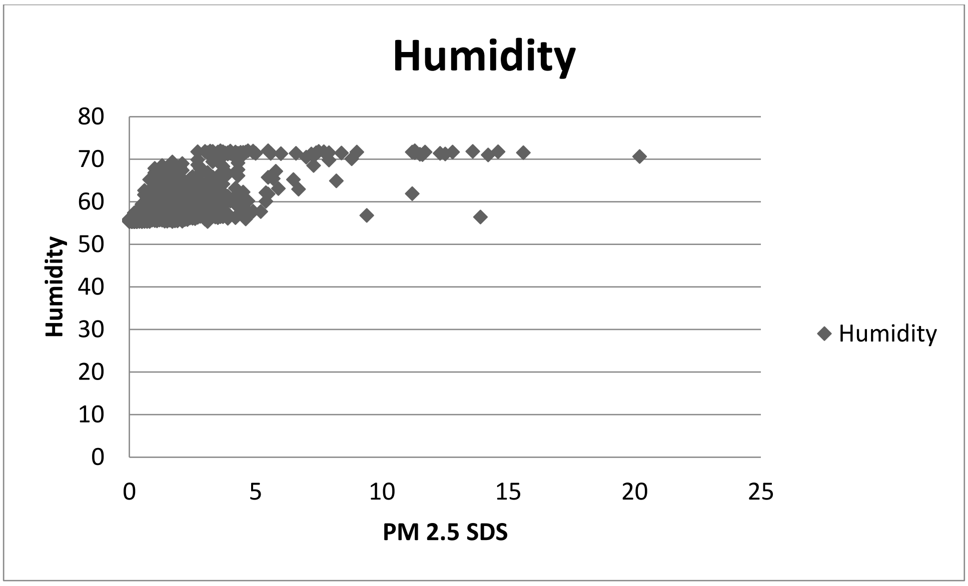


Figure 19: scatter plot of humidity against PM2.5 SDS for closed fan

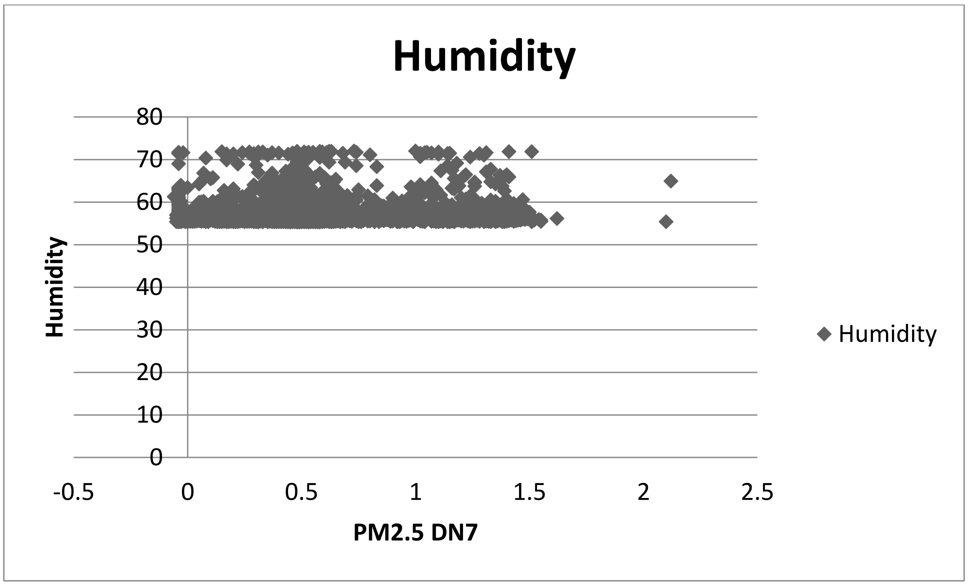


Figure 20: scatter plot of humidity against PM2.5 DN7 for closed fan

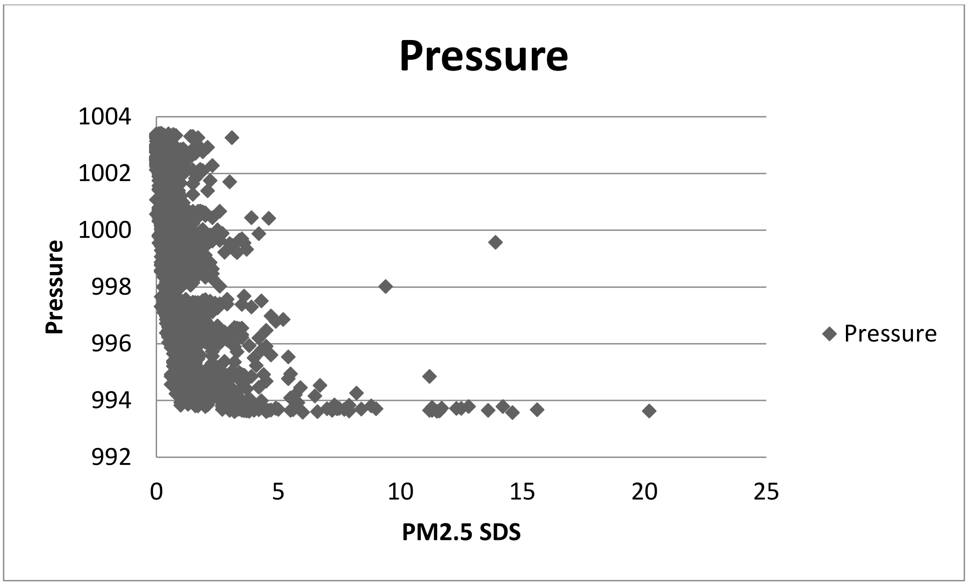


Figure 21: scatter plot of pressure against PM2.5 SDS for closed fan

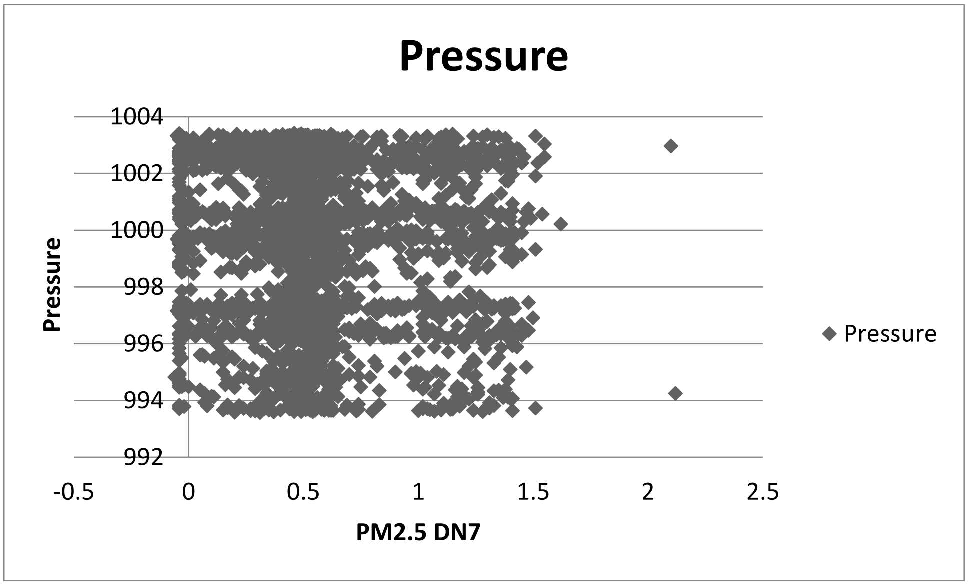


Figure 22: scatter plot of pressure against PM2.5 DN7 for closed fan

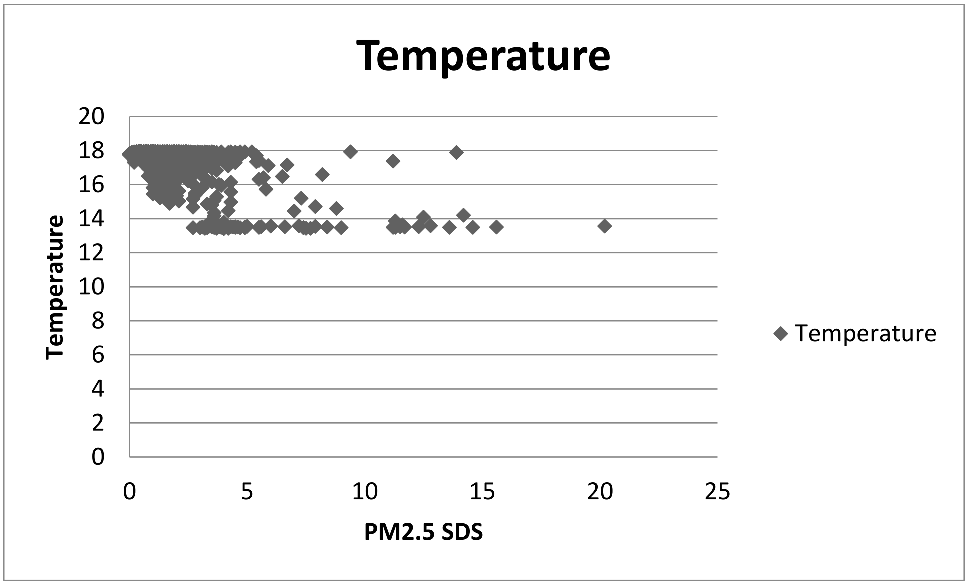


Figure 23: scatter plot of temperature against PM2.5 SDS for closed fan

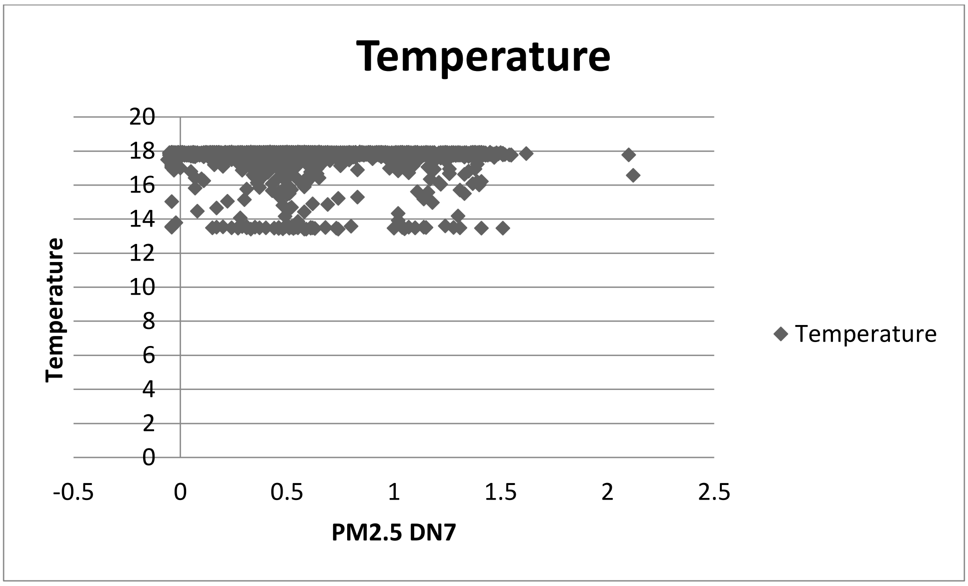


Figure 24: scatter plot of temperature against PM2.5 DN7 for closed fan

