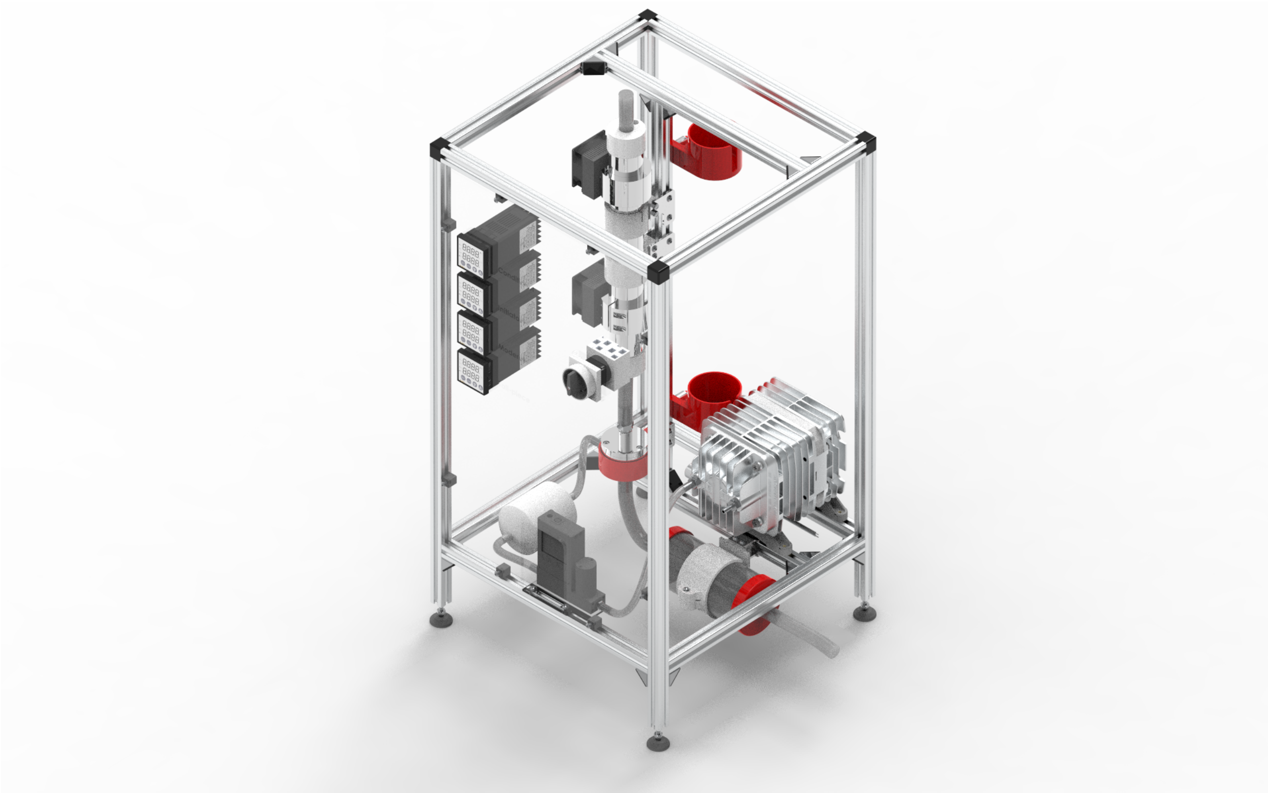
Design of an Airborne Particle Concentrator



Machine Design Advanced Course Part II, MF2077

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Abstract

Airborne particulate matter (PM) pollution has been proven to have drastic health impacts on the human body and the widespread prevalence of this pollution caused by human activity makes it an extremely pertinent issue. Research into this matter can be improved by the use of airborne particle concentrators. This paper presents the design and manufacturing process of a particle concentrator that enhances the research on the health impacts of airborne particulate matter. Solid Edge 2023 was used to create CAD models and manufacturing drawings and COMSOL multiphysics v5.6 was used to simulate the virtual impactor, which is the core component of the concentrator. Various manufacturing techniques such as 3D printing, water jet cutting, and in-house machining were applied to produce the parts of the device. The concentrators efficiency was tested and some areas for improvement were identified, such as cooling efficiency and electronic component optimization. The paper concludes by discussing the implications of the project for future research in the field of airborne particle science.

Key words: particle concentrator, airborne particles, virtual impactor.

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Metallic AB in Stockholm deserves great praise. They were able to machine our required parts with a low lead time and at a competitive rate.

Abbreviations

Table 0.1: List of abbreviations

Abbreviation	Description
KTH	Kungliga Tekniska högskolan
SU	Stockholm university
nPETS	Nanoparticle Emissions from the Transport Sector
PM	Particulate Matter
GT	Growth Tube
VI	Virtual Impactor
MFC	Mass Flow Controller
PLA	Polylactic acid
PETG	Polyethylene terephthalate glycol
PTFE	Polytetrafluoroethylene
PVA	Polyvinyl Alcohol
FDM	Fused Deposition Modelling
SLS	Selective Laser Sintering
PID	Proportional - Integral - Derivative
ID	Internal Diameter
OD	Outer Diameter
CPC	Condensation Particle Counter
OPC	Optical Particle Counter

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1 Introduction

Airborne particulate matter pollution has been proven to have drastic health impacts on the human body and the widespread prevalence of this pollution caused by human activity makes it an extremely pertinent issue [1]. This project seeks to study the harmful health impacts of airborne nanoparticles - the smallest of pollutant particles. In this report we will enable this by designing and manufacturing a particle concentrator to increase the ratio of particulate matter pollution particles to air in the output. This will be connected to an Air-Liquid Interface (ALI) at Stockholm University (SU) to research the effects of nanoparticles on lung cells. One such concentrator system had been temporarily loaned by Tampere University in Finland for lung cell research at SU. Our role is to create a new and more effective version of this system for permanent use at SU. KTH Professor Ulf Olofsson is the project supervisor, responsible for advising and monitoring our progress.

The main motivation for this project is coming from the airborne particle researchers at SU who are studying the effects of nanoparticle pollutants on lung cell behavior. In order for the existing ALI system to be able to study particles from the air, the concentration of said particles must be drastically increased. Therefore, our goal is to create a particle concentrator which can increase the concentration of airborne particles. Our hope is to create a device so successful that the interest will exceed SU and reach other airborne particle researchers from other places. The project is not critical in the sense of survival of the organizations, if we consider SU and KTH as the organizations being affected by this project. However, the design and manufacturing of the device would significantly favour the researchers at SU since they do not own a particle concentrator of their own. Additionally, the study of the impacts of airborne pollution which we are enabling is a pertinent public health issue.

This report starts by examining the existing tools that are used to concentrate airborne particles. It then also details the design and manufacture of the particle concentrator and its differences from existing concentrators. The report examines the different environmental and social impacts of particulate air pollution. We then explore the ways in which city transport planning impacts the levels and toxicity of particulate matter air pollution in urban spaces.

The project has extended over two semesters and consists of two parts: research and design phase, and the manufacturing and testing phase. This report represents a summary of the whole project, including the design work, research, manufacturing, assembly, and testing.

1.1 Project Objectives

The purpose of the project is to investigate the effects of transit planning on airborne nanoparticle toxicity and levels. We will design and manufacture a durable airborne particle concentrator that can achieve a concentration factor of at least 5x and be moved by a single person in the field. Additionally, the impact of urban transit planning decisions on particulate matter/nanoparticle levels and toxicity will be studied and used to form recommendations for methods to reduce exposure to said air pollution.

1.2 Project Deliverables

First a literature study is being done so all project members understand the challenges of the project and the basic function of the device that is being designed. Then conceptual designs and different versions of the device are being created. A design is decided upon and the device is then manufactured and calibrated during testing. Additionally, a summary of secondary research is provided focusing on the effects of transportation design on air pollution.

1.3 Scope statement

The design work will be performed during the Spring Semester of 2023. The device will be assembled and tested during the Autumn Semester. The design and assembly will be performed by the authors of this report, Ulf Olofsson will be the supervisor of the project and the researchers at SU will be the ones operating the device.

Both phases of the project (design and assembly) will be conducted at KTH. A single particle concentrator will be produced. Measurements of the ambient air particle concentration and the particle concentration after the particle concentrator will be made to see if the goals are achieved. Concentrations higher than 50 times will be out of scope.

1.4 Stakeholders

The stakeholders of this project are the researchers at SU, the supervisor Ulf Olofsson, researchers at KTH (primarily from the Tribology department) and the course administrator for MF2076/7 Kjell Andersson. The result of this project will not affect anyone except the researchers at SU directly. However, the result that the SU researchers present could be the foundation for new laws and regulations about air pollution.

1.5 Project charter

The project charter document can be found in Appendix C.

1.6 Requirements

The requirements for this project can be seen in Table 1.1.

Table 1.1: Requirements Specification Table

No.	Requirement	No.	Sub-requirement
1	Performance	1a	The particle concentration factor should be $\geq 5\times$.
		1b	The particle sample size should be $\leq 1\mu m$.
		1c	The output flow of the device should be 1.5 l/min.
		1d	The particles exiting the device and entering the ALI system should be dried to its original size.
2	Working environment	2a	Should be able to withstand corrosion environment.
		2b	Should be able to withstand temperature range of -35 to +40 deg Celsius.
		2c	Should be able to withstand normal humidity outdoors.
3	Life in service	3a	Should have service life of xx years.
		3b	Components that are exposed to wear should be easy to replace.
4	Maintenance	4a	VI should be easy to assemble and disassemble for maintenance.
		4b	Easy access to part that are likely to require maintenance.
		4c	Need for special tools.
5	Target product cost	5a	Bench-marking.
6	Transport	6a	Should be able to transport with e-bike.
7	Quantity	7a	A single concentrator shall be produced.
8	Manufacturing facility	8a	IIP.
		8b	External workshop.
9	Size	9a	Should fit on an e-bike.
		9b	Should fit in existing cage in the metro.

Table 1.1: Requirements Specification Table

No.	Requirement	No.	Sub-requirement
		9c	One person should be able to lift it.
10	Weight	10a	One person should be able to lift it.
11	Appearance and finish	11a	It should match the existing aesthetic.
		11b	It should not draw to much attention.
		11c	It should not interfere with the particle chemistry.
12	Materials	12a	It should not interfere with the particle chemistry.
13	Standards and specifications	13a	Follow standards for hoses and connections.
		13b	Follow standards for sensors.
		13c	Follow standards for framing and fasteners.
14	Ergonomics	14a	Should be able to read sensors clearly.
		14b	Non-slip carry handle on the frame.
		14c	Adjustments should be easily performed.
15	Process	15a	The concentrator shall use the virtual impactor principle.
16	Time-scales	16a	Concept generation and design should be finished during VT 2023.
		16b	Manufacturing and assembly should be finished during HT 2023.
17	Testing	17a	Should be finished during HT 2023.
		17b	Field test should be performed in subway and road tunnel.
		17c	Control test should be performed in a controlled environment.
		17d	Standard particle counter should be used.
18	Safety	18a	Emergency skill switch should be installed.
		18b	Hot water and pressurized water should not be able to contact the user.

Table 1.1: Requirements Specification Table

No.	Requirement	No.	Sub-requirement
19	Installation	19a	Should be movable.
		19b	Easy to connect to intake and ALI system.
20	Documentation	20a	Complete spare parts list and drawing. The machine should be able to be disassembled and assembled from the documentation.
		20b	The project should be documented in a technical drawing.
21	Disposal	21a	Made from recyclable materials.
		21b	High material hygiene level.

2 Literature Study

The particle concentrator is designed to enable research of the toxicity of ultrafine airborne particles from disc brakes and exhaust emissions in metros and road tunnels. Nanoparticle emission from the transport sector (nPETS) is a EU-project working to investigate the emissions of a nanoparticles from all transport modes [2].

The information about the system we are working with comes from looking at the existing device, explanations from Karine Ehlin at Stockholm University and literature research.

2.1 Background & Impact

This section will explore the core issues that motivate the research being conducted by us and the researchers at SU.

2.1.1 What is Airborne Particulate Matter (PM) Pollution?

Particulate Matter (PM) is a type of air pollution that is made up of a mixture of solid particles and liquid droplets. Sources of PM are split into two types: primary, and secondary[3]. Primary PM is produced directly from a source, such as construction sites, unpaved roads, or industrial processes. PM from secondary sources are instead produced from complex chemical reactions in the atmosphere. These reactions are often the result of chemical pollutants from industry and automobiles. The majority of PM pollution is from secondary sources [3].

PM is traditionally split up into PM10, and PM2.5, being smaller than 10 micrometers and 2.5 micrometers respectively (Figure 2.1). Particles smaller than 10 microns are identified as inhalable particles, which is the primary reason that they are interesting to researchers. Particles at this size may enter into the lungs. Particles that are smaller than 2.5 microns may even enter into the bloodstream and cause further damage [3]. Nanoparticles (NP) are even smaller than PM, measuring from 1 to 500 nanometers (or 0.5 microns). There is substantially less research into NP, which is the reason that the researchers at SU are seeking to concentrate and study the effects of NP. It is expected, however, that the evidence of NPs' environmental impact will increase as their prevalence in nature increases due to human activity [4].

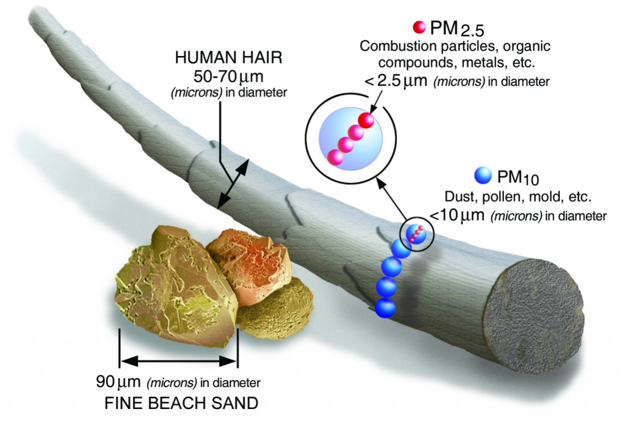


Figure 2.1: Visualizing the Size of PM[3]

There are two primary human-caused sources of PM pollution: transportation and industrial activity [5]. Because of this, usually people in urban areas have more exposure to PM than those in rural areas. In fact, in 2021 97% of the European urban population was exposed to levels of PM2.5 higher than the cutoff levels recommended by the World Health Organization [1]. These guidelines have been developed by the World Health Organization by studying the effects of different levels of various pollutants to provide a benchmark off which individual countries can measure their pollutant levels. Beyond these cut-offs, adverse health effects (described below) are expected[6]. There will always be some air pollution present, and these guidelines present reasonable goals of pollution levels to stay below.

2.1.2 The Health Impacts of Airborne PM Pollution

Since research into NPs' health impacts is quite new, this section will largely focus on the existing studies into larger particles. Because the toxicity of particles typically increases as the particle size decreases, researchers assume that the health impacts of NP will be at least as severe, if not worse, than that of PM2.5 [4].

The health impacts of PM air pollution are primarily concentrated in the respiratory system as this is the primary entry point of PM into the body. After both short-term and long-term exposure to air pollution, risks for several respiratory health issues increase significantly [1]. For example, a study done in Busan, Korea published in 2017 found that hospitalized cases of acute bronchitis, allergic rhinitis, and asthma all increased as the level of PM, especially PM2.5, air pollution increased [7]. Another study found that even young and healthy adults can suffer from reduced lung function when exposed to high levels of PM2.5 [8]. It has been found hospitalizations across all age groups increase for respiratory illnesses in the presences of PM10; respiratory illnesses see a larger effect than any other type of illness [9]. To summarize, the respiratory health impacts can range from minor to severe illnesses.

The effects of PM can also be found in the circulatory system if particles are able to enter into the bloodstream. As such, these particles must be extremely small, so PM2.5 or NP are capable of this, while PM10 is usually not [4]. The most severe impacts of PM exposure come in the form of various cardiovascular diseases. As well as worsening existing heart conditions, PM exposure also increases the risk of several cardiovascular issues such as ischemic heart disease, heart failure, and cerebrovascular disease [10]. PM exposure both long and short term also has impact on the normal functioning of the heart. This comes in the form of hypertension (high blood pressure), both left and right ventricular hypertrophy, and cardiac arrhythmias (irregular heart beat). As seen in Figure 2.2, the effects of PM exposure and the mechanisms by which it exacerbates cardiovascular problems varies widely [10]. Airborne PM pollution contributes not only to respiratory issues, but also more serious cardiovascular diseases.

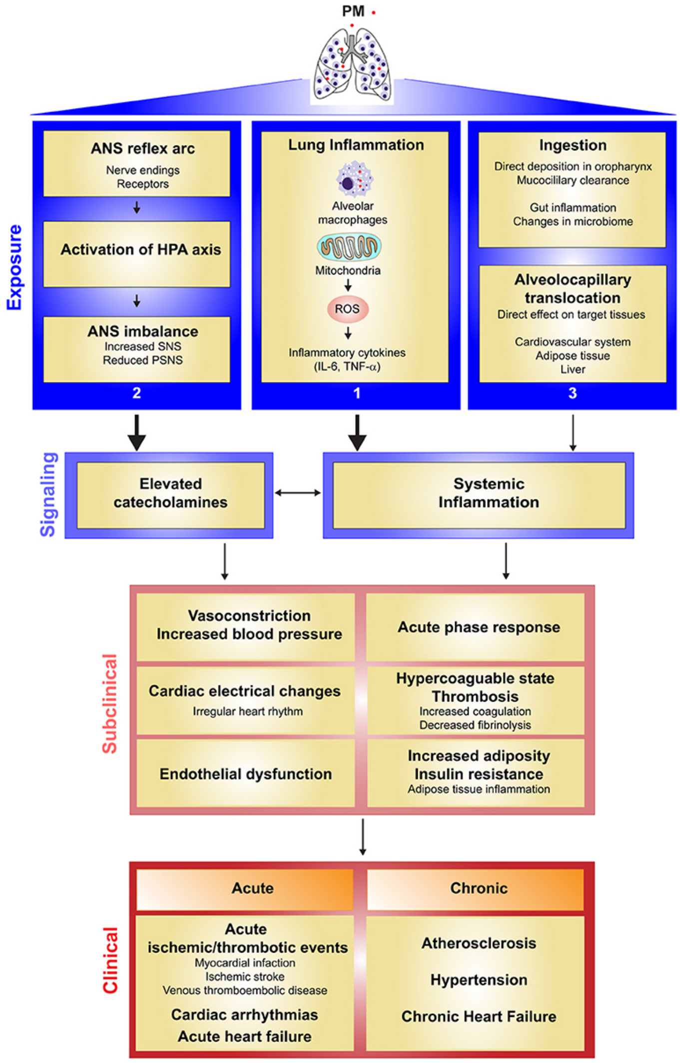


Figure 2.2: Description of Cardiovascular Effects of PM[10]

With long-term exposure, PM air pollution was also identified as the leading environmental cause of cancer[11]. Similarly, it is shown that mortality caused by cancer raises with long-term PM exposure. When higher levels of PM2.5 are present, the rates of all-cause mortality and mortality from cardiopulmonary and lung cancers increase [10]. This was further supported by a 2019 study in the New England Journal of Medicine which found that raised PM levels were reinforced the connection between increased all-cause, cardiovascular, and respiratory mortality rates across over 600 different countries [12]. All of these studies show that air pollution and particularly airborne PM contribute not only to short-term irritation or minor illness, but also serious conditions such as lung cancer and death.

As stated above, the smaller PM particles usually produce the worst associated health risks due to their ability to reach further into the respiratory and even cardiovascular systems[13]. With this in mind, it is clear to see the potential for severe negative impact even smaller particles like nanoparticles have on human health. This subject of research has only recently come into focus for the scientific community; given its complexity it is extremely difficult to gather widespread data on it[14][15]. This is the main motivation for SU researchers to investigate these impacts further.

2.1.3 Who is Most Severely Impacted by PM Air Pollution?

Specific age groups are especially susceptible to the adverse respiratory effects of PM pollution: older people who have chronic heart or lung issues, people with asthma, and children[13]. Children are especially susceptible because of their quicker breathing, smaller relative body sizes, more time spent outdoors, and undeveloped immune systems. Exposure to PM2.5 has been linked to slower and smaller lung development. Additionally, higher levels of PM10 and PM2.5 correlate with increased levels of mortality in both of these age groups [13]. While PM exposure is a pertinent issue which affects all people, it is clear that specific groups of people (children and the elderly) require additional care and attention.

Because emissions from industrial facilities and roadways are some of the largest sources of PM and NP, it is often those who reside around these industrial areas or major roadways who face the highest levels of particulate air pollution [5]. Many studies have concluded that several factors greatly affect the likelihood of someone living close to a source of pollution: race and economic status[16]. This concept of studying the way demographics can affect one's exposure to environmental hazards is called environmental justice. This can also be seen at a larger scale: a look at pollution levels in the EU shows that the GDP of a country inversely collates with the PM pollution exposure as seen in Figure 2.3[1]. There is a significant amount of overlap between low GDP and high air pollution areas according to this study. This indicates that countries with poorer financial conditions are more likely to also struggle with issues of PM air pollution. It has also been found that race appears to be an even more important factor than poverty level when it comes to exposure to pollution or proximity to pollution sources. [17]. This issue has been commonly identified and studied under the name environmental racism. Even when economic level is controlled for, minority groups were found to be much more likely to live near major sources of pollution and suffer high levels of PM2.5 exposure in several USA studies as shown by Figure 2.4[18]. In this figure, one can see that the percentage of white respondents experiencing PM exposure is on average much lower than any other racial group, even across different survey locations (Urban vs. Rural). This indicates that race has a large effect on the likelihood of being exposed to PM pollution. These findings are consistent across many different situations (e.g. urban, rural, different regions, exposure levels)[19]. It is evident that the issue of air pollution and PM exposure is not felt by all evenly. Tools must be used to learn more about these inequalities and policy must be employed to rectified the situation.

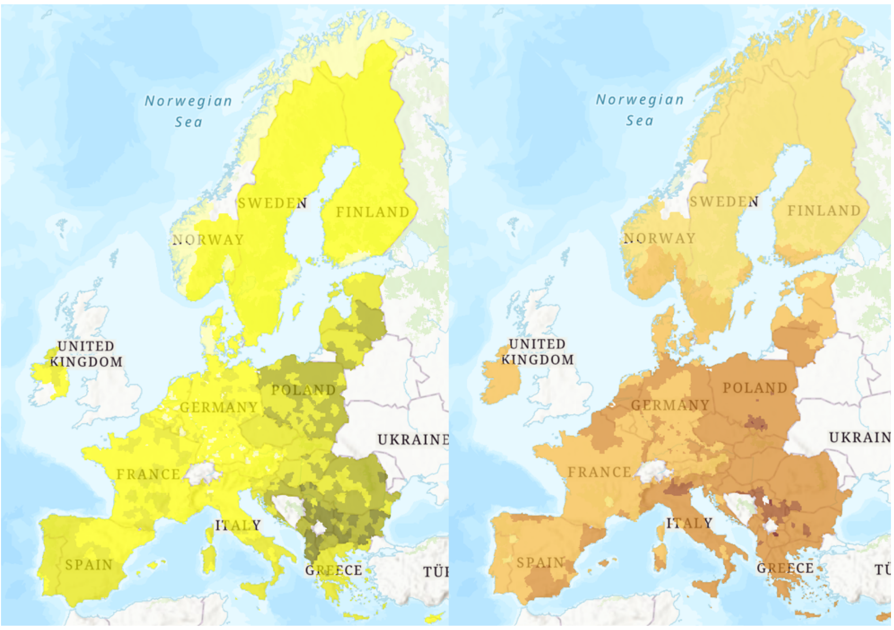


Figure 2.3: EU GDP Information - darker yellow indicates lower GDP (left), EU PM2.5 Information - darker orange indicates higher levels of PM2.5 pollution(right)[1]

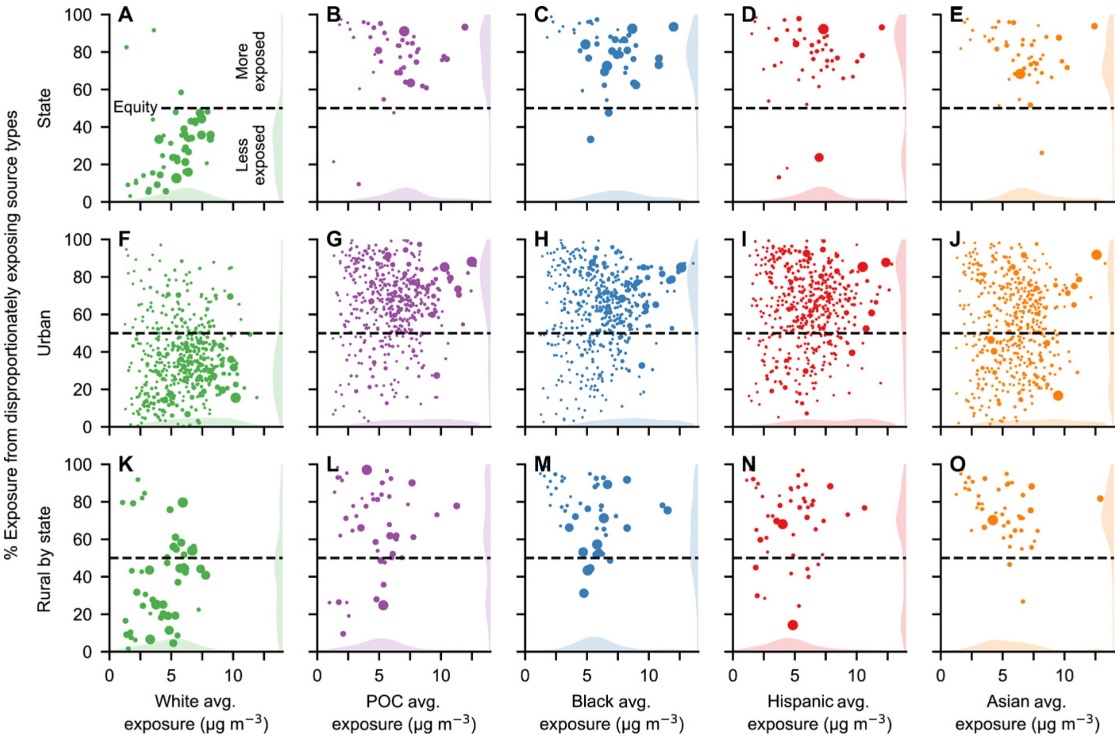


Figure 2.4: "Percent of PM2.5 exposure caused by emission source types that disproportionately expose each racial-ethnic group by location and race-ethnicity"[19]

The reasons for these issues of environmental justice are quite complex. These concerns can occur both internationally and within one country. Often, internationally disparate pollution levels can be explained by countries' differences in environmental legislation. Stringent environmental and labor legislation, as often found in wealthier countries, may dictate that factories meet certain environmental and pollution standards, which also make them more costly to build and run [20, 21]. Some large companies then decide to outsource their manufacturing tasks and instead build and operate factories in foreign countries with relaxed environmental and labor laws, then import the goods once they are completed. These countries are usually poorer nations where the population is more often economically disadvantaged. The high levels of pollution from the factories in these areas, coupled with poorer working conditions in general lead to higher exposure levels for lower income individuals [20, 21]. These ideas may partly explain the correlation shown in Figure 2.3.