Open fan

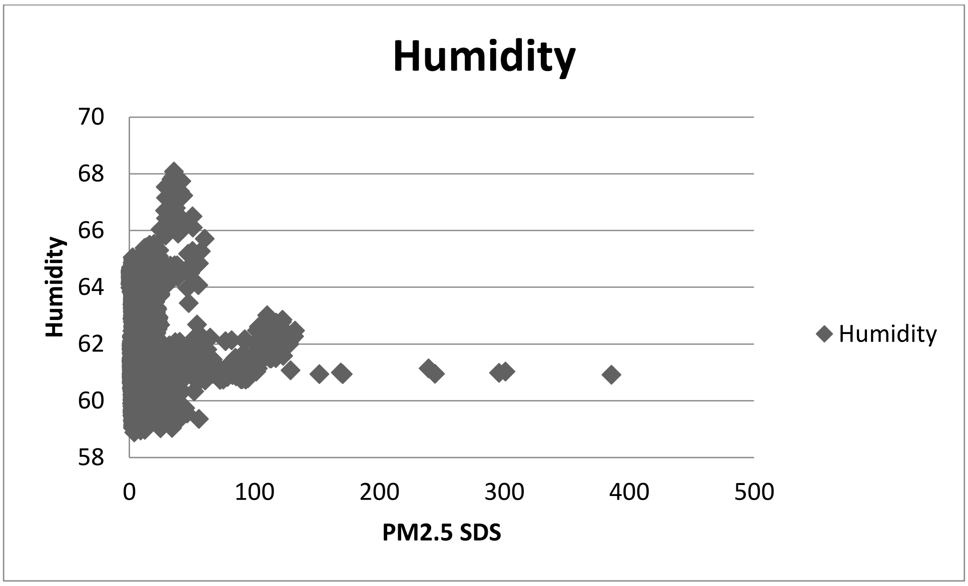


Figure 25: scatter plot of humidity against PM2.5 SDS for open fan

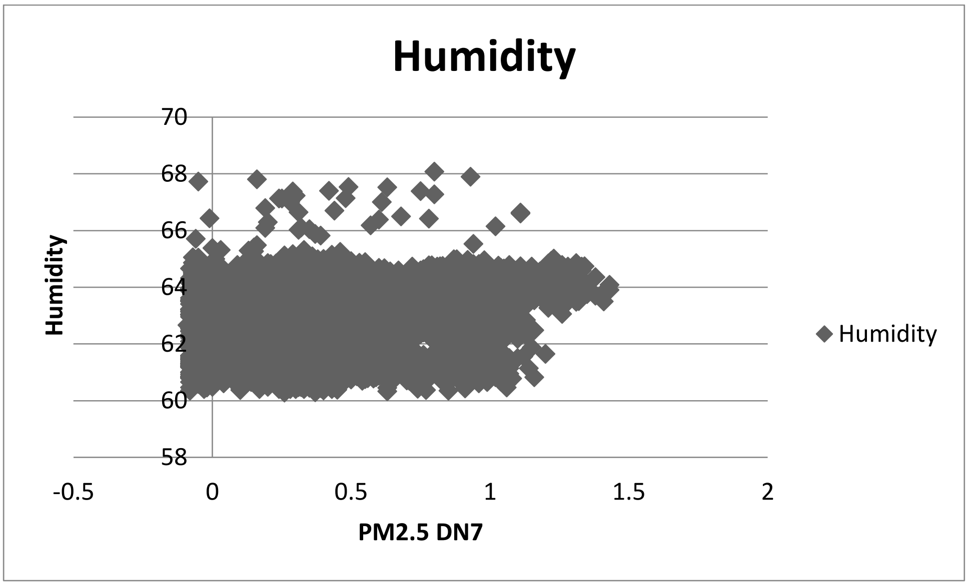


Figure 26: scatter plot of humidity against PM2.5 DN7 for open fan

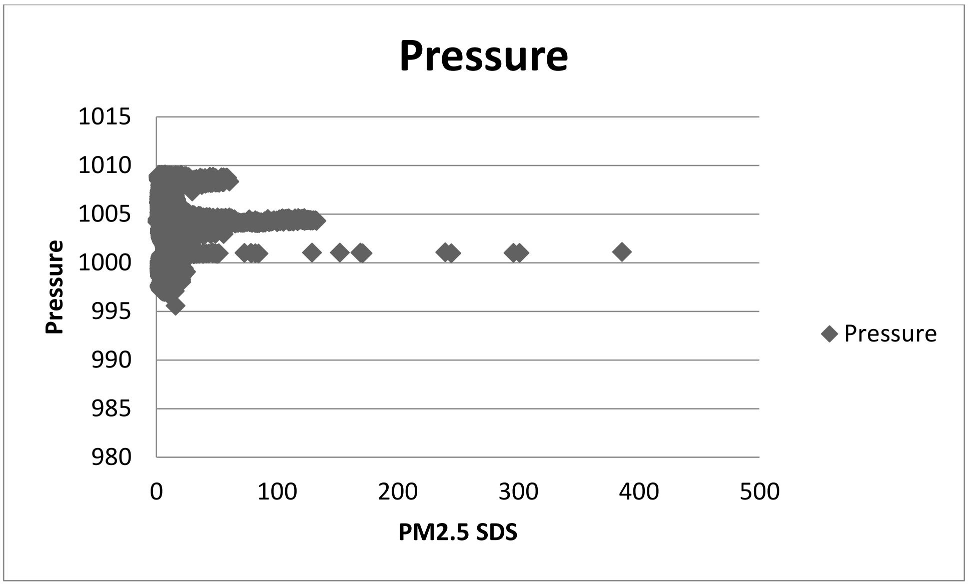


Figure 27: scatter plot of pressure against PM2.5 SDS for open fan

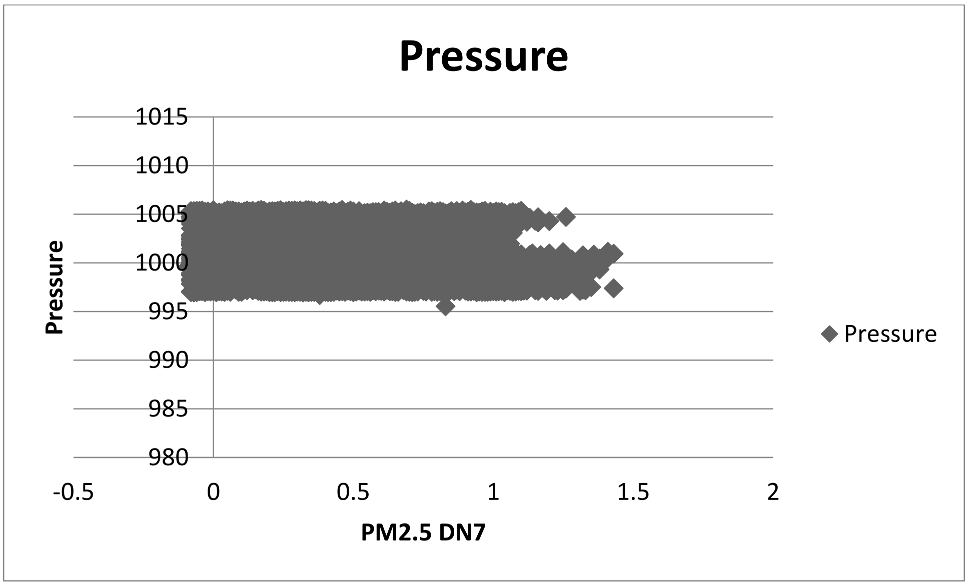


Figure 28: scatter plot of pressure against PM2.5 DN7 for open fan

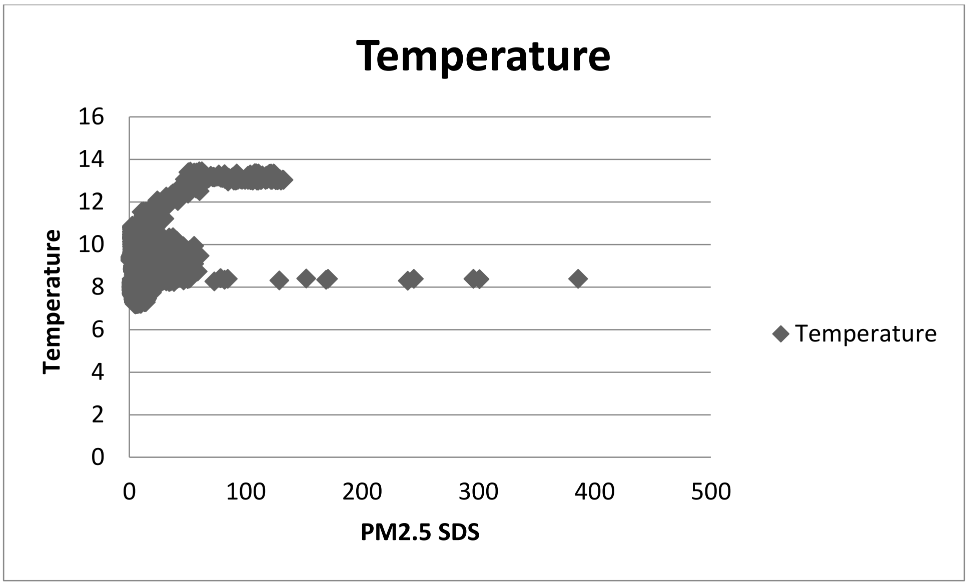


Figure 29: scatter plot of temperature against PM2.5 SDS for open fan

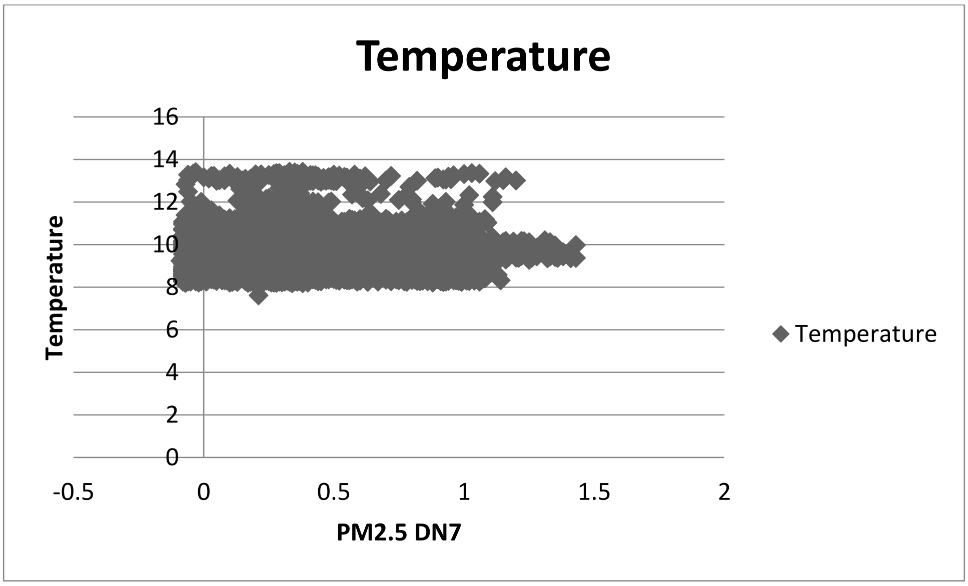


Figure 30: scatter plot of temperature against PM2.5 DN7 for open fan

Different sensors fan closed

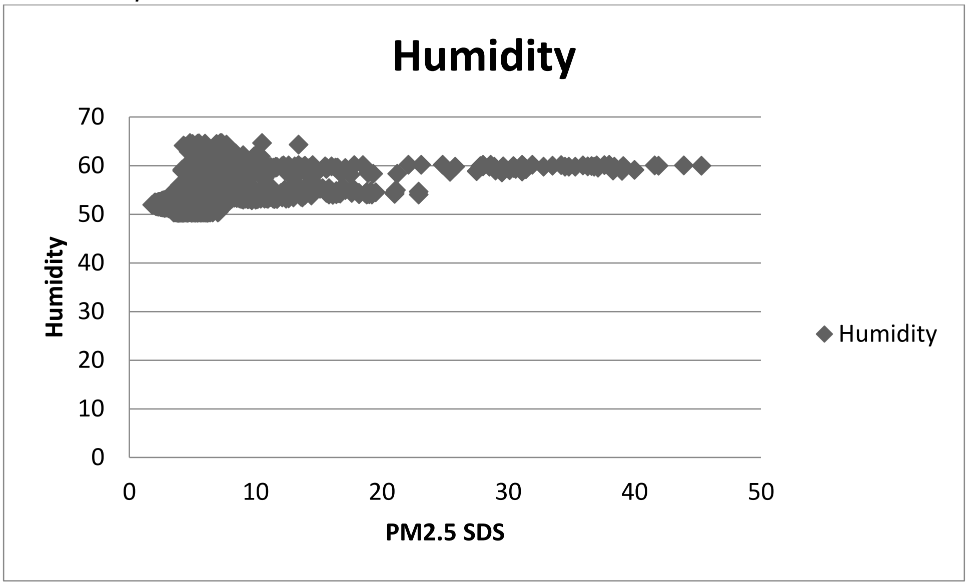


Figure 31: scatter plot of humidity against PM2.5 SDS for different sensors closed fan

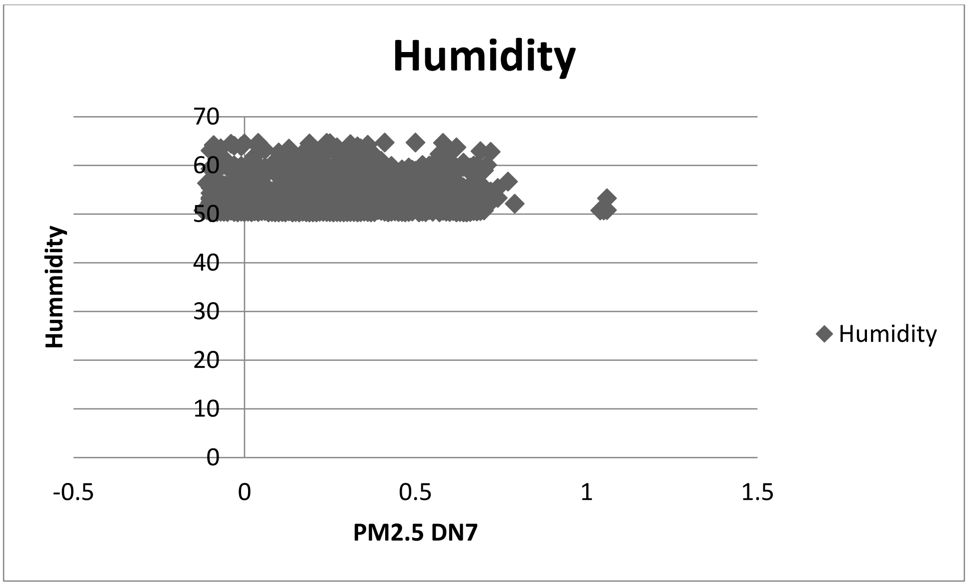


Figure 32: scatter plot of humidity against PM2.5 DN7 for different sensors closed fan

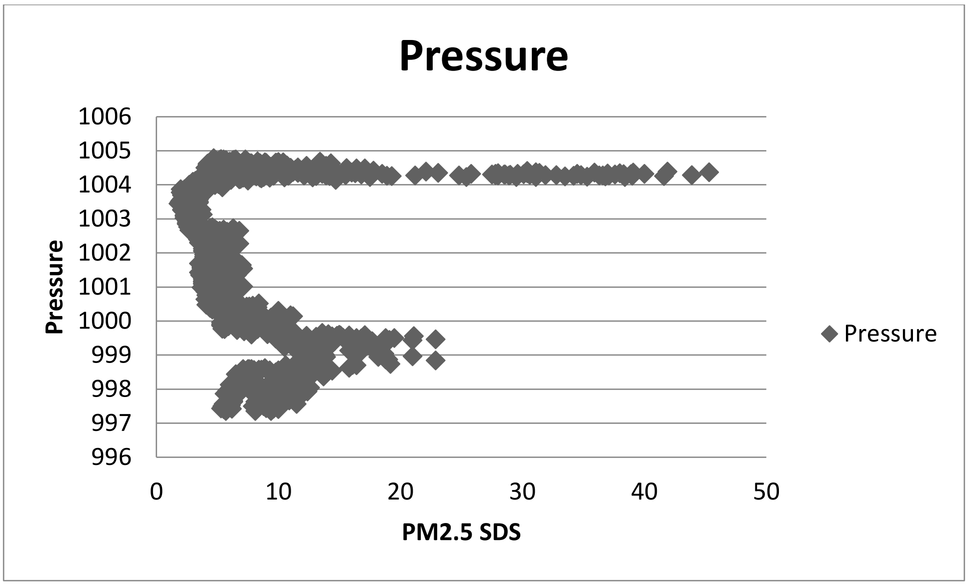


Figure 33: scatter plot of pressure against PM2.5 SDS for different sensors closed fan

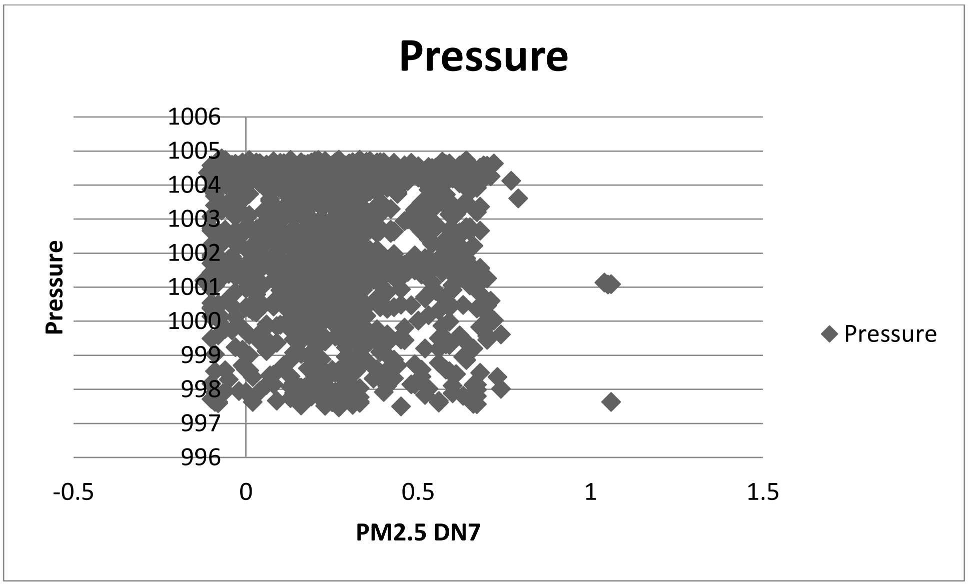


Figure 34: scatter plot of pressure against PM2.5 DN7 for different sensors closed fan

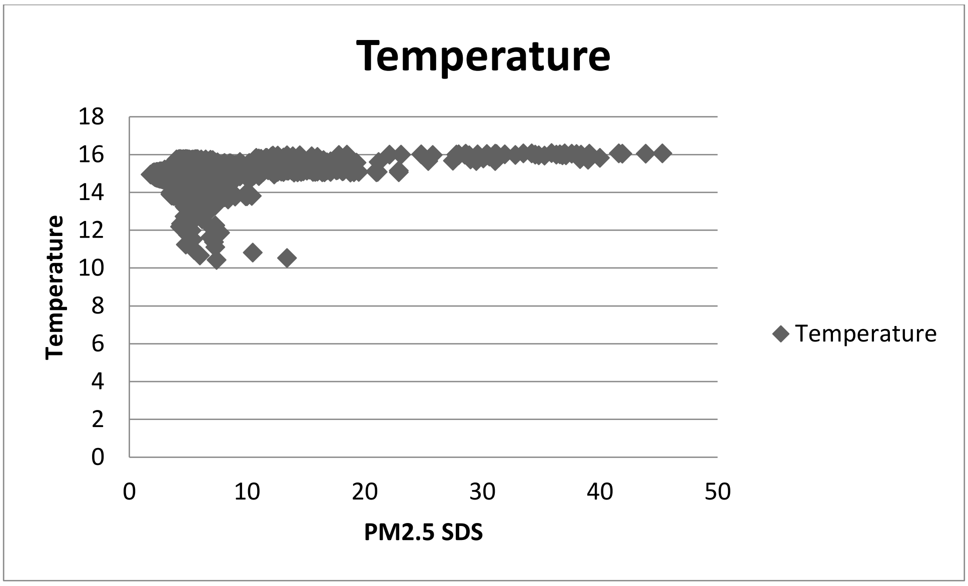


Figure 35: scatter plot of temperature against PM2.5 SDS for different sensors closed fan