At a national level, the issue persists even in relatively developed countries like the USA. The reasons for this situation require historical context about the racist practices used to develop and plan cities (which to some degree continue today)[22, 23]. A broad overview will be covered in the following paragraph, however the complexity of this issue cannot be stressed enough, and the coverage in this report is by no means exhaustive. One example is the practice of "redlining", in which banks will refuse loans to individuals residing in districts which are seen as high-risk. This prevents individuals in these districts, usually people of color, from economically advancing. Additionally, the planning of cities has historically built destructive infrastructure projects like highways through these poorer districts, displacing people from their homes, separating those remaining, and - as seen in Figure 2.4 above - subjecting these people to high levels of air and sound pollution. Finally, the environmental protection legislation in place to prevent such events is disproportionally utilized to prevent factories and other projects from being built in wealthy, white neighborhoods. This is known as NIMBYism (standing for Not In My Back Yard), where even those people advocating for change, refuse to be let it impact them[22, 23, 24].

2.1.4 Environmental Effects

It is also important consider the more indirect impacts of PM air pollution, such as its effect on the climate around us. Aerosolized PM2.5 is the main cause of haze or reduced visibility in the environment[3]. Examples of this phenomena can be seen time and time again such as the historic Great Smog of London, the continuous struggle against smog in Los Angeles, USA (Figure 2.5), or the haze over several American cities caused by Canadian wildfires in June, 2023 [25, 26, 27]. These instances of course were coupled with the health impacts of PM air pollution, but the haze itself can be disruptive. With reduced visibility, common day-to-day actions can be disrupted, flights may be cancelled, and activities such as driving may become more dangerous. Additionally, different types of PM, such as black carbon, may have a warming effect on the environment, while others may instead have a cooling effect (e.g. sulfate and nitrate)[13]. As shown, secondary impacts of PM air pollution can cause even more unexpected harm to humans.

Figure 2.5: Smog over Los Angeles, USA [26]

Another major form of environmental impact caused by PM pollution is the deposition of PM on plants, soil, and water[13]. Deposition of PM can happen in multiple ways: wet, dry, and occult deposition[28]. Wet deposition occurs when the particles (usually PM2.5) in the air join with water vapor in clouds and enter into the ecosystems and watersheds below as precipitation. Dry deposition happens at a slower, but continuous rate as dry PM10/dust directly deposits on exposed surfaces. Occult deposition, the least predictable or common but still effective, occurs when gaseous pollutants dissolve in fog or cloud water droplets, and then directly settle onto exposed surfaces. The impact of all forms of deposition are largest when the entire ecosystem or watershed is inspected. The chemistry of PM is not specified (instead the particle size is), this means that particle deposition can have widely varying impacts on land and water ecosystems. Some examples of potential ecosystem-level impacts include acidification and nitrogen saturation which impact nutrient cycling, and heavy metal deposition which could impact the growth of vegetation and normal functions of ecosystems. On a smaller scale, deposition may directly impact vegetation through altering the pH level on the leaf surface[28]. It is also thought that deposited NP may have even more significant environmental impacts in water ecosystems [4]. It is shown that PM can not only have severe impacts to humans both directly and indirectly, but also to the ecosystems and watersheds on which we depend.

2.1.5 Summary

This section has provided the background and motivation for continued research into the various impacts of Particulate Matter and Nanoparticles. Most of the background research was centered on PM10 and PM2.5 due to the availability of research, but it can be clearly seen that as the particle size decreases to the Nanoparticle size range, the negative impacts will likely remain or become more prominent. This could especially be argued for the cardiovascular health impacts of particles, which are caused largely by particles small enough to enter the bloodstream. It is important to continue research specifically into nanoparticles so that the true impact of pollution can be understood and the resulting policy can be better informed. This is the motivation for the design and manufacturing of the particle concentrator described in this report. The fundementals of this design and it's downstream uses are articulated in the following sections.

2.2 Overview of system

This section will explain how the particle concentrator and connecting ALI system works together with information from the literature that was the base of our design. A simple overview of the system can be seen in Figure 2.6, for a more detailed overview see Figure D.1 in Appendix D. The system consists of a particle concentrator that connects to an ALI system, where the particles interact with lung cells. This project is focusing on the particle concentrator.

In short, the system works as follows, air flows into the particle concentrator, first into the growth tube where the particles mass increases with the help of water. Then further on into the virtual impactor, which separates the flow into major and minor flow to concentrate the air that goes into the ALI system. A more detailed explanation of how the particle concentrator works will be explained below under each section.

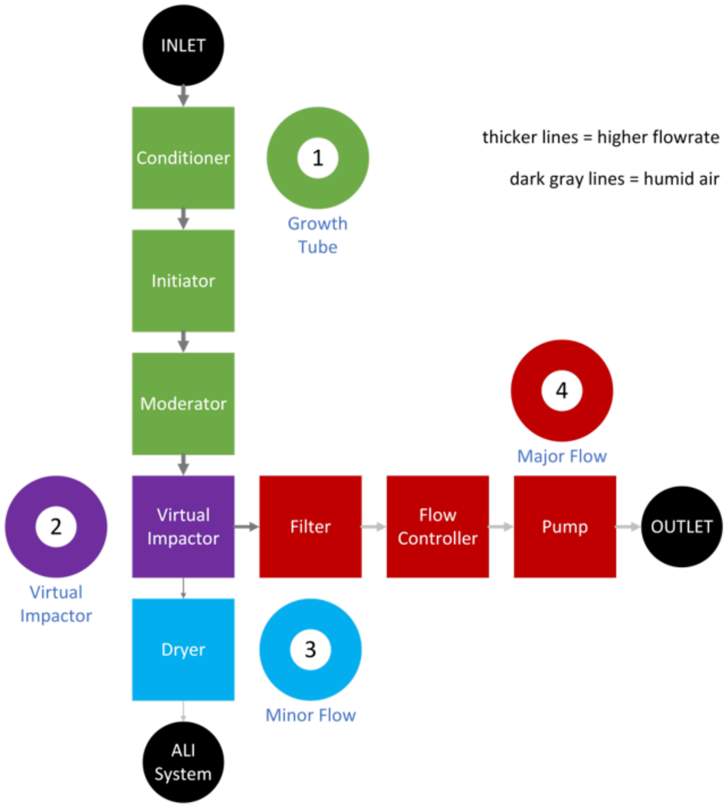


Figure 2.6: A simple overview of the system.

2.3 Growth tube

To achieve particle growth, Hering and Stolzenburg (2005), Hering et. al (2019) and Hering et. Al (2014) all describe a warm, wet-walled growth tube. It consists of a wet wick with three different temperature and humidity zones. The first zone is called conditioner and is a cooled and humidified flow, the temperature is around 5 degree Celsius. The second zone is called initiator and is a supersaturated flow with around 50 degree Celsius and 100 % humidity. In this zone the gas is saturated with water vapour from the walls of the wick. The third and last zone is called moderator, it cools the gas and removes excess moister from the gas [29, 30]. The temperature is around 15 degree Celsius. The temperature differences between the first and second zone effects the supersaturation, the higher temperature, the higher supersaturation and therefore may activate smaller size of particles [31]. In Figure 2.7, all three zones are dispayed. Moister is introduced to the air and when the temperature lowers, the water particles absorbs by the air particles which enlargens their mass [29, 32].

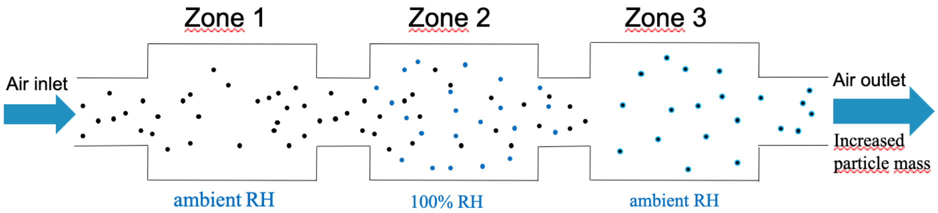


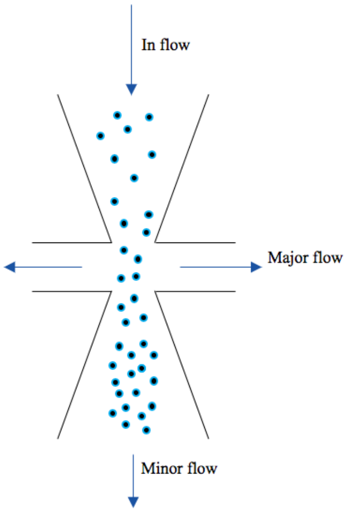
Figure 2.7: Schematic of the all growth tubes zones.

2.4 Virtual impactor

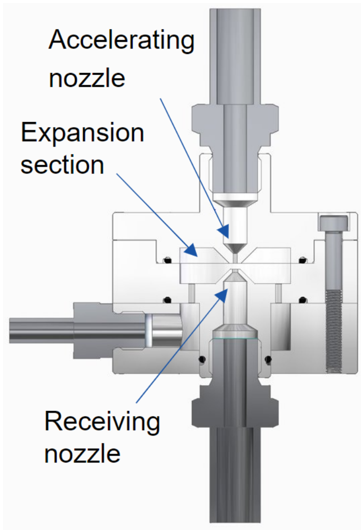
The virtual impactor concentrates the air particles by manipulating the flow with aerodynamic principles. This is done with the usage of different nozzles.

The air first goes through the inlet, then trough an accelerating nozzle before entering the expansion section where the air expands. Due to the decrease of the nozzle diameter the flow is accelerated [33]. A change in the aerodynamic forces make the larger particles, whose less affected by the expansion, follow original path while the smaller particles, which have greater aerodynamic forces, are redirected. In other words a separation between larger and smaller particles occus, larger particles continue through the system while smaller particles follow the flow and continue out of the system. The flow is therefore separated into two airstreams in minor and major flow. Particles with low inertia deviate from flowlines while particles with greater inertia follows the streamline [34, 35], see Figure 2.8a. The water enlarged particles flow with the minor flow and the major flow only consists of air which makes the concentration of particles greater [36].

Liu et al. (2021) describes some general measurements when designing the accelerating nozzle and receiving nozzle, see Figure 2.8b. The diameter of the receiving nozzle is generally 1.3-1.4 times of the accelerating nozzle diameter. Liu et al (2021) also states that the distance between the two nozzles should be larger than the accelerating nozzle diameter, a recommendation is 1.2-1.5 times the accelerating nozzle diameter [33].



(a) Schematic of how a virtual impactor works.

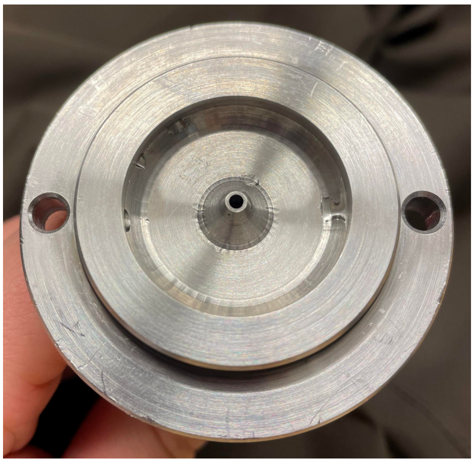


(b) Virtual impactor with nozzles.

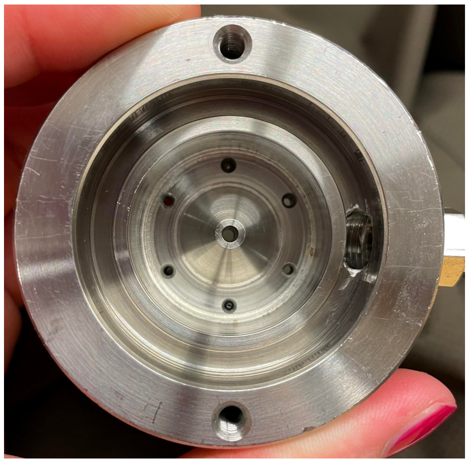
2.5 Virtual impactor - disassembly

In order to get a better understanding of the Virtual impactor geometry, a visit to SU was organised to disassemble, measure and reverse engineer the current Virtual impactor. Figure 2.9 shows some images of the three main parts making up the virtual impactor.

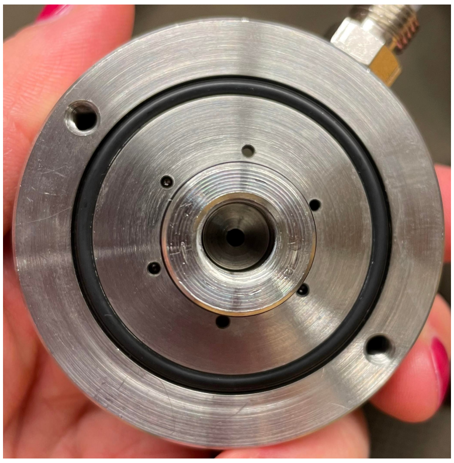
The measurements were taken using a digital caliper. This allowed for accurate measurements to the nearest 0.01 mm. Sketches where then made using the measurements. These sketches were then used to model the Virtual Impactor in Solid Edge.



(a) Top nozzle



(b) Upper chamber - Top view



(c) Upper chamber - Bottom view

(d) Lower chamber

Figure 2.9: Current Virtual Impactor Images

2.6 Dryer

When the particles have been separated in the VI, the water needs to be removed before entering the ALI system. Silica gel is often used to dry the particles to their original size. Karine Ehlin has designed her own silica gel dryer with a tube of a fine metal mesh inside another tube of silica gel which she uses to dry particles for the ALI system. Another way to dry the particles is to heat up the air after the VI, a solution currently used in the system.

2.7 Air-Liquid Interface

The following information and photo come from an informal conversation on September 14th, 2023 with Karine Elihn, researcher and head of the project at Stockholm University. The function of the ALI is to take the particles from the input, select only those that are smaller than 0.1 micron, then expose live lung cells to said nanoparticles and study their development compared to a control exposed to the same, but filtered, gas-mixture. As shown in Figure 2.10, the inlet of the ALI comes directly from the concentrator. This flow will be air from the on-site location but with increased particle concentration. The flow then runs through 2 stages of cyclones and one impactor; these only allow the desired size-range of particles to continue though the system. The flow is monitored and humidified to close to 100% humanity, this is to best simulate the conditions in a human-lung. The flow is finally directed on top of the chambers containing live lung cells. An electrostatic charge is used to ensure that the particles deposit correctly onto the cells. Half of this flow is filtered before entering the chambers, providing control cases to compare. A Scanning Mobility Particle Sizer (SMPS) is used before and after to monitor the particle deposition.