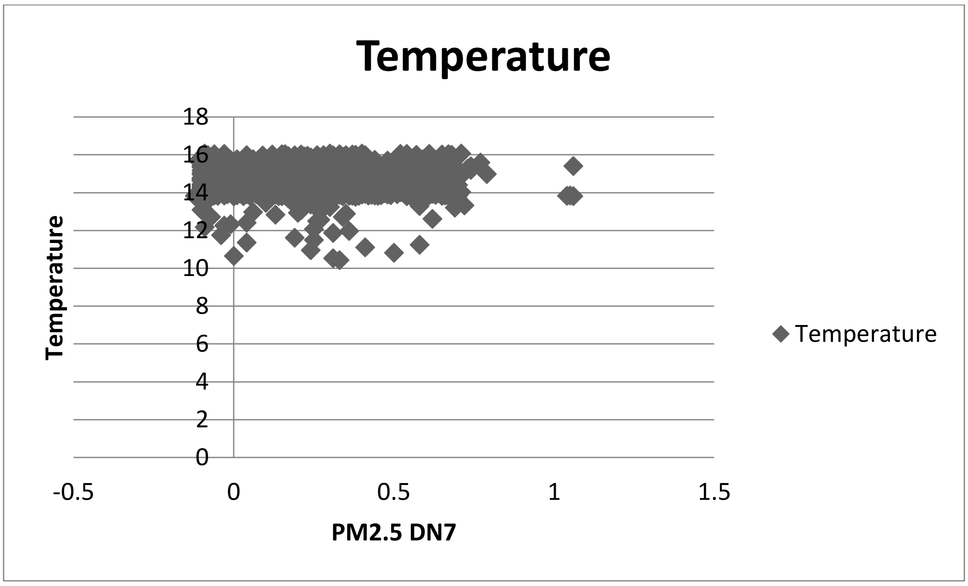


Figure 36: scatter plot of temperature against PM2.5 DN7 for different sensors closed fan

Different sensors open fan

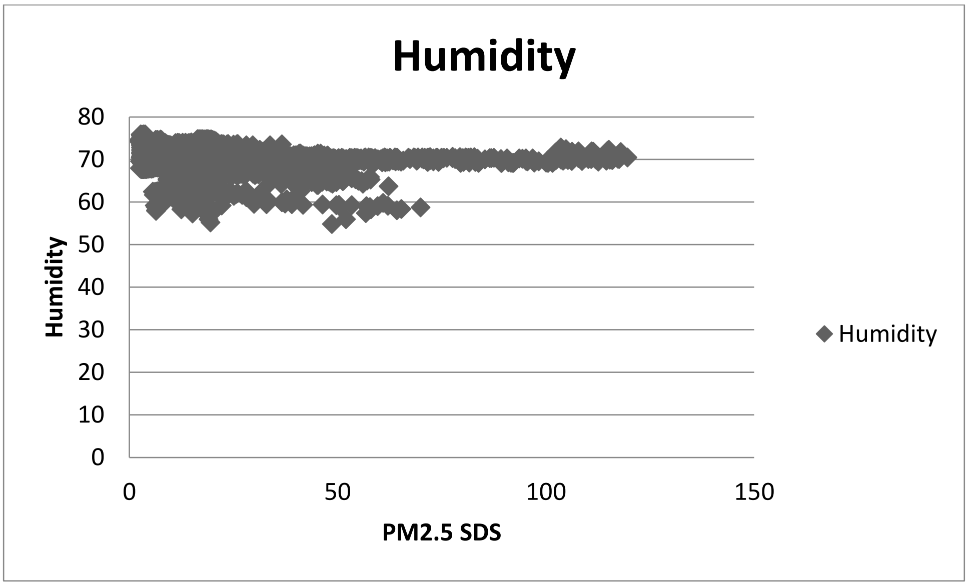


Figure 37: scatter plot of humidity against PM2.5 SDS for different sensors open fan

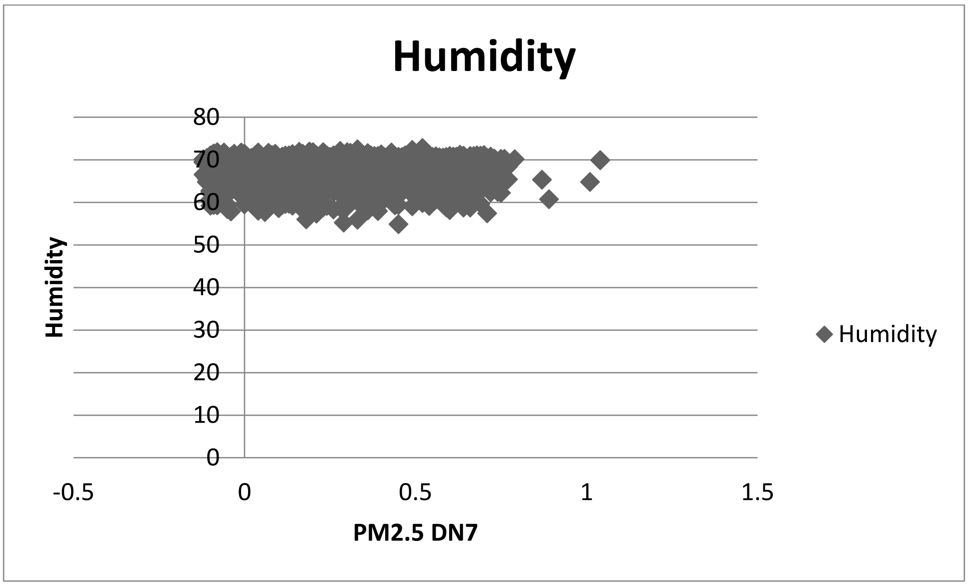


Figure 38: scatter plot of humidity against PM2.5 DN7 for different sensors open fan

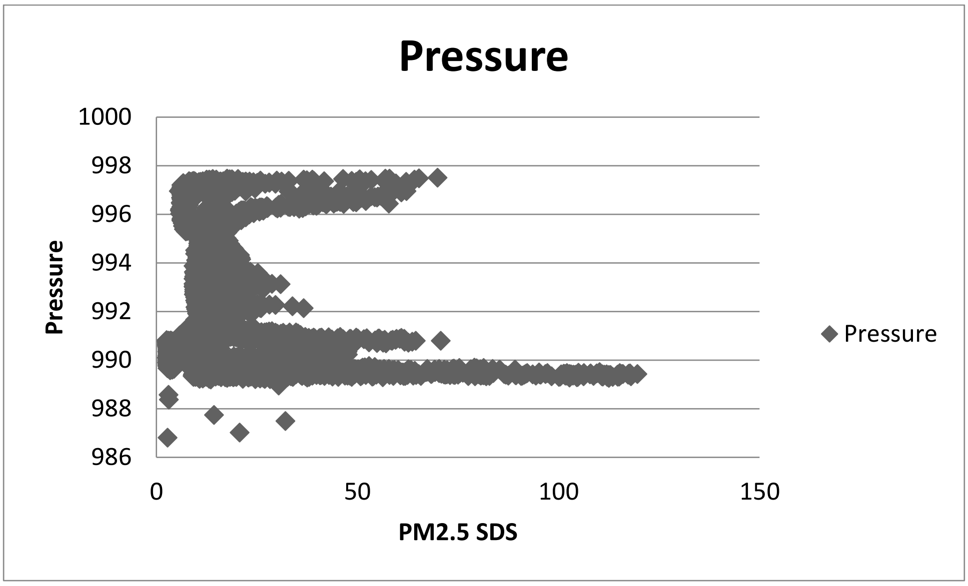


Figure 39: scatter plot of pressure against PM2.5 SDS for different sensors open fan

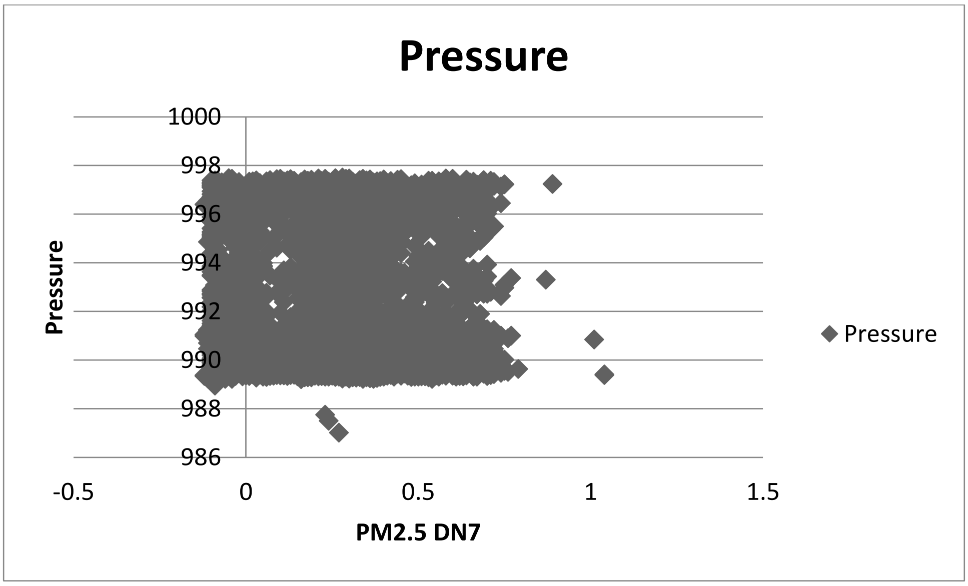


Figure 40: scatter plot of pressure against PM2.5 DN7 for different sensors open fan

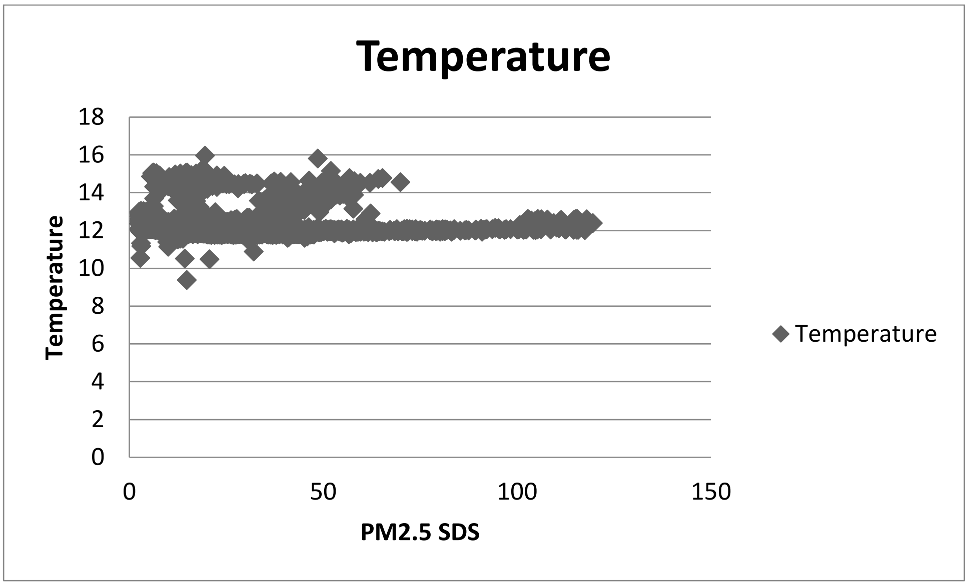


Figure 41: scatter plot of temperature against PM2.5 SDS for different sensors open fan

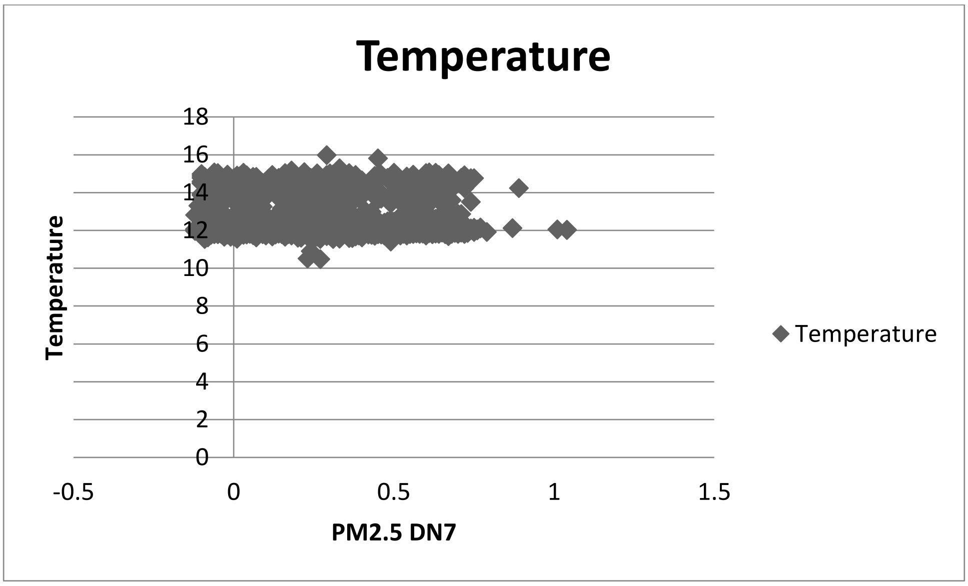


Figure 42: scatter plot of temperature against PM2.5 DN7 for different sensors open fan

4.2.3 Linearity and Non-linearity of outputs

Pairwise correlation for PM2.5 SDS and PM2.5 DN7 between the concentration of the particles and the environmental effects, including humidity, temperature and pressure revealed high particles concentration measured by both sensors. Since the two sensors are of low cost, the sensors can be applied with a view to obtaining real-time and local concentrations of PM in polluted cities, in which the day-to-day upper limit of concentrations of particles is approximately 600 mg/m^3, while the hourly upper limit of concentrations of particles is approximately 1 mg/m^3 (Spinelle et al., 2016).

Piecewise linear regression is usually used alongside correlation analysis in the calculation of slope and interpretation of values, and the values are then used in converting raw data to appropriate unit form. Linear regression is instrument in the analysis as it helps in making slope in addition to intercept comparison across different units. Moreover, linear regression is also used in the standardized equivalency tests for the UK criteria certification scheme MCERTS and European standard EN14662-2 of comparing candidate and reference method. In most cases, this is taken into consideration when more complicated, non-linear regression analysis are not introduced to the correlation analysis during investigation is less accurate, complementary, low-cost air quality sensors.

The R^2, NRMSE and RMSE may be used in the evaluation of the tested sensors. Equation 2 and equation 3 shown below are used to calculate RMSE and NRSME:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - y_{i,cal}\right)^2}{n}} \qquad (2)$$

$$RMSE = \frac{RMSE}{\bar{x}} \qquad (3)$$

where n represents the amount of sample pairs, $y_{i,cal}$ represents the ith the calibrated sensor value sample, x_i represents the ith reference value sample, and $\bar{x}$ is the mean of the reference values. To prevent arbitrary unit comparisons, it is advisable to use sensor values.

When enacting regulations on atmospheric PM or in the case of practical applications, it is advisable to use lower particles concentration ranges to enhance linearity of sensors. However, when testing the same type of sensors, some usually deviate significantly from others even when the linearity is high. Such a systematic deviation may not be sufficiently explained by the fluctuations in concentrations at the sides of the sensors' chambers. As such, each of the sensors should be separately calibrated before being utilized in commercialized monitors because the concentrations of the particle reported by the sensors may be significantly affected by the existing systematic error.

4.2.4 Accuracy and precision

The standards for PM2.5 as given in the UK criteria certification scheme MCERTS and European standard EN14662-2 high-quality data has minimal relative error and imprecision. The quality assurance goal for both the UK criteria certification scheme MCERTS and European standard EN14662-2 for measurement of measurement of PM2.5 is defined within ±15 per cent (Defra, 2018). However, there are various possible errors associated with PM2.5 sensors. For example, significant errors of up to 50% have been observed when using various measurement techniques; when using identical systems of different age, placement and age; and when using samplers of different design and manufacturers (Spinelle et al., 2016). However, measurements with a precision of approximately 10% can be obtained when using co-located samplers of identical design and same level of cleanliness. As such, it is quite difficult to achieve calibration of equivalent methods with the PM2.5 sensors, making it necessary to ensure compliance with national standards and consistency.

There are a number of ways in which possible sources of error in the measurements of PM2.5 may arise, and these include during sampling, when transporting the collected samples to the laboratory, or at the laboratory. Additionally, sampling error is commonly brought about by the loss of semi-volatile components, including nitrates and certain organics, through sublimation and evaporation during variable humidity and temperature conditions. The loss of semi-volatile components of PM2.5 can be reduced by limiting the rise in temperature of the sample filter during sampling to 3 °C above ambient temperature, as well as after collecting sample (when the sample is awaiting retrieval from the sampler it is retained in) (Spinelle et al., 2016). Sampler operational conditions define the ambient humidity as 0% to 100% per cent and the ambient temperature range between –30 °C and 45°C (Spinelle et al., 2016). The sample volatilization and condensation are usually affected by these extremely broad operational conditions, and these makes comparisons of data across the country difficult, especially in areas with adverse climates. Moreover, temperatures in some locations with adverse climates may routinely fall below or rise above the set ambient limits. Moreover, daily ambient temperature variations may affect the integrity of the sample at individual monitoring sites. Variations in seasonal weather may also introduce sampling errors at some of the monitoring sites.

Other possible sources of sampling errors include sampler malfunction or leakage, sampler design, the age the sampler, the cleanliness of the sampler, and sampling flow rate and time. Errors may also be introduced in the sample during transportation from the sampler to the laboratory as a result of poor handling and storage of the sample, failure of the protective container holding the sample, and humidity and temperature fluctuations. Significant error may also be introduced during the handling and storage, conditioning, equilibration and weighing of the sample in the laboratory.

4.2.5 Signal processing

Low-cost air monitoring devices are used as air quality indicators in areas suffering from air pollution as a result of PM released from industrial combustion, traffic in addition to residential heating units and offices. The low-cost sensors make use of elements cheap laser scattering sensor that give values of particulate matter, both PM2.5 and PM10, with respect to

ASCII data that have been prepared readily for a microcontroller that has a number of functions including the management of other sensors such as humidity and sensor, displaying data, in addition to acting as the power supply, an alert system, and even provision of networking connectivity. However, a typical low-cost sensor's data sheet hardly provides detailed data as far as accuracy is concerned, and this makes it important to take into consideration the uncertainty in measurement.

One of the most realistic checks in the evaluation of the remaining uncertainty in measurement involves a comparing the measurement to an instrument of reference that is well calibrated in actual experiments. As far as the measurement of particulate matter is concerned, there are a number of parameters influencing the results, and these include the mass distribution of the particle versus its size, shape of the particle and the particles' chemical and physical composition. It is a tedious job to cover the entire n-dimensional space of variations of parameters with realistic experiment with a view to assessing the uncertainty in the measurement. Therefore, there is a desire for a more pragmatic approach with a view to finding out the expectation from a low-cost sensor as far as accuracy is concerned.

A typical low-cost PM-sensor takes measurement by the use of the technique of laser scattering. An air stream from a fan directs the particles are directed inside a measurement chamber where the laser-diode beam's light is then scattered. The signal processing is made up of an electro-optical front end whose function is to yield electrical pulses from the scattered light, with the area reflecting the particle size or pulse height. Finally, the PM values are calculated using a post processing unit (based in a microcontroller) to digitize the pulse information. The scattered light is sensed by the electro-optical analog front end with a photodiode that is responsible for yielding a photo current from light intensity.

4.3 Comparison with other data

When monitoring particulate matter, it is important to compare the collected data with other data as one of the main ratification checks, and this involves pollutants that are monitored at the measurement sites in addition to those monitored in the nearby locations and regions. This involves checking whether the measurements of PM2.5 within the site is less that the co-located concentrations of PM10 as is expected, albeit by allowing a room for excursions with instrument uncertainties. The consistency of the volatile measurements of PM2.5 within the site should be compared with that of the regional and co-located concentrations.