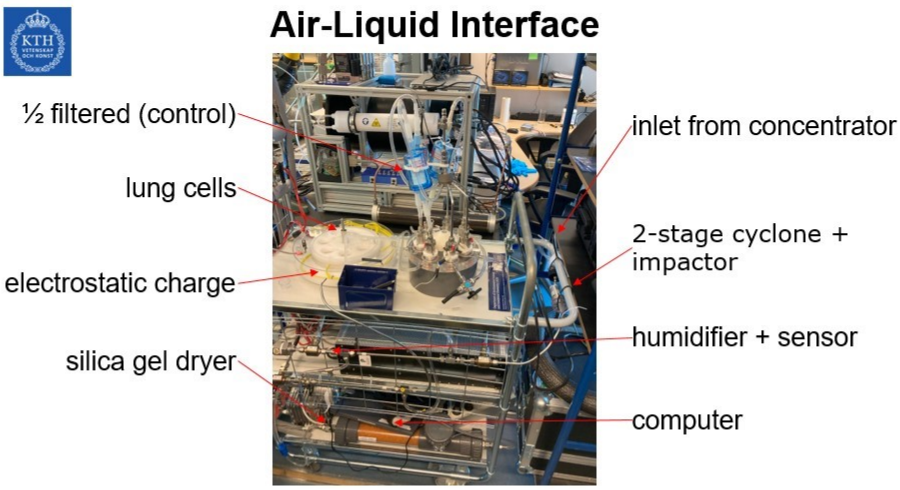


Figure 2.10: Schematic of the ALI system.

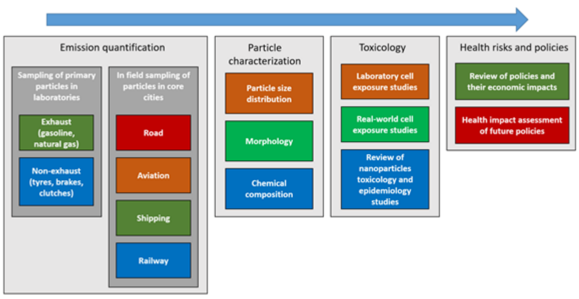


Figure 2.11: Organization of nPETS Projects

2.8 nPETS

The nPETS (Nanoparticle Emissions in the Transport Sector) research project focuses on studying the impact of nanoparticle emissions resulting from transportation on human health. The group receives funding from the European Union to develop innovative methods for the quantification and monitoring of nanoparticle pollution levels [2]. Stockholm Universitys project on airborne nanoparticles is sponsored by nPETS, therefore our project also falls within the research group. In Figure 2.11, our project falls within the Railway segment under the Emission Quantification Segment because the combined SU system will be used to study the emissions cause by rail usage in metro systems.

3 Methodology

3.1 Secondary Research

The primary goal of our secondary research was to identify the ways in which urban transport design may increase or decrease levels airborne particulate matter pollution exposure. The research centered specifically on the impact of public transit because this is the focus of the nPETS group which sponsored this project. The particle concentrator which we designed is used to further study the impacts of air pollution from transit. Potential factors that may apply impact the air pollution levels include rate of public transport usage and quality[37][5].

To accomplish this goal, we performed case research on two cities with differing public transport adoption, and compared the air pollution in these areas. In order to isolate transit as a variable, the cities must have similar population, climate, and industrial make-up. One of these cities was chosen for its high adoption of public transit, while the other city was chosen due to its under-performing transit system.

3.1.1 Case Selection

Step 1: Population

We first narrowed down the selection by looking at cities with a similar population of 1 to 1.5 million inhabitants. This population range was chosen because issues of particulate matter exposure tend to occur more often in densely populated areas[5]. Additionally, the majority of the world population lives in urban areas, thus a population of at least a million was chosen to represent these experiences. A cap of 1.5 million inhabitants allows for a large selection without including vastly different cities due to population. To do this, a database with all the population data of all cities was downloaded and filtered.

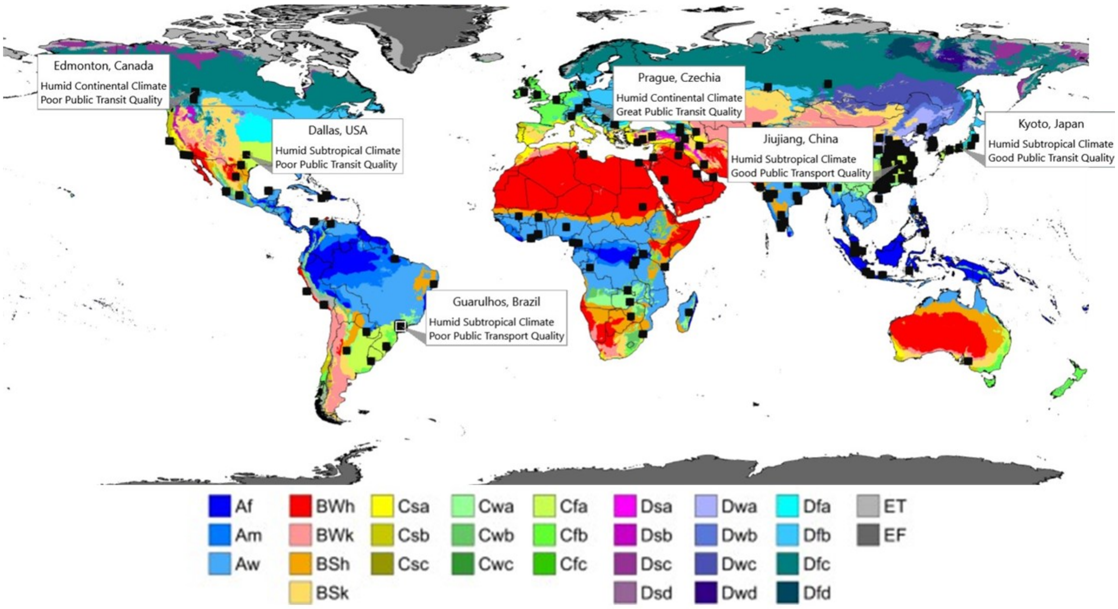


Figure 3.1: Cities of the world with 1-1.5million inhabitants with Köppen-Geiger climate classification map overlaid[38][39]

Step 2: Climate

Then this shortlisted group of countries was mapped with an overlay of Köppen-Geiger Climate Classification information, allowing us to choose six remaining cities based on similar climate. This was done because often climate-related factors can directly (e.g. Smog collection) or indirectly (e.g. climate control energy usage) influence the levels of particulate air pollution [26][40].

Step 3: Public Transport Performance

Three of these cities was chosen due to inefficient or under-performing public transit, and three was chosen because of high performing public transit. These were determined through national or international rankings of the city public transit systems.

Step 4: Industrial Activity

Finally, the industry of the areas was analyzed and considered. This aspect is important because there are two primary anthropocentric sources of PM pollution, transportation and industry [5]. Because we looked to inspect primarily the effects of transportation design on a city's airborne PM levels, we sought to control for this important variable. From this group, two cases with similar industrial levels were selected according to their varying use of public transit.

3.1.2 Assessment

Once the cases were selected, a literature review of scientific studies into PM levels at both locations was conducted. Scientific articles and reports with key words pertaining to public transit, particulate matter, air pollution, transportation design, etc. was helpful in identifying potential resources. We utilized Google Scholar as the primary search engine and ScienceDirect and Elsevier as the primary publication sources. Google Scholar was used as the starting point because it has a broad range of report topics and allows for the discovery of important search terms. ScienceDirect and Elsevier have many articles more focused on the topic of PM air pollution. The focus of this research was identifying potential or implemented plans to reduce air pollution cause in the transport sector - potentially through the shifting of private transportation to public. The information from both cases was then compared and the feasibility of improving the transit efficacy in the poor-performing city was assessed. From this, we drew our conclusions.

3.2 Concepts

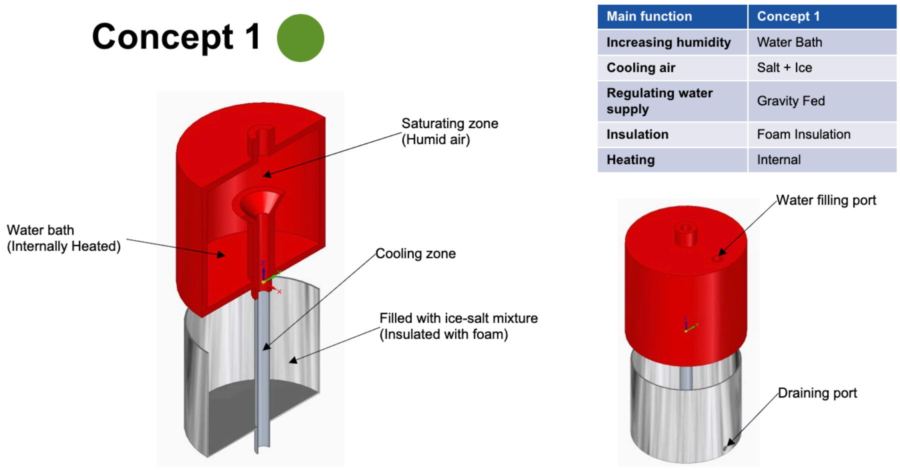
To be able to create a final concept for the particle concentrator a generation of different concept for the growth tube was made. To help with generating concepts a morphological matrix was made. This generated three different concepts; concept 1 - green, concept 2 - blue and concept 3 - pink, see Figure 3.2.

Growth tube	Solutions			
Main function	**Option 1**	**Option 2**	**Option 3**	**Option 4**
Increasing humidity	Water Bath	Saturated Sponge	Ultrasonic Humidifier	
Cooling air	Air Cooling	Salt + Ice	Peltier Cooler	Water Cooling
Regulating water supply	Gravity Fed	Water pump		
Insulation	Foam Insulation	Glass Fiber		
Heating	External	Internal		

Figure 3.2: Morphological matrix of growth tube.

3.3 Generation

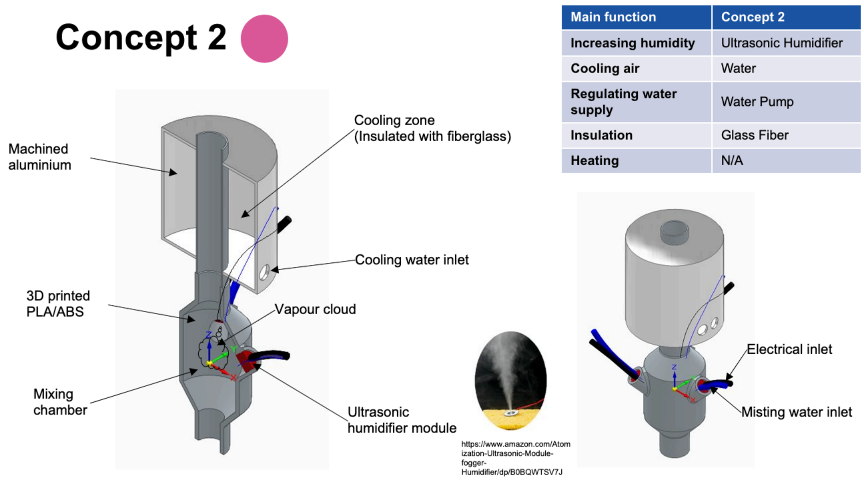
The morphological matrix generated three different concepts. The main requirement of the growth tube is to increase humidity, be able to cool the air, regulate water supply, have insulation and be able to heat the air. The first concept can be seen in Figure 3.3, which uses a water bath to increase humidity, salt and ice to cool the air, regulate water with gravity, foam as insulation and internal heating.



Main function	Concept 1
Increasing humidity	Water Bath
Cooling air	Salt + Ice
Regulating water supply	Gravity Fed
Insulation	Foam Insulation
Heating	Internal

Figure 3.3: First concept of the growth tube.

The second concept can be seen in Figure 3.4 and is completely different from the first concept. An ultrasonic humidifier is used together with water cooling for air cooling and glass fiber to insulate



Main function	Concept 2
Increasing humidity	Ultrasonic Humidifier
Cooling air	Water
Regulating water supply	Water Pump
Insulation	Glass Fiber
Heating	N/A

Figure 3.4: Second concept of the growth tube.

The difference between the first and third concept is the increased humidity, cooling air and the heating. The third concept uses an saturated sponge for humidifying, a peltier cooler to cool the air and external heating. Concept 3 can be seen in Figure 3.5.

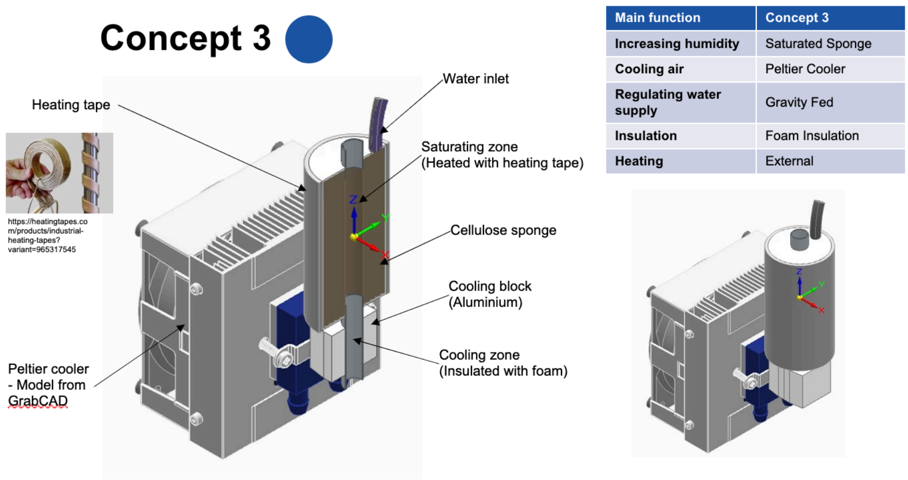


Figure 3.5: Third concept of the growth tube.