The results have shown that humidity has significant effect on the low-cost sensors performance. There are a number of reasons for this, the most obvious being the lack of system in the low-cost sensor for drying the particles prior to being entered into the optical filter, thus making the aerosol particles to be counted together with fog droplets. This results in a positive artefact in comparison to TEOM. The other reason is the growth of the particle by condensation of water vapour. There can be condensation of water vapour onto the particle, depending on the particles' chemical composition, making the particles to grow by condensation. Such a growth in the diameter of the particle is reflected in the particle mass by radius to the power of three and would result in a positive artefact in comparison to the TEOM, owing to the fact that TEOM measures dry particles. When calculating the density distribution of a particle, the particles' refractive index is a critical parameter. Condensation of water vapour varies the Mie equation's imaginary component, commonly referred to as the extinction coefficient of the material.

4.4 Challenges of low-cost air monitoring sensors

The main considerable issue with the low-cost air monitoring sensors is how accurate and efficient is its performance due to the following factors: sensitivity to other air pollutants;

long term performance; sensor interferences; and sensitivity to meteorology and environment. In addition, tests should meet with UK criteria certification scheme MCERTS in parallel with European standard EN14662-2. Some of these factors are discussed in the following sub-sections.

4.4.1 Sensitivity to other pollutants

Gaseous cross-sensitivity is described as the false sensor response sensor that comes about owing to its gaseous co-pollutants sensitivity that exists together with the targeted pollutant. The fully understand the impact of cross-sensitivities on a sensor's response, it is important to know the co-pollutant gas concentration owing to the fact that the sensor response usually comes about as a result of cross-sensitivity of a gas. As such, the variation in sensor response can be estimated by the multiplication of the cross-sensitivity of gases with their correlating ambient concentration. The EU specified limits can be used for the concentrations of CO, NO2, and SO2. The estimated sensors outputs variations are quite low for NO, NO2, CO2, and NH3 interferences, ranging between − 2.4 ppb and 2.0 ppb. There is negligible influence of cross-sensitivity of gases on a MOS O3 sensor (Lin et al., 2015). However, various co-pollutants will be present will be present under such conditions, meaning that overall cross-sensitivity of the sensor will be a combination of individual cross-sensitivities. However, the sensor will appear like it has no cross-sensitivities problems in case the individual cross-sensitivities cancel one another. Thus, it is advisable for sensor manufacturer to first evaluate the cross-sensitivity coefficients of the sensor under laboratory conditions to levels of co-pollutants that is anticipated, before carrying out field calibration under the actual deployment conditions.

4.4.2 Sensitivity to meteorology, environment and sensor interference

Sensors such as MOS, EC3 are quite sensitive to relative humidity and temperature, among other environmental factors, as these environmental factors have significant effect on the outputs of the sensors. According to Spinellea et al. (2016), some sensors responses decrease by a range between 0.7 ppb and 3.8 ppb O3 per one °C temperature resulting increase in chamber testing in a range of 12 °C to 32 °C. Moreover, the relative humidity also impacted on the sensors response with a variation ranging between − 0.65 ppb O3 and 0.84 ppb for every increase in relative humidity. On the other hand, filed testing has revealed negligible or little association between response of the sensors and humidity or temperature (Lin et al., 2015).

The outputs of other sensors such as EC O3 sensors are also affected by environmental factors with the change in the different sensor's response ranging between − 0.022 and 1.29 ppb ozone for every increase in relative humidity. Spinelle et al. (2016), however, failed to record any influence of temperature or humidity on the EC sensors response in the process of their research study. The existing gaps between chamber measurements and measures attributing to the filed measurements' failures to isolate the effect of a specific factor (e.g. humidity) on the response of the sensor from other confounding factors (such as and sensor aging and gaseous interferences).

4.4.3 Long term performance

Long term performance of sensors depends on the stability of sensors for long term deployment. Various studies have revealed that low-cost sensors generally maintain their performance for sufficiently long duration, which covers a few months, ranging between 2 months and 6 months. However, most of the sensors become unsuitable for indicative monitoring purposes in the United Kind and, by extension, in the European Union after long term performance; as they fail to meet the expected quality criteria, including the United Kingdom criteria certification scheme MCERTS as well as the European standard EN14662-2. However, for long term performance, the sensors tend to perform better at high concentrations of pollutants, and this present an enhanced opportunity to use the sensors for long term performance in areas with high pollution. Long term performance is also closely associated with sensor aging, and the latter is one of the confounding factors in the response of sensors to temperature and relative humidity, among other environmental factors.

Summary

This chapter has presented the test and results of the thesis. The study looked into the correlation between PM2.5 SDS and each of Pressure, Temperature and Humidity. From the results of the correlation analysis, it was evident that there was no significant relationship between each of humidity, pressure and temperature and PM2.5 DN7 both in the case of closed fan and open fan.

The stud also looked into Repeatability, reproducibility and stability. This involved the use of piecewise linear regression alongside correlation analysis in the calculation of slope and interpretation of values, and the values are then used in converting raw data to appropriate unit form. Besides, Linearity and Non-linearity of outputs was also looked into and involved ppairwise correlation for PM2.5 SDS and PM2.5 DN7 between the concentration of the particles and the environmental effects, including humidity, temperature and pressure revealed high particles concentration measured by both sensors.

There are a number of ways in which possible sources of error in the measurements of PM2.5 may arise, and these include during sampling, when transporting the collected samples to the laboratory, or at the laboratory.

Chapter 5: validation, verification and Discussion

This thesis has investigated the outdoor low-cost monitoring air quality to enable their use in traffic management mainly in the United Kingdom. PM2.5 and PM10 data that were measured for this study was used from August 2019 to December 2019, and the collected data captured a number of variables including different sensors in the case of both open fan and close fan but both involving humidity, temperature, pressure, PM2.5 SDS and PM2.5 DN7. The results of the study also revealed strong correlation between various measurements under investigation. For instance, in the case of closed fan, there was strong correlation of 0.704 between humidity and PM2.5 SDS011. However, there was a strong negative correlation of -0.799between humidity and pressure as well as a strong negative correlation of -0.884 between humidity and temperature while the DN7C3CA007 shows less negative correlation. These findings were in agreement with findings from other studies which revealed the relationship between humidity, temperature and pressure, and their effect on the particulate matter.

The focus of this study was informed by the updated European Air quality guidelines (AQG) which was aimed at providing detailed information regarding the manner in which human health is adversely affected by the exposure to various air pollutants. These guidelines were aimed at providing a basis for the protection of human health from air pollution effects. In particular, the intention of these WHO guidelines was to provide guidance and information for NPL laboratory in making suitable management decisions. similar guidelines have been used by the European Union (EU) as a basis for setting binding air quality target values and limiting values for every member countries of the European Union (EU) for several pollutants, including OJ L 163 (1999), OJ L 313 (2000) and OJ L 067 (2002).

Based on the results of correlation analysis, the findings agree with previous studies which found that road transport is one of the major sources of air pollution which affects not only the quality of human life but also the natural environment, calling for drastic actions for reduction of harmful particulate matter and gases, especially in urban areas (Ferreira, 2014; Allegrini, 2008). By reducing energy consumption and reducing emissions from activities related or transportation or improving traffic flow, but also to monitor pollution of air (Ferreira, 2014; Allegrini, 2008). There are various solutions air pollution that are already in existence, and these include networks of static measurement stations, which are not only characterized by reliability but also high accuracy. using these systems has continued to face severe limitations owing to the high cost of acquisition and maintenance (Hasenfratz, 2015). Penza (2012) mentioned that as far as profitability is concerned, it is possible to use vehicles that have been equipped with measurement devices as mobile air pollution monitoring laboratories that have high temporal and spatial resolution.

Both the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and DN7C3 CA007 sensor (PM2.5 DN7 sensor) that were used in this study met the United Kingdom criteria certification scheme MCERTS as well as the European standard EN14662-2. The low-cost air sensors' proliferation of measurements presents challenges in the interpretation of data, as few researchers have examined the performance of sensors (including precision, accuracy, and reliability, among others) under real world conditions. Quantification of the low-cost air quality sensors' performance is an active research area, as more research studies are being focused on the assessment of measurements in a number of controlled conditions and real-world environments, by ensuring that the tests meet with UK criteria certification scheme MCERTS in parallel with European standard EN14662-2. Other studies have examined the network sensors' performance in addition to the use of the measurements from the data to quantify pollution hot spots. MCERTS performance standard covers the various air pollutants including:

In spite of the reasonably good performance of the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and the DN7C3 CA007 sensor (PM2.5 DN7 sensor), their deployment is open to potentially high misuse, especially when deployed outside the research environment for personal air quality monitoring and for citizen science applications where the users might not have the necessary skills and knowledge for judging the sensors' uncertainty adequately. The deployment of the sensors in such cases will most likely not be limited to environments that have relative humidity less than 80%, while there may be no user's notification informing them about the unreliability of the readings when the relative humidity exceeds 80%, although most of the manufacturers usually provide a recommended operating range of the relative humidity. Moreover, there may be significantly high relative uncertainties for hour-to-hour values recorded by the sensors, and it is important for users to be aware of such limitation with a view to taking cautions during interpretation of such measurements. However, considering the overall performance assessment results and the low cost of the sensors, it can be concluded that the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and the DN7C3 CA007 sensor (PM2.5 DN7 sensor) have better potential for implementation of dense monitoring network in situations in which the environmental conditions exhibit relative humidity which is relatively low, of less than 80%. On the other hand, when the sensor is deployed under environmental conditions exhibiting relative humidity which is relatively high, it is important to establish suitable automated filtering and correction routines with a view to removing inconsistent observations from the dataset as an alternative to providing the users, at minimum, with clearer indications of the uncertainty of the observations that have been estimated. By meeting these conditions, it can be concluded that networks of Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and DN7C3 CA007 sensor (PM2.5 DN7 sensor) could complement, in the near future, the regulatory outdoor air quality monitoring networks in addition to improving the temporal and spatial resolution of PM2.5 data, thus resulting in the opening up of a wide range of applications for regulatory agencies, research community in addition to raising awareness.

There is also the need to quantify the uncertainty and validity of sensor measurements for various aerosol and meteorological loading environments. Moreover, it is equally important to validate sensor measurements on the basis of already established methods in real world owing to the fact that laboratory experiments tend to fail to reflect the meteorological and pollution conditions' variability found in the real world (Genikomsakis et al., 2018). This is a necessary step to ensuring the deployment of sensors for objectives that boost confidence in the quality of data.

The interest and demand for data on air quality has made companies to focus on the accuracy of these smart inexpensive sensors. There are a number of these sensors that are directly marketed to consumers that have interest in their personal exposure. There are a wide range of applications for the sensors, although the applications are dependent on the quality of the measurements of interest.