3.4 Evaluation

Evaluation of the concepts was done using Pugh matrix and weighted matrix, see Appendix B. With help from the matrices the third concept was chosen.

3.5 Detailed design

This section outlines the detailed design process of the two most important sub-assemblies of the particle concentrator device, the growth tube and the virtual impactor. Various 2D fluid flow simulations of the virtual impactor geometry are outlined here as well.

3.5.1 Growth Tube

There are six main components making up the growth tube. they are listed below:

1. PVA sponge tube
2. Aluminium tubes
3. Thermal separators
4. End caps
5. Cooling modules
6. Heating module

PVA Sponge Tube:

The PVA sponge tube is the key component for the growth tube assembly. It is responsible for absorbing water to create the concentration gradient required for water vapour to transfer into the air stream in the heating zone.

The sponge has the following dimension ID = 20 mm, OD = 40 mm and L = 330 mm. The length of the sponge was determined by scaling a similar geometry from [31]. See Appendix E for the calculations, the length was rounded up to the nearest multiple of 10 mm. The ID of the sponge tube closely matches the 1/2 inch Tygon tubing used at the inlet and outlet of the growth tube. The OD of the sponge tube closely matches the ID of the aluminium tube sections. The sponge is shipped in a dry condition and the true dimensions are only realised when the sponge is saturated with water.

Aluminium Tube Sections:

The aluminium tube sections make-up the main body of the growth tube. Aluminium was chosen as the material rather than steel due to aluminium's anti corrosion properties, as well as its light weight. aluminium also has good heat transfer properties which is useful for transferring heat at the heating and cooling zones.

The tube sections have an OD of 45 mm and a wall thickness of 2 mm. the lengths of the three tube were calculated in the same way as the PVA sponge's length, by scaling the dimensions found in the paper by Hering [31].

Thermal Spacers:

The thermal spacers' functions are two-fold. 1. They provide thermal isolation between the three temperature zones of the growth tube (conditioner, initiator and moderator), and 2. they provide mounting points for the water jet cut brackets mentioned later on in this section. These brackets are used to mount the growth tube assembly to the frame assembly.

The thermal spacers are attached to the aluminium tube sections by use of interference fits. This is because the growth tube is a static component with no applied loads other than its own weight. PETG was chosen as the material because of its improved thermal performance compared to PLA, and because the KTH prototype centre had a spool of it on hand.

End caps:

The end caps are used to attach the various tubing securely to the growth tube. The 1/2 inch Tygon tubing is attached to the growth tube by inserting the tubing in the the larger of the two holes. The 1/4 inch tubing attached by inserting it into the smaller of the two holes. This 1/4 inch tubing is used to supply the sponge with water from the adjustable water bottle. The lower inside surface of the end cap is slanted to allow for the water to channel towards the smaller hole.

(a) Top surface (b) Lower surface

Figure 3.6: End caps for the growth tube

Cooling Modules:

The cooling modules are responsible for cooling the air in the conditioner and moderator zones. They achieve this by way of peltier cooling modules, heat sinks and custom cooling blocks.

The cooling blocks are responsible for transferring the heat of the growth tube to the cold side of the peltier module. The cooling blocks are made from aluminium for the same reason that aluminum tubes were used for the main structure of the growth tube, the good heat transfer. Also aluminium is much easier to machine than steel.

The cooling block is designed to be a single piece construction see Figure 3.19. This allows for the heat to conduct all the way around the inner surface.

The cooling block is attached the the aluminium tubes of the growth tube by tightening the two M4 socket-head cap screws along the edge. This causes the cooling block to clamp onto the pipe. The heat sink is attached to the cooling block via the two M3 tapped holes on the flat face of the cooling block. The peltier cooler is sandwiched between the cooling block and the heat sink. The heat sink, peltier cooler and cooling block together make up the cooling module seen in Figure 3.7 below.

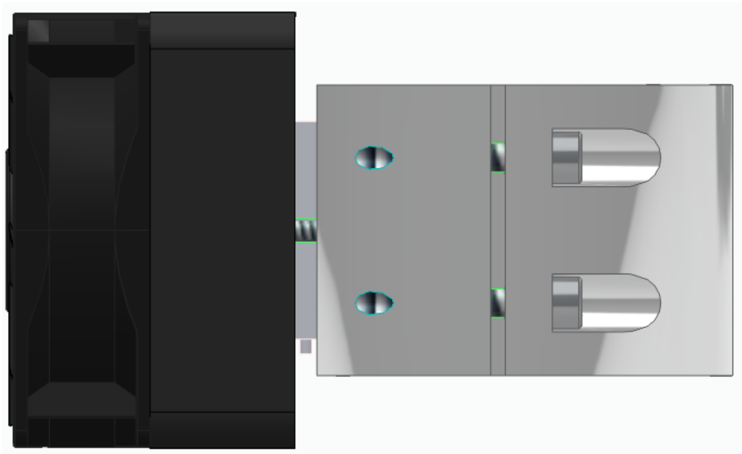


Figure 3.7: Cooling module - Right view

The interface between the heat sink and the peltier cooler as well as the interface between the peltier cooler and the cooling block both contain thermal paste. This helps to improve the heat transfer between the parts of the cooling module.
The cooling block clamps onto the relevant aluminium tube section by tightening two M4 socket head cap screws.

Heating Module:

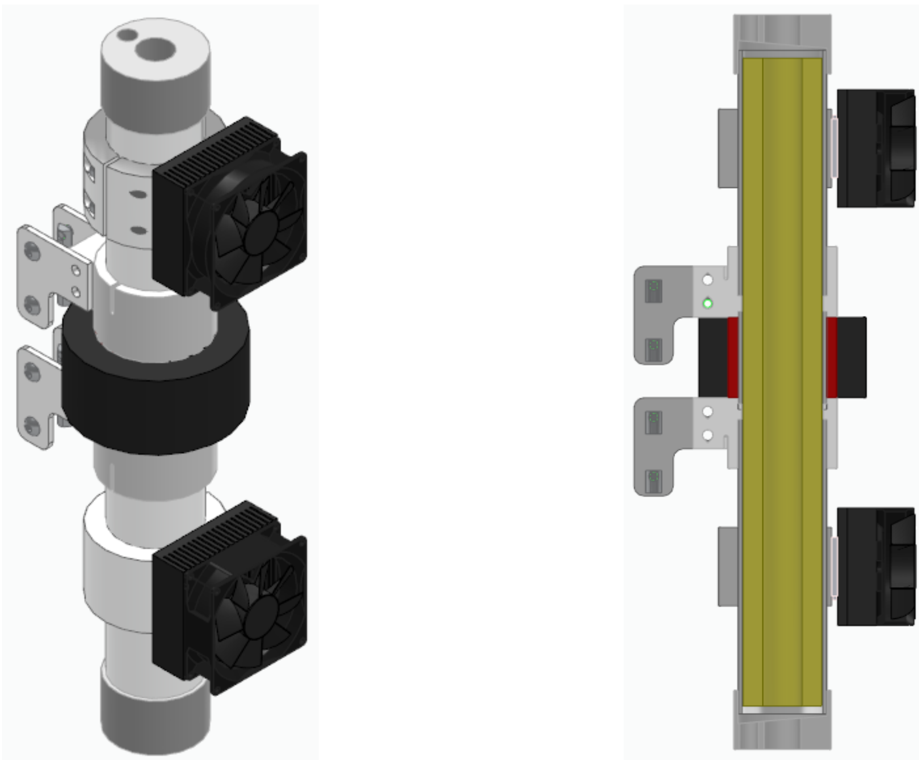
The heating module is responsible for heating the air in the initiator zone. This evaporates a portion of water in the sponge bringing humidity to the air stream. this humidity then condenses onto the particles, increasing their mass.

The heating module is made up by winding a section of heating tape onto the bare section aluminium tube. Insulation is applied over teh heating tape after it is applied to improve the thermal efficiency. Figure 3.8 below shows and image of the heating module before the insulation is applied. The heating tape is controlled using a temperature controller for power and a thermocouple for feedback.

Figure 3.8: Heating module

Growth tube assembly:

Figure 3.9 below shows isometric and section views of the final growth tube model. Note, the actual position of the heat sinks and fans differs from this figure. This is so that the reader can see the fans, heat sinks and mounting brackets in one section view.



(a) Isometric view **(b)** Section view

Figure 3.9: Growth tube final CAD model

3.5.2 Fluid simulations

The function of the virtual impactor was simulated using COMSOL multiphysics v5.6. For all domains the material was set to air, and for the particles the material was set to water, since the particles are grown with humid air. The CAD model of the virtual impactor was inverted and extracted as a 2D profile, this model was imported in to COMSOL, see Figure 3.10. Polygon lines were used to split the model into domains. The top domain is were the input is located and were the particles were released. The interior walls close to the flow divider were used as particle counters, see Figure 3.11. The walls used for the major flow output, minor flow output, input and slip walls can be seen in Figure 3.11.

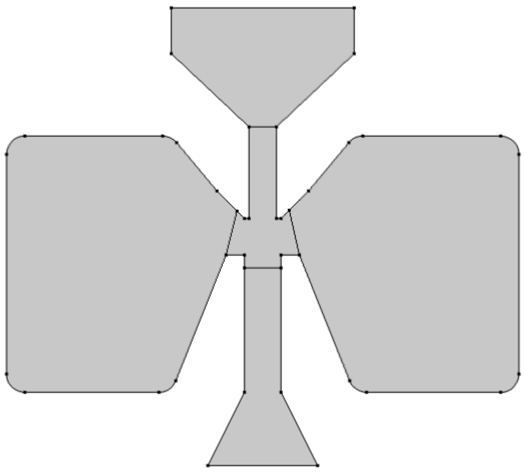


Figure 3.10: Model used for simulation in COMSOL.

The input parameters for the stationary flow simulation can be seen in Table 3.1a. The result from the flow simulation was used as the initial condition for the particle simulation, for which the input parameters can be seen in Table 3.1b.

Table 3.1: Input parameter for simulations

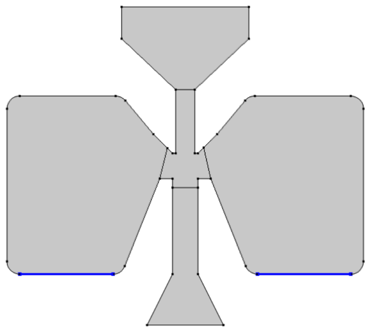
Name	Value	Unit
out flow major	14	l/min
out flow minor	1.5	l/min
Input pressure	1	Pa

(a) Input parameter for flow simulation

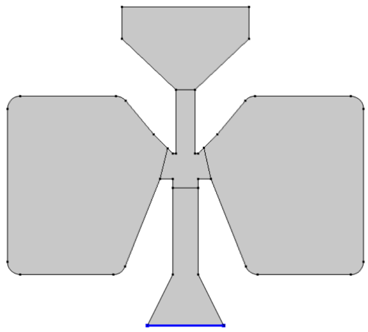
Name	Value	Unit
Particle release	50	pcs
Time	0.3	s
Time step	0.001	s

(b) Input parameter for particle simulation

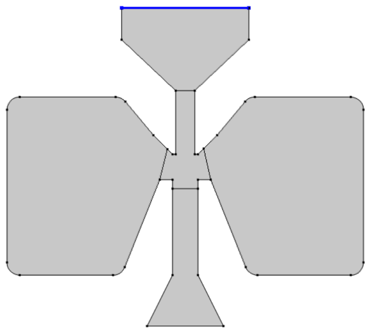
Once the domains were defined the simulation ran a number of times. Between each run a incremental changes were made to the geometry. The changes to the geometry were limited to one change between each run and the changes that were made were inspired by the literature that was studied in the beginning of the



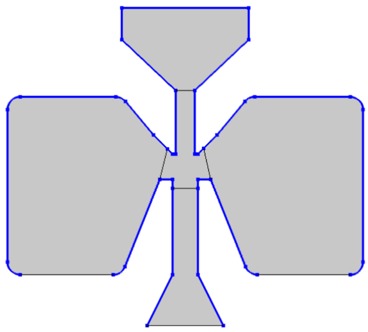
(a) Major flow output



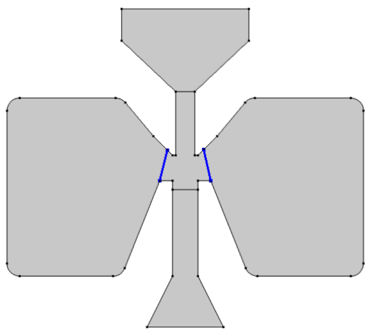
(b) Minor flow output



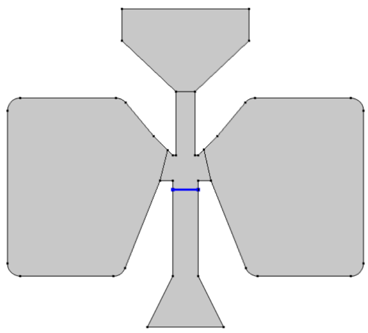
(c) Flow inlet



(d) Slip wall



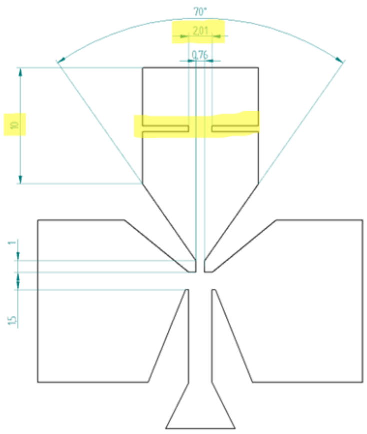
(e) Interior wall as particle counter for major flow



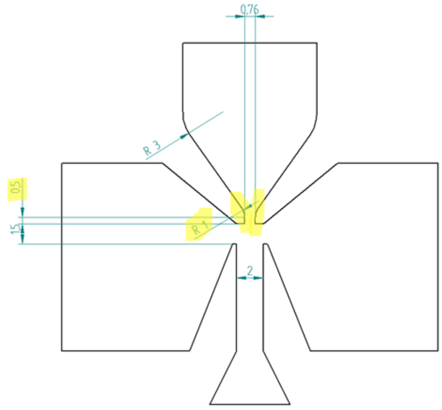
(f) Interior wall as particle counter for minor flow

Figure 3.11: Boundary conditions for flow simulation

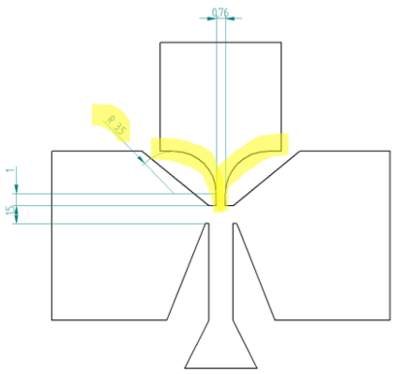
project. The aim of the changes was of course to increase the concentration of the virtual impactor without changing the input parameters. A series of figures of some of the geometry changes and their respective concentration factor can be seen in figure 3.12.



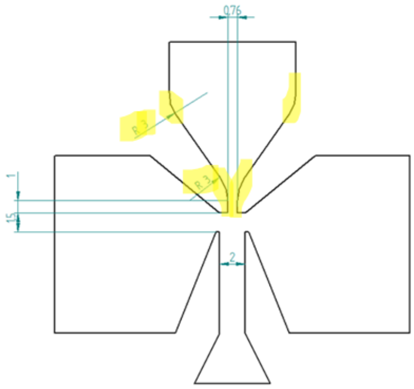
(a) Third version of the geometry changes for the Virtual impactor.



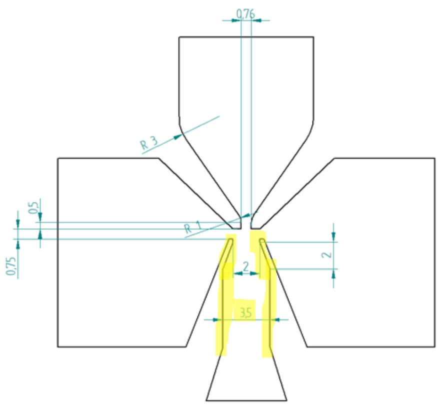
(b) Fourth version of the geometry changes for the Virtual impactor.



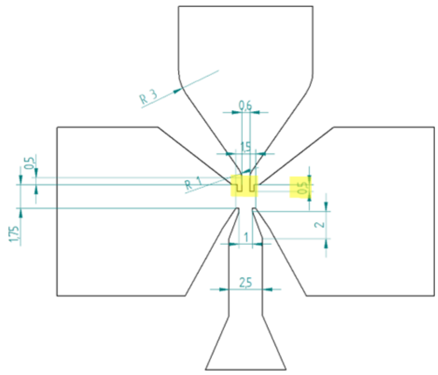
(c) Fifth version of the geometry changes for the Virtual impactor.



(d) Sixth version of the geometry changes for the Virtual impactor.



(e) Ninth version of the geometry changes for the Virtual impactor.



(f) Eighteenth version of the geometry changes for the Virtual impactor.

Figure 3.12: Some of the different parameters of the geometries that were changed in the pursuit of the optimal virtual impactor geometry.

3.5.3 Virtual Impactor

In their paper "Design and Simulation of Virtual Impact Sampler of 5um Particle Size" [33], Liu et al. point out that there are four crucial dimensions for the geometry of virtual impactor nozzles. These dimensions are listed in Figure 3.13 below.

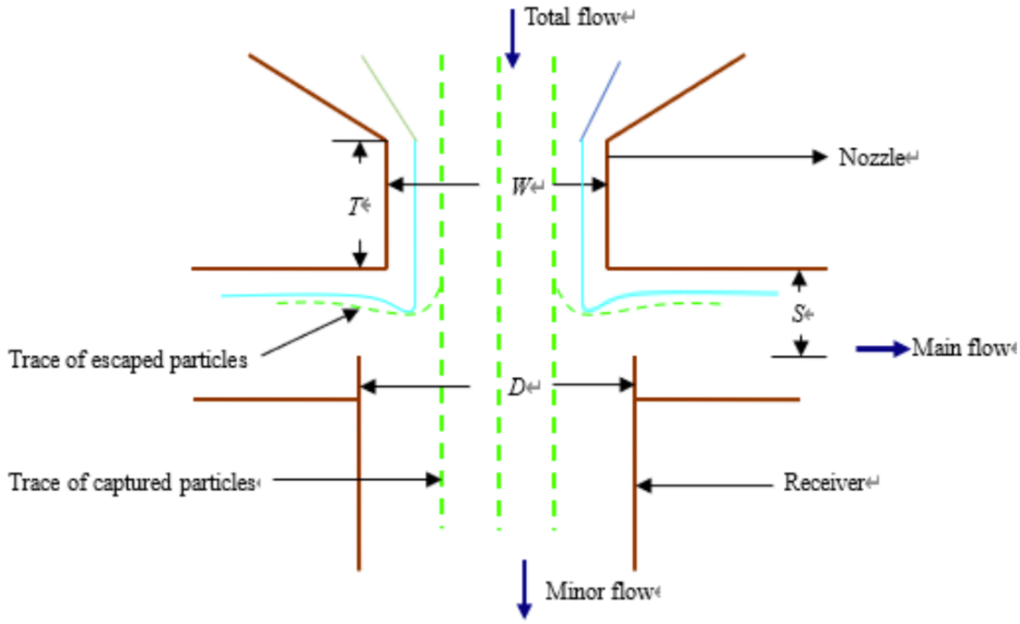


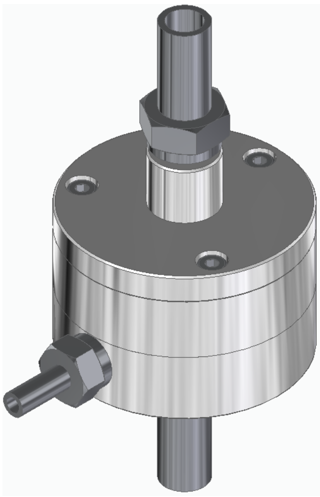
Figure 3.13: Key dimensions for the Virtual Impactor [33]

The four key dimensions; W, D, S, and T are all related to one another [33]. We chose a top nozzle diameter, $W = 1$ mm. The relationships of the dimensions and the chosen values are listed in Table 3.2 below.

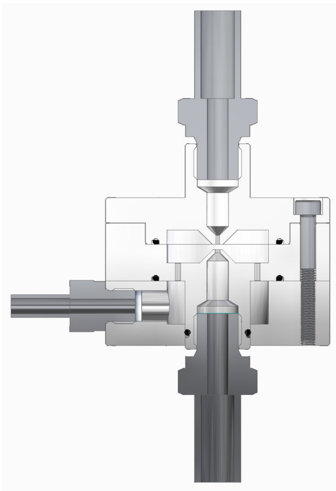
Table 3.2: Key dimensions for the Virtual Impactor according to [33]

Dimension Description	Symbol	Range	Chosen Value
Top nozzle diameter	W	Reference	1.0 mm
Lower nozzle diameter	D	$1.3W \leq D \leq 1.5W$	1.4 mm
Nozzle gap	S	$1.2W \leq S \leq 1.5W$	1.3 mm
Accelerating section length	T	$2W \leq T \leq 3W$	2.5 mm

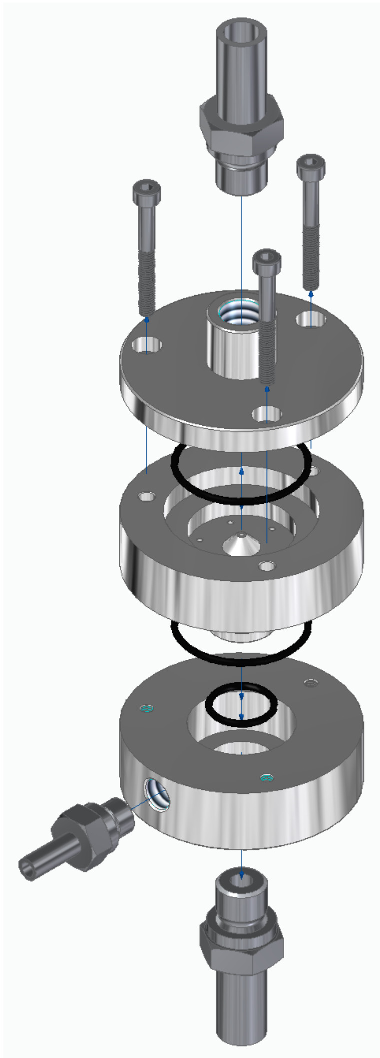
The virtual impactor (VI) consists of three main components: Top Plate, Middle Section and Bottom Plate. These three components create two chambers, the upper chamber and the lower chamber. Figure 3.14b shows the two chambers. These three main components are made from stainless steel (316 or similar). This is because of the materials anti-corrosion properties, the virtual impactor will have humid air pumped through it. There are also minor components within the VI, these are: various Swagelok® air fittings, various O-rings and M4 socket-head cap screws. These components can be seen in Figure 3.14 below. Figure 3.14c gives a particularly good view of the components.



(a) Isometric view



(b) Section view



(c) Exploded view

Figure 3.14: Virtual Impactor assembly

3.6 Manufacturing

Several custom parts needed to be manufactured to realize the design of the particle concentrator

3.6.1 Aluminium frame assembly

A frame was constructed from lengths of 20 x 20 mm aluminium extrusion profile. This frame can be though of as the skeleton of the device, i.e., all of the various components and assemblies are mounted to the frame. The frame was designed in Solid Edge 2022/23 and has overall measurements: $H = 750$ mm, $W = 400$ mm, $D = 400$ mm. The members are fastened together with various 2-way and 3-way connectors. Parts external to the frame members are attached to the frame via M5 threaded screws, M5 T-nuts and other miscellaneous fasteners. Figure 3.15 below show the final frame assembly.

Figure 3.15: Isometric view of the frame assembly

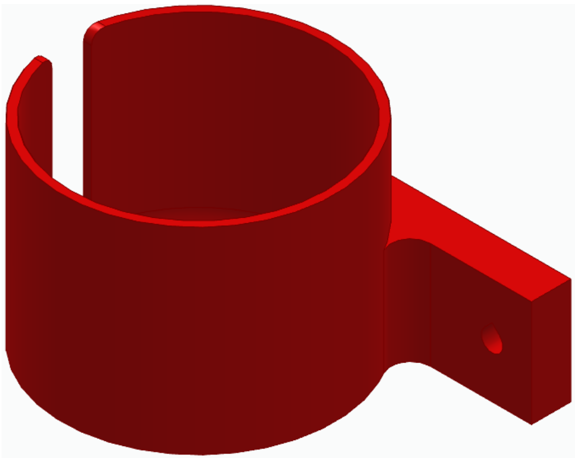
The frame assembly has several custom 3D-printed components used to hold various auxiliary parts such as the water bottles for supplying the growth tube, and mounts for the virtual impactor and the dryer. These parts are explained in greater detail in Section 3.6.2

Fasteners:

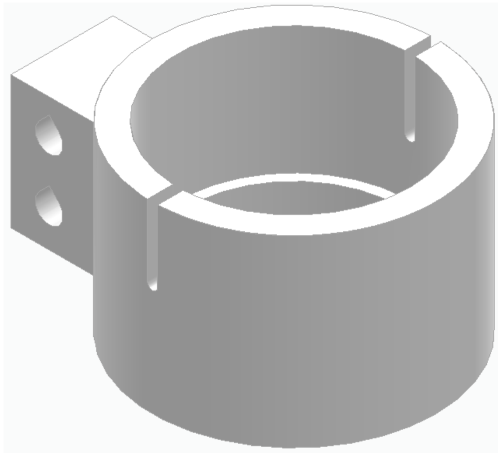
The various screws and fasteners were purchased from item24.com, especially for the frame assembly. Any extra screws required were acquired from the KTH small parts stores. A concerted effort was made during the design phase to limit the size of the fasteners. This would reduce the number of different tools required assemble the concentrator.

3.6.2 3D Printed parts

Several 3D printed components were required. 3D printing[1] was chosen as the primary manufacturing method for non-load-bearing and non-crucial parts. This is because high strength is unnecessary, complex geometries can be manufactured, and parts can be made quickly and easily.



(a) Water bottle holder - PLA



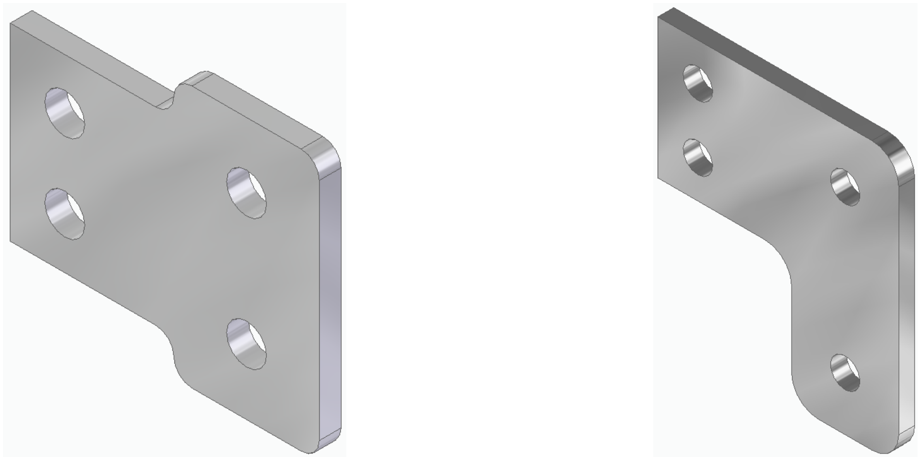
(b) Thermal separator - PETG

Figure 3.16: Some of the 3D-Printed parts

3.6.3 Water jet cut parts

Some of the parts that were designed for the particle concentrator were suitable to manufacture with a water jet cutter. The parts that were manufactured with the water jet cutter were the aluminium brackets that connect the growth tube, dryer and virtual impactor to the frame. The brackets were suitable to manufacture with the water jet cutter because of the simple design, consistent thickness of the brackets and the choice of material.

[1] The Fused Deposition Modelling (FDM) method was chosen, as it is simple and what was on hand at the KTH prototyping centre.

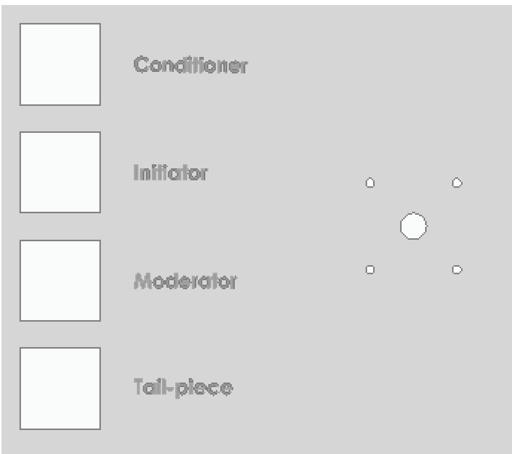


(a) Virtual impactor mounting bracket **(b)** Growth tube mounting bracket

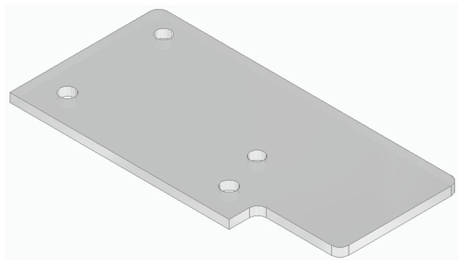
Figure 3.17: Two waterjet-cut mounting Brackets

3.6.4 Laser cut parts

A few parts that were designed for the particle concentrator were manufactured with a laser cutter, mainly the front panel of the particle concentrator. This manufacturing method is a suitable method of manufacturing based on the material used for the front panel, in this case it was a 5 mm thick acrylic sheet. An alternative material could have been a thin wood panel as well but the acrylic provides transparency to the inner workings of the particle concentrator.



(a) Close-up view of the front panel cutouts



(b) MFC mounting bracket

Figure 3.18: Laser cut acrylic parts

3.6.5 In-house machined parts

We only needed two parts to be machined in-house at KTH. These parts were the two cooling blocks for the growth tube assembly. These cooling blocks are used to attach the peltier cooler and heat-sink to the outer tube of the growth tube assembly in the conditioner and moderator zones. Figure 3.19 below shows the isometric view of the cooling block.

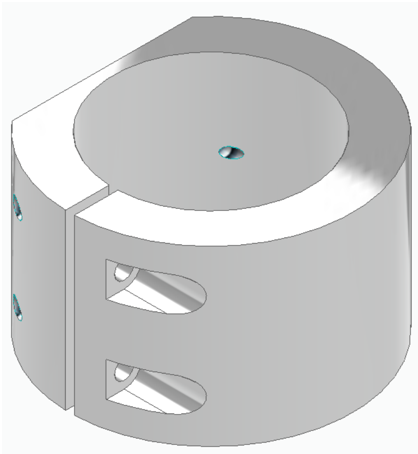
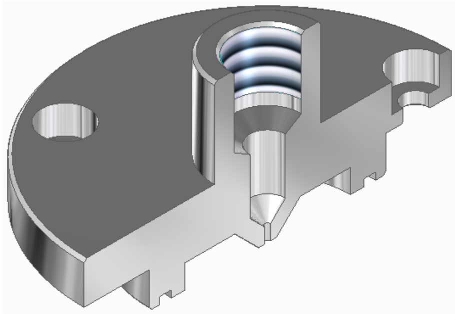


Figure 3.19: Cooling block - Isometric view

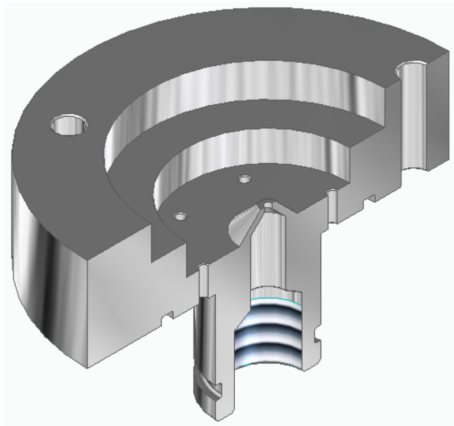
3.6.6 Manufacturing at Metallic

Initially we as a group had the idea to 3D print the virtual impactor parts via the Selective Laser Sintering (SLS) process. These parts would have been outsourced to an external company. This manufacturing method was not chosen due to potential static electricity build-up in the polymer material. After consultation with our supervisors, the decision was made to machine the parts of the virtual impactor out of aluminium. These parts required tight dimensional tolerances and surface tolerances and were therefore unsuitable for manufacture in-house at KTH.

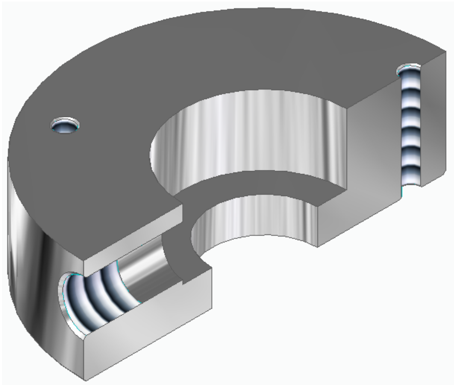
Our supervisor Karine Elihn, suggested that we manufacture our Virtual Impactor at Metallic in Tullinge, Stockholm. This manufacturer has experience in manufacturing impactors used in aerosol research. These impactors have similar geometry to our Virtual Impactor (small diameter holes and small diameter cone shaped nozzles), it was for this reason, as well as the relatively short lead-time on the parts, that Metallic was chosen as the manufacturer. Figure 3.20 below shows the three machined parts making up the Virtual Impactor.



(a) Top section



(b) Middle section



(c) Lower section

Figure 3.20: Section views of the parts of the Virtual Impactor

3.6.7 Part manufacturing summary

Table 3.3 below summarises the bespoke parts needed for the particle concentrator. Information about quantity required, material and manufacturing method is provided.

Table 3.3: Part manufacturing summary

Part Name	Quantity	Material	Manufacturing Method
Cooling block	2	Aluminium	In-house machining
VI - Top section	1	Aluminium	Machining at Metallic
VI - Middle section	1	Aluminium	Machining at Metallic
VI - Lower section	1	Aluminium	Machining at Metallic
Flow reducer	2	PETG	FDM 3D Printing
Thermal separator	2	PETG	FDM 3D Printing
Virtual impactor support	1	PLA	FDM 3D Printing
Water bottle holder	2	PLA	FDM 3D Printing
Dryer end caps	2	PLA	FDM 3D Printing
Dryer holder - Top	1	PLA	FDM 3D Printing
Dryer holder - Bottom	1	PLA	FDM 3D Printing
Electronics panel	1	Acrylic	Laser cutting
MFC Mounting plate	1	Acrylic	Laser cutting
GT mounting bracket	4	Aluminium	Water jet cutting
VI mounting bracket	4	Aluminium	Water jet cutting

3.7 Bought parts

3.7.1 Electronics

In the process of designing and building a machine for particle concentration, a heating tape was utilized to warm the initiator and the conduit connecting the virtual impactor and the dryer. This decision was influenced by advice from Tampere University, which suggested either a heating tape or a specially designed heating cradle. The heating tape was found to be the most suitable for the requirements.

For the necessary cooling of both the conditioner and the moderator, a Peltier module was employed. This module, equipped with a heat sink and a fan, operates by dissipating heat from the hot side, thereby enhancing the cooling effect on the opposite side. This method was found to be an effective solution for the cooling requirements.

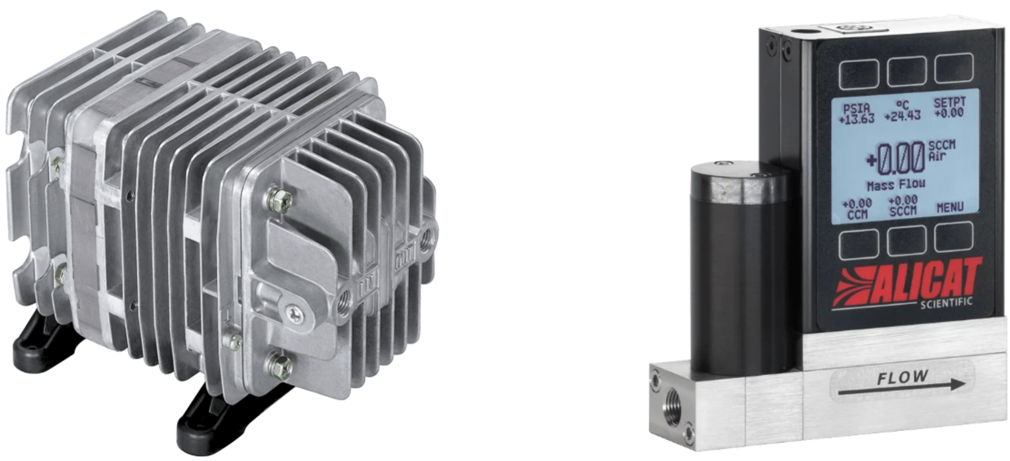
To regulate the heating tape and Peltier modules, PID temperature controllers were used, one for each temperature-controlled section. The inclusion of temperature sensors is crucial as they provide the necessary feedback to the PID controllers, ensuring effective temperature control within each individual section. This comprehensive setup allows for precise temperature regulation, a critical factor in the success of the machines operation.

The design of the electrical system incorporates several key components to ensure safety and efficiency. A main breaker switch is employed as a vital safety measure, offering a means to disconnect all electrical power in the system for safe maintenance and emergency shutdowns. The systems wiring and cables are meticulously chosen based on their electrical and thermal properties. These components are engineered to carry the necessary current without overheating and are insulated to avert electrical shocks and short circuits. Furthermore, the system incorporates 12V power supplies to provide a stable and reliable power source for the fans. These power supplies are specifically designed to convert the main power source into a lower voltage while maintaining a consistent current, ensuring the smooth operation of the system.

3.7.2 Air equipment

Vacuum pump and Flow controller

The flow controller and vacuum pump work in conjunction with one another to pull an accurately defined flow through the major flow section of the virtual impactor.



(a) Nitto vacuum pump **(b)** Alicat Flow controller - MFC

Figure 3.21: Vacuum pump & Flow controller

Air tubing

Two different tubing sizes are used, ¼ inch and ½ inch (these measurements correspond to the inner diameter of the tubing). The tubing used for the major flow is ¼" ID, this is because all of the equipment used in the major flow loop (water trap/filter, flow controller, vacuum pump etc.) have ¼" tube adapters in their air fittings to seal the connections properly. The growth tube, virtual impactor and dryer all use ½" Tygon tubing.

Tygon tubing has the benefit of not getting statically charged like conventional vinyl tubing. It is also the standard tubing type used at SU in aerosol research.

Air fittings

The concentrator devices uses a variety of air fittings to connect the various parts of the growth tube, virtual impactor, flow controller and pump. These fittings have two ends, a threaded end and a tube adapter end. The threaded end is used to attach the fitting to the relevant piece of equipment and the tube adapter end is used to attach the tubing (vinyl or Tygon). The air fittings all have different threads because the parts come from different regions of the world (flow controller - USA, vacuum pump - Japan). PTFE tape was applied to the threads of all of the air fittings. Table 3.4 below shows all of the different air fittings used the particle concentrator.

Table 3.4: Swagelok fittings used

Part Number	Description	Used In
SS-8-TA-1-4RS	1/2" Tube fitting, G 1/4" thread	Virtual Impactor
SS-4-TA-1-2RS	1/4" Tube fitting, G 1/8" thread	Virtual Impactor
SS-4-TA-1-2	1/4" Tube fitting, 1/8" NPT thread	Flow controller
SS-4-TA-1-4RT	1/4" Tube fitting, 1/8" ISO tapered thread	Vacuum pump

3.8 Testing Plan

This section will present our proposed testing plans for the equipment in the particle concentrator. The testing is divided into the first section, detailing the individual component testing, and the second plan to test the combined systems.

3.8.1 Individual subsystem testing

Once the different subsystems has been assembled and before the final assembly, individual testing of the subsystems are performed. The sub-systems that are to be individually tested are the virtual impactor and the growth tube. If there is time, the dryer will also undergo individual testing. The aim of these individual tests are to create a better understating of the different settings that are available for each subsystem. This is needed to tune the subsystems for optimal performance.

Growth tube:

To test the efficacy of the particle growth tube, we require
Required equipment:

- Growth tube assembly
- Temperature controlling system
- Humidity Sensor
- Particle generation (e.g. pin-on-disk tribometer or aerosol generator)
- Condensation Particle Counter

Testing Steps Part 1 (Humidity):

1. Measure the humidity of the air as a baseline
2. Saturate the sponge in the particle growth tube and run the heating and cooling systems
3. Run the baseline air through the particle growth tube and measure the humidity at the outlet
4. Compare the humidity of the baseline to the outlet
   (a) The test succeeds if the humidity of the outlet is substantially higher than the baseline
   (b) The test fails if the humidity of the outlet is the similar to the baseline

Testing Steps Part 2 (Particle Size):

1. Generate particle of a known/measured size distribution
2. Saturate the sponge in the particle growth tube and run the heating and cooling systems
3. Run the baseline air through the particle growth tube and measure the size distribution at the outlet
4. Compare the size distributions of the baseline vs outlet
   (a) The test succeeds if the size distribution of the outlet is substantially higher than the baseline
   (b) The test fails if the size distribution of the outlet is similar to the baseline

Virtual impactor:

To isolate and test the efficacy of the virtual impactor, we require particles of a known size distribution. These particles should be sufficiently large such that they can pass through the virtual impactor without the aid of growing via the growth tube. This means that the particle size should be roughly 1-10microns. Additionally, to simulate the flow of the ALI system, we also require a minor flow of roughly 1.5L/min. The the major flow will then be adjusted using the mass flow controller to test different flows.