There is the potential for the low-cost sensors to provide insight into the temporal and spatial variability of pollutants; the sensors provide data that could inform studies of personal emission and exposure inventories in case the quality of data measurement is sufficient in meeting the objectives. Researchers working on air quality having been interested in assessing the sensor network deployment in addition to the potential value of integrating them into air quality regulatory network that are already in existence (Genikomsakis et al., 2018). However, different levels of data quality and confidence in them have necessitated different interpretations of data.

In recent years, the advancement in the field of information and technology (ICT) and low-cost micro-sensors have provided an opportunity of achieving the objective of providing useful and updated air quality information by improving the temporal and spatial resolution for air quality data through complementing the already existing outdoor air quality monitoring networks. There are various low-cost air monitoring sensors for measuring the particulate matter, and these include the Laser PM2.5 Sensor SDS011 (PM2.5 SDS), DN7C3 CA007 sensor (PM2.5 DN7 sensor), Air Beam, GP2Y1010, Plantower PMS1003, Shinyei PPD42NS, Wuhan Cubic PM3007, and Alphasense Optical Particle Counter (OPC-N2), among others. All these sensors work on the principle of optical light scattering by the use of a laser in addition to the application of Mie theory on the scattered light with a view to determining the size of particulate matter. Moreover, these sensors have compact sizes, operate at a high sampling frequency, have low energy consumption and have varied costs ranging from tens to hundreds of Euros. Owing to their size, ease of use and cost, these sensors are suitable for use in the outdoor environment and are already being deployed by citizen scientists. However, it is crucial to assess the accuracy, precision and reliability of the sensors in a repeatable and comprehensive manner under real-world environments and conditions before they are widely used. So far, while their performance under different time scales and various environmental conditions has not been understood yet.

It is becoming more evident that development of portable devices that are cost-effective that are mountable on roads with a view to supporting wider applications interest in intelligent transportation systems (ITS) is a challenge in the field of research. For example, sensing units mounted on vehicles for public transportation that are meant for displaying near real-time pollutants level as well as generation of high-resolution maps for urban air pollution on motorbikes for planning healthier routes as well as capturing fine-grain environmental information for the monitoring of quality of mobile air (Al-Ali et al., 2010; Elen, 2013; Velasco, 2016; Keifer & Benrendt, 2016; Ioakimidis & Rycerski, 2016). The combination the latest low-cost sensors market development with available information and communication technologies has made it possible to design and implement portable, inexpensive and compact sensor units for the creation of profiles of concentration of aerosols that have detailed temporal and spatial resolution in addition to deploying networks of the devices in the form of mobile agents who operates simultaneously under analysis of scheme of big data with a view to developing applications and providing additional services in the intelligent transportation systems (ITS) context (Park et al., 2011; Choi, He, & Barbesant, 2012; Hu et al., 2012). The need for quantifying the low-cost sensors' performance in the actual condition has been emphasized by various researchers (Al-Ali et al., 2010; Elen, 2013; Velasco, 2016; Keifer & Benrendt, 2016; Ioakimidis & Rycerski, 2016). To that end, various experiments have been conducted with a view to examining the consistency, durability and stability of the sensing units, by the use of hourly data for the concentrations of particulate matter (Mukherjee, Stanton, & Graham, 2017;Zikova et al., 2017; Silva et al., 2016). This present study is focused on outdoor low-cost monitoring air quality, especially PM2.5 and PM10, whose exposure causes chronic and acute human health effects, such as premature mortality coming about as a result of lung cancer and cardiopulmonary diseases.

The main APMS components have been introduced in this thesis in relation to low-cost sensors, in addition to describing the testing of the sensing unit in the fields as proposed by the use of measurements taken on the sides that has an instrument of calibration. It should be noted that this thesis is focused on investigating low-cost measurements system for mapping ambient concentration of particulate matter (MP2.5 and PM10) in the ambient air after being calibrated on-field by the use of optical particle counter instrument. The secondary focus has been placed on detecting, whenever possible, the pollutants' source and to characterize them chemically. As such, the ability of air pollution monitoring system that is incorporated with the technologies of low-cost sensor for performing reliable measurements of the concentration of PM2.5 and PM10 in the air following calibration done out on the fields using optical sensors has been examined in this thesis.

The duration of exposure and the size of the particles are key determining factors of the potential adverse effect on health. PM_{10} has the ability of penetrating and lodging inside the lungs, thus posing a risk to health. However, $PM_{2.5}$ is associated with the strongest evidence for health effects because they are fine particles. Ultrafine particulate matter poses even greater risk to health as they can not only penetrate deeper into lung tissue but also enter the bloodstream. However, there is limited and inconclusive evidence on effects of exposure to ultrafine particulate matter on health. Short term exposure to particulate matter may bring about respiratory symptoms including irritation to throat and nose, chest tightness, shortness of breath, and coughing, as well as irritation of the eyes. Individuals with existing respiratory and cardiovascular conditions, older adults and children are particularly at risk of the effects of particulate matter when the levels of air pollution are elevated. This also results in increase in hospital admissions and deaths because of such causes. According to Gakidou (2016), the United Kingdom experienced widespread high levels of particulate matter pollution of air ($PM_{2.5}$ at urban background sites up to 83µg/m^3) in a number of days in March and April 2014. Gakidou (2016). Long term exposure to particulate matter reduces life expectance, possibly due to contribution to development and progression of respiratory and cardiovascular diseases, in addition to exacerbation of symptoms to individual already suffering from these diseases.

Long term exposure to particulate matter also increases the risk of lung cancer (Gakidou, 2016). The already existing evidence of the impact of the exposure of particulate fines on human health has consistently shown adverse effect on health at exposures that the urban population are currently experiencing. Moreover, there is strong correlation between exposures to high concentrations of particulate matter and increased morbidity and mortality, both over time and daily. Although air pollution is not the sole cause of death in most of these cases, it is considered as one of the major contributing factors. Cohort studies have revealed that the risk associated with living in locations that have elevated levels of particulate matter over long period of time health issues. The PHE Public Health Outcomes Framework (PHOF) health indicator on the air pollution estimated the percentage of adult mortality that can be sign of long-term particulate matter pollution (especially $PM_{2.5}$) in local authorities' areas in the United Kingdom. It was found it ranges from at most 3% in areas with least pollution to more than 7% in some of the London boroughs Thompson (2016) reported that the average for the United Kingdom was 5.1% in 2016.

5.1 Summery

Particulate matter has various causes of mortality, especially in cardiopulmonary mortality. $PM_{2.5}$ deeply penetrates the respiratory system of human. However, no fully safe levels of particle exposure have been identified yet. However, the conclusions under consideration are relating to particulate matter measured based on mass rather than various sources or components of particulate matter. Currently, there is no clear understanding of the properties of particles, such as the presence of particular chemical substances or the size of the particles, which are most responsible for the toxic effects. According to WHO (2018), particulate matter, especially $PM_{2.5}$, is a complex interacting mixture of numerous components which may differ from each other based on their toxicity, although the available data are not sufficient to confidently separate their effects on health. Due to the absence of clear evidence to the contrary, it has been recommended that the coefficient should equally apply to every component of $PM_{2.5}$, and this includes particulate matter measured as nitrate and sulphate.

Chapter 6: Conclusion and future recommendation

The most important parts of the air pollution monitoring system have been introduced in this thesis, in addition to describing the testing of the sensing unit in the fields as proposed by the use of measurements taken nearby road connected with computer that has an instrument of reading calibration as the comparison making item as well as showcasing its precision on specifying the concentrations of the PM on one minute resolution in an experiment carried out on the area. It should be noted that this thesis is focused on investigating low-cost measurements system for mapping ambient concentration PM in the ambient air after being calibrated on-field.

The result of this study revealed that there was a strong correlation between humidity and pressure as well as a strong negative correlation between humidity and temperature on SDS011 sensors and a less effect on the DN7C3CA0076 sensor, also SDS011 shows a slight misled in particle size since its output is digital based while, DN7C3CA007 shows no signal processing effect and a less sensitivity to humidity, temperature and air pressure. These findings were in agreement with findings from other studies which revealed the relationship between humidity, temperature and pressure, and their effect on the particulate matter. The particles level was within the accepted level (1 to 8 μm) however, taking into consideration the impact these environment factors (humidity, temperature and air pressure) on particles movement, the particles level maybe higher when considering whether changing and global warming. Thus, more actions need to be taken to reduce the pollutions level. The measurements of the particulate matter help in checking compliance with air quality regulations and legislation. The data collected through the measurements by the use of the sensor adopted in this study are critical in the understanding of the physical and chemical processes affecting particulate matter, and consequently questioning already existing models in addition to supporting the development of models, as well as decisions regarding measures for reducing the concentrations of particulate matter.

Based on the reviewed literature, it was revealed that the duration of exposure and the size of the particles are key factors determining effects of the potential adverse on health. PM_{10} has the ability of penetrating and lodging inside the lungs, thus posing a risk to health. However, $PM_{2.5}$ is associated with the strongest evidence for health effects because they are fine particles. Ultrafine particulate matter poses even greater risk to health as they can not only penetrate deeper into lung tissue but also enter the bloodstream. However, there is limited and inconclusive evidence on effects of exposure to ultrafine particulate matter on health. Short term exposure to particulate matter may bring about respiratory symptoms including irritation to throat and nose, chest tightness, shortness of breath, and coughing, as well as irritation of the eyes.

Both the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and DN7C3 CA007 sensor (PM2.5 DN7 sensor) that were used in this study were validated and analysed. The low-cost air sensors' proliferation of measurements presents challenges in the interpretation of data, as few researchers have examined the performance of sensors (including precision, accuracy, and reliability, among others) under real world conditions. In spite of the reasonably good performance of the Laser PM2.5 Sensor SDS011 (PM2.5 SDS) and the DN7C3 CA007 sensor (PM2.5 DN7 sensor), their deployment is open to potentially high misuse, especially when deployed outside the research environment for personal air quality monitoring and for citizen science applications.

6.1 Future recommendation

- Future work should also take into consideration development and deployment of source apportionment techniques with a view to estimating the impacts of air quality of the interventions. This is because of the large confounding factors affecting the evaluation of interventions including meteorology, vehicle fleet and non-traffic sources variability.
- Based on the results of the scatter diagrams, both PM2.5 SDS and PM2.5 DN7 were characterized with high reproducibility, although some part of the data was significantly distant from the ideal relationship. This could have been as a result of high humidity.
- More technical experiment is required to validate more sensors with high precession and potential of developing a real mentoring network across the country.