Required equipment:

- Virtual impactor assembly
- Major flow pump and mass flow controller
- Particle generator (e.g. pin-on-disk tribometer, spark discharge, or aerosol generator)
- Condensation Particle Counter or Optical Particle Counter

Testing Steps:

1. Generate a stream of aeresolized particles of know size distribution
2. Measure the particle concentration of the output of the particle generator. This gives us a baseline to compare the measurement results.
3. Attach the virtual impactor assembly to the outlet of the particle generator
4. Compare the particle concentration of the control verses experimental trials
   (a) The test succeeds if the particle concentration of the experimental trials is substantially higher than the baseline
   (b) The test fails if the particle concentration of the experimental trials is similar to or lower than the baseline

Dryer (Optional):

If time allows, we will also perform a test on the efficacy of the dryer. This is the lowest priority because the concept of the silica-gel dryer is commonly used and less novel than the other components of our system.

Required equipment:

- Dryer assembly
- Pump and mass flow controller
- Humidifier or growth tube assembly
- Humidity sensor

Testing Steps:

1. Use the pump to pull air through the humidifer
2. Measure humidity of the output of the humidifer. This gives us a baseline to compare the measurement results
3. Attach the dryer assembly to the outlet of the humidifier
4. Measure the humidity of the output of the dryer
5. Compare the humidity of the control verses experimental trials
   (a) The test succeeds if the humidity of the experimental trials is substantially lower than the baseline
   (b) The test fails if the humidity of the experimental trials is similar to the baseline

3.8.2 Whole system testing

Connected Flow System:

After the testing of the individual components, we plan to complete a test of both the growth tube and virtual impactor at the same time. Because the particles with increase in mass when passing through the growth tube, the particle size supplied to the system should be in the nanoparticle range, as this is our target particle size for end-use.
Required equipment:

- Growth tube assembly
- Temperature controlling system
- Virtual impactor assembly
- Major flow pump and mass flow controller
- Dryer assembly
- Particle generator (e.g. pin-on-disk tribometer, spark discharge, or aerosol generator)
- Condensation Particle Counter or Optical Particle Counter

Testing Steps:

1. Generate a stream of aeresolized particles of know size distribution
2. Measure the particle concentration of the output of the particle generator. This gives us a baseline to compare the measurement results.

3. Saturate the sponge in the particle growth tube and run the heating and cooling systems
4. Run the baseline air through the particle growth tube and measure the size distribution at the outlet
5. Attach the virtual impactor assembly to the outlet of the growth tube
6. Compare the particle concentration of the control verses experimental trials
   (a) The test succeeds if the particle concentration of the experimental trials is substantially higher than the baseline
   (b) The test fails if the particle concentration of the experimental trials is similar to or lower than the baseline

This section has described the planned testing of our design for a particle concentrator. The feasibility of these tests will is dependent of the timely delivery of necessary components, and the availability and proper functioning of the testing equipment at SU.

4 Results

4.1 Secondary Research

This section covers the results and findings from the secondary research conducted during this project. First, the selection of cases is examined and the reasons behind this decision explained. Then, the findings of the research conducted will be discussed. The research centers around the comparison of the two cities' PM air pollution levels and how the transit design in these areas impacts these levels. The findings are titled: Finding 1: Comparing PM levels in Edmonton and Prague, Finding 2: Scope and Pollution Studies, Finding 3: Subway tunnel pollution levels, Finding 4: TOD and Urban development strategies.

4.1.1 Case Selection

The two case locations that were selected are Edmonton, Canada and Prague, Czechia. With populations of roughly 1.1 million and 1.3 million respectively, they fall within the proposed city populations[41]. Both Edmonton and Prague also classify as Humid Continental climates on the Köppen-Geiger Climate Classification (Figure 4.1) which confirms that they have similar climate characteristics (e.g. rainfall, temperature range, etc.). Additionally, the industrial make-up of both cities is relatively comparable. Both cities have large manufacturing and technology sectors. The main difference in industry between the two cities is that Edmonton has a history of massive oil and gas industry, although this is currently declining[42]. Prague, on the other hand, also relies heavily on its tourism industry[43]. This difference in industrial make-up will be accounted for in Finding 1 when the sources of emissions are analyzed. Any difference in source percentages regarding industry would be relevant to this point. The main difference between the two cities are their population densities and public transit availability. Public transit performance and availability is being assessed by comparing each city to others in the respective country/continent, then comparing the average performance of both regions. Public transit effectiveness usually is measured by several factors such as ridership, extent, efficiency, and frequency. This report looks at the performance holistically. Edmonton has poor-normal performing public transportation when compared to other Canadian cities, as shown in Figure 4.2[44]. It is also worth mentioning that public transit systems in Canada and the rest of North America typically have lower ridership and availability when compared to those of Europe [45]. Prague, on the other hand, hosts one of the best performing public transport systems in the world, let alone within Czechia [46][47]. This difference in public transit performance between the two cities is the main reason that they were chosen. The difference in population density between the two cities can also be viewed as a result of the effective design of their transit system, and their urban planning legislation. This difference will be explored in-depth in the Discussion section.

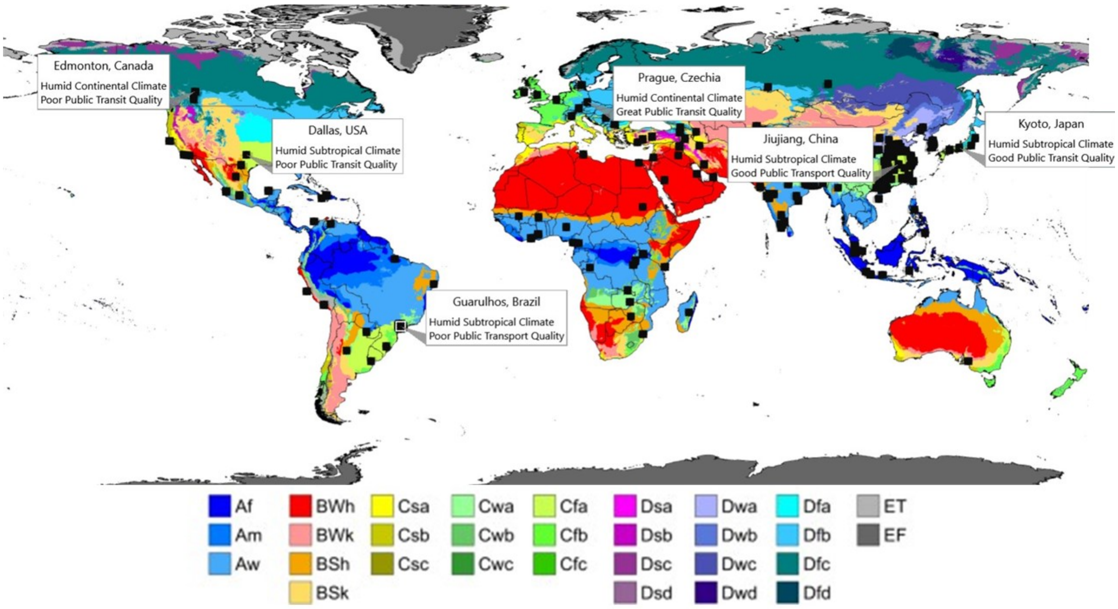


Figure 4.1: Cities of the world with 1-1.5million inhabitants with Köppen-Geiger climate classification map overlaid[38][39]

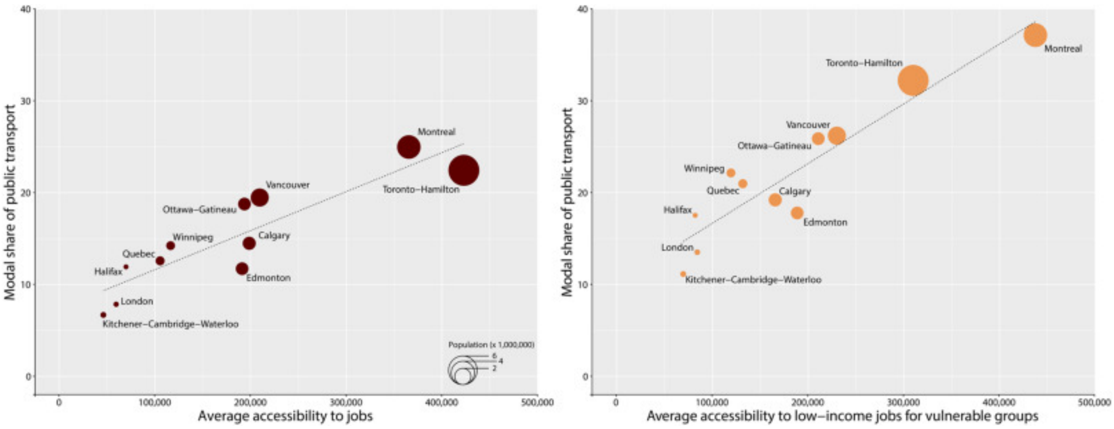


Figure 4.2: Accessibility and Public Transport in Canadian Cities[44]

4.1.2 Finding 1: Comparing PM levels in Edmonton and Prague

During the review of reports on Edmonton, Canada, and Prague, Czechia, a focus was put on the PM levels at both locations, especially from transportation sector sources. In Edmonton, one study found that the average PM2.5 level was 7.11 g/m3. This level was similar to levels at other stations in Edmonton: central 8.0 g/m3, east 9.0 g/m3, south 8.0 g/m3[48]. The sources of these pollutants were apportioned as shown in Figure 4.3. One can see that traffic contributes 13.5% and road salt contributes 4.4% of PM2.5 emissions on average. Both of these emission sources are directly related to the automobile-based transportation.

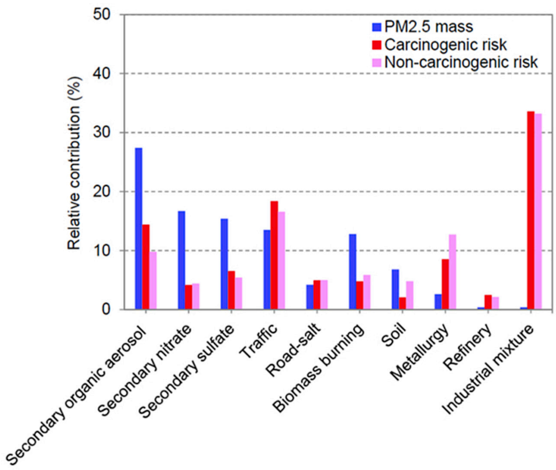


Figure 4.3: Appropriation of PM2.5 Sources in Edmonton[48]

A study of two suburban sites in Prague, Czechia found that their average annual PM2.5 pollution was 24.4g/m3 and 25.1g/m3. The sources of this pollution were split and displayed in Figure 4.4. Here, traffic accounts for 15% and road dust accounts for 11% of PM emissions, however road salt only contributes a small portion[49].

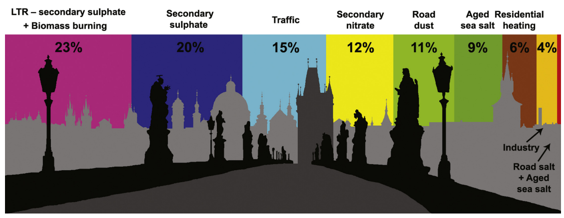


Figure 4.4: Enter Caption

Some potential source of discrepancies between the sources include that the first study on Edmonton does not have a "road dust" section. In fact, some of the emissions from the "soil" source are likely to be caused by road dust kicking up soil particles[48]. Additionally, it is very difficult to properly attribute the original sources of secondary PM. For example, the secondary nitrates referenced in the Edmonton study may be caused by NOx emissions from the transport sector, since it is a primary source of this pollutant[45]. Despite these comments, it is still clear that Prague has a substantially higher level of PM2.5 air pollution when compared to Edmonton. This result appears to unintuitive, since public transportation often has a connection with reduced air pollution. Reasons for this result will be explored in the following findings, as well as the discussion.

4.1.3 Finding 2: Scope and Pollution Studies

Another point made clear in the literature was that the scope of studies focused on measuring air pollutant levels is extremely important. For the case of this study, we are analyzing and comparing the simple levels of PM2.5 present in the air. However, if the study focused on the amount of PM inhaled by the average person, different results may appear. This is especially important when different types of transportation are inspected. For example, if the goal of a report is to study whether active transportation (e.g. walking, biking) or car-based transportation exposes people to more PM pollution, different results have come from different reports[50]. This is because active transportation increases people's breathing rate and therefore people using active transport have more opportunities for PM to enter their respiratory system. Even though the PM levels that active transit users are surrounded by are often lower than those of car users, the PM entering their respiratory systems my be higher[50]. Thus is it vital that the scope of study is correctly assessed and consistent.

It was also discovered that the composition of PM and NP pollution is important to study. This is because certain types of particulate emissions may be demonstrated to be carcinogens and/or increase the prevalence of other health disorders [45]. One example of this is the emissions from diesel engines (often used in the public busses in Canada) often have high levels of Black Carbon(BC) and Ultra-fine Particles (UFPs) which are designated as carcinogenic [51]. UFPs can also be considered NP since their size is specifically under 100nm. The composition of PM can also be used to attribute the sources of pollution. This was used in both of the major studied discussed in Finding 1, and also in most other transit-oriented pollution studies [48, 49, 52]. In conclusion, it is vital to consider the context and scope surrounding studies into the emissions in the transit sectors. It is also extremely important to consider the composition of PM pollution and its impact on its health impact.

4.1.4 Finding 3: Subway tunnel pollution levels

A study of the Prague underground metro platforms has found that the PM10, PM2.5, and PM1 levels are substantially