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Appendix

Descriptive Statistics for closed fan					
	N	Minimum	Maximum	Mean	Std. Deviation

PM2.5_SDS	2779	.00	20.20	.8965	1.39440
PM2.5_DN7	2779	-.06	2.12	.5762	.36484
Humidity	2779	55.33	72.00	57.3704	3.12572
Pressure	2779	993.58	1003.42	9.9950E2	2.80884
Temperature	2779	13.42	17.95	17.6651	.71411
Valid N (listwise)	2779				

Descriptive Statistics for open fan					
	N	Minimum	Maximum	Mean	Std. Deviation
PM2.5_SDS	9478	.80	385.90	11.9111	15.13051
PM2.5_DN	5589	-.09	1.43	.4102	.29917
Humidity	15365	58.88	68.35	63.3153	1.87777
Pressure	15365	982.17	1009.05	9.9804E2	7.72778
Temperature	15365	7.18	13.43	9.6674	1.06165
Valid N (listwise)	5589				

Descriptive Statistics for different sensors closed fan					
	N	Minimum	Maximum	Mean	Std. Deviation
PM2.5_SDS	1611	1.80	45.30	7.0880	5.87727
PM2.5_DN7	1510	-.12	1.06	.2636	.20336
Humidity	1534	50.32	64.67	53.8550	3.46832
Pressure	1534	997.36	1004.79	1.0021E3	2.08205
Temperature	1534	10.43	16.08	14.7421	.75864
Valid N (listwise)	1510				

Descriptive Statistics for different sensors open fan					
	N	Minimum	Maximum	Mean	Std. Deviation
PM2.5_SDS	8807	2.50	119.60	16.9281	15.29700
PM2.5_DN7	4152	-.12	1.04	.2785	.21602
Humidity	8385	54.83	75.92	69.1826	2.99163
Pressure	8385	986.82	997.51	9.9265E2	2.67870
Temperature	8385	9.38	15.98	12.2869	.47633
Valid N (listwise)	4152				

DN7C3CA007 codes

```
#include <TimeLib.h>

#define TIME_HEADER  "T"   // Header tag for serial time sync message
#define TIME_REQUEST  7    // ASCII bell character requests a time sync message

int measurePin = 0;
int ledPower = 12;

int samplingTime = 280;
int deltaTime = 40;
int sleepTime = 9680;

float voMeasured = 0;
float calcVoltage = 0;
float dustDensity = 0;

void setup(){
  Serial.begin(9600);
  pinMode(ledPower,OUTPUT);
  //setSyncProvider( requestSync);  //set function to call when sync required
  //Serial.println("Waiting for sync message");
}

void loop(){

if (Serial.available()) {
    processSyncMessage();
 }
 if (timeStatus() == timeSet) {
   digitalWrite(ledPower,LOW); // power on the LED
   delayMicroseconds(samplingTime);

   voMeasured = analogRead(measurePin); // read the dust value

   delayMicroseconds(deltaTime);
   digitalWrite(ledPower,HIGH); // turn the LED off
   delayMicroseconds(sleepTime);

   // 0 - 5V mapped to 0 - 1023 integer values
   // recover voltage
   calcVoltage = voMeasured * (5.0 / 1023.0);

   // linear eqaution taken from http://www.howmuchsnow.com/arduino/airquality/
   // Chris Nafis (c) 2012
   dustDensity = 0.6 * (calcVoltage -0.1)   ;
  delay(60000);
   //Serial.print("Raw Signal Value (0-1023): ");
   Serial.print("[");
   Serial.print(voMeasured);
```

```
     Serial.print(",");
    // Serial.print(" - Voltage: ");
     Serial.print(calcVoltage);
     Serial.print(",");
    // Serial.print(" - Dust Density: ");
     Serial.print(dustDensity);
     Serial.print(",'");
     digitalClockDisplay();
    Serial.print("'],");

  }


}

void digitalClockDisplay(){
  // digital clock display of the time
  Serial.print(year());
  Serial.print("-");
  Serial.print(month());
  Serial.print("-");
  Serial.print(day());
  Serial.print(" ");
  Serial.print(hour());
```

```
  printDigits(second());
}
void processSyncMessage() {
  unsigned long pctime;
  const unsigned long DEFAULT_TIME = 1357041600; // Jan 1 2013

  if(Serial.find(TIME_HEADER)) {
     pctime = Serial.parseInt();
     if( pctime >= DEFAULT_TIME) { // check the integer is a valid time (greater than Jan 1 2013)
       setTime(pctime); // Sync Arduino clock to the time received on the serial port
     }
  }
}

time_t requestSync()
{
  Serial.write(TIME_REQUEST);
  return 0; // the time will be sent later in response to serial mesg
}
void printDigits(int digits){
  // utility function for digital clock display: prints preceding colon and leading 0
  Serial.print(":");
  if(digits < 10)
    Serial.print('0');
  Serial.print(digits);
```

SDS011 code

```python
import serial, time, struct, array
from datetime import datetime

ser = serial.Serial()
ser.port = "/dev/ttyUSB0" # Set this to your serial port
ser.baudrate = 9600

ser.open()
ser.flushInput()

byte, lastbyte = "\x00", "\x00"
cnt = 0
while True:
    lastbyte = byte
    byte = ser.read(size=1)
#    print("Got byte %x" %ord(byte))
    # We got a valid packet header
    if lastbyte == "\xAA" and byte == "\xC0":
        sentence = ser.read(size=8) # Read 8 more bytes
#        print "Sentence size {}".format(len(sentence))
        readings = struct.unpack('<hhxxcc',sentence) # Decode the packet - big endian
#        print array.array('B',sentence)
        pm_25 = readings[0]/10.0
        pm_10 = readings[1]/10.0
        # ignoring the checksum and message tail

        if (cnt == 0 ):
            line = "PM 2.5: {} μg/m^3  PM 10: {} μg/m^3".format(pm_25, pm_10)
            print(datetime.now().strftime("%d %b %Y %H:%M:%S.%f: ")+line)
        cnt += 1
        if (cnt == 5):
```

BME 280 code

```
import bme280
import smbus2
import json
import datetime
from time import sleep

port = 1
address = 0x77 # Adafruit BME280 address. Other BME280s may be different
bus = smbus2.SMBus(port)

bme280.load_calibration_params(bus,address)
#def read_all():
while True:
    bme280_data = bme280.sample(bus,address)
    humidity  = bme280_data.humidity
    pressure  = bme280_data.pressure
    ambient_temperature = bme280_data.temperature
    new_obj = {'time': datetime.datetime.now().strftime("%Y-%m-%d %H:%M:%S"), 'humidity':
    with open('/var/www/html/bme.json') as f:
        data = json.load(f)

    data.append(new_obj)

    with open('/var/www/html/bme.json', 'w') as f:
        json.dump(data, f)

    print(humidity, pressure, ambient_temperature)
    #time to take to rest (10)
    sleep(60)
```

MATLAB CODES

C: ▸ Users ▸ saleh ▸ Documents ▸ MATLAB

Current Folder

Name

- Untitled.m
- sameSensor_openFan.mat
- sameSensor_closedFan.mat
- differentSensor_openFan.mat
- differentSensor_openFan.m
- differentSensor_closedFan.mat

Editor - C:\Users\saleh\Documents\MATLAB\differentSensor_openFan.m

datasens.m | matdata.m | differentSensor_openFan.m

This file can be opened as a Live Script. For more information, see Creating Live Scripts.

```
clear all; % clearing everything to avid any ambigious output
close all; % closing all graphs
clc        %clearing the command window
%%
 load sameSensor_openFan % Loading the desired data
  load sameSensor_closedFan % Loading the desired data
  load differentSensor_openFan % Loading the desired data
 load differentSensor_closedFan % Loading the desired data

pm25SDS
  Start=1;
 % TIME = DateTime;
 END=length(TIME);
subplot(2,2,1)
scatter(pm25SDS,Temperature,'DisplayName','pm25SDS Vs. Temp')% sctter plotting the pm25SDS vs the temp
grid on;grid minor % adding grid to the plot
title 'pm25SDS Vs. Temp'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'Temp (C)' % naming the y axis
subplot(2,2,2)
scatter(pm25SDS,Pressure,'DisplayName','pm25SDS Vs. pressure')% sctter plotting the pm25SDS vs the temp
grid on;grid minor % adding grid to the plot
title 'pm25SDS Vs. pressure'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'pressure (Kpsi)' % naming the y axis

subplot(2,2,3)
scatter(pm25SDS,Humidity,'DisplayName','pm25SDS Vs. Humidity')% sctter plotting the pm25SDS vs the temp
grid on;grid minor % adding grid to the plot
title 'pm25SDS Vs. Humidity'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'Humidity (grmas/qubicMeter)' % naming the y axis

DateTimee=datetime(TIME);
 subplot(2,2,4)
scatter(DateTimee(Start:END),pm25SDS(Start:END),'DisplayName','pm25SDS Vs. time')% sctter plotting the pm25SDS vs the temp
grid on;grid minor % adding grid to the plot
title 'pm25SDS Vs. time'% adding title to the plot
ylabel 'Air quality in ug/cubiqMeter' % naming the x axis
xlabel 'Time (hr)' % naming the y axis
```

```
% PM25 DN7
%
Start=1;
END=length(PM25DN7);
%%
subplot(2,2,1)
scatter(PM25DN7,Temperature(Start:END),'DisplayName','PM25DN7 Vs. Temp')
grid on;grid minor
title 'PM25DN7 Vs. Temp'
xlabel 'Air quality in ug/cubiqMeter'
ylabel 'Temp (C)'
subplot(2,2,2)
scatter(PM25DN7,Pressure(Start:END),'DisplayName','PM25DN7 Vs. pressure')% sotter plotting the PM25DN7 vs the temp
grid on;grid minor % adding grid to the plot
title 'PM25DN7 Vs. pressure'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'pressure (Kpsi)' % naming the y axis

subplot(2,2,3)
scatter(PM25DN7,Humidity(Start:END),'DisplayName','PM25DN7 Vs. Humidity')% sotter plotting the PM25DN7 vs the temp
grid on;grid minor % adding grid to the plot
title 'PM25DN7 Vs. Humidity'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'Humidity (grmas/qubicMeter)' % naming the y axis
```

```

DateTime = TIME;
 DateTimee=datetime(DateTime); % changing the dateTime in order to be plotted
 subplot(2,2,4)
scatter(PM25DN7,DateTimee(Start:END),'DisplayName','PM25DN7 Vs. time')% sotter plotting the pm25SDS vs the temp
grid on;grid minor % adding grid to the plot
title 'PM25DN7 Vs. time'% adding title to the plot
xlabel 'Air quality in ug/cubiqMeter' % naming the x axis
ylabel 'Time (hr)' % naming the y axis

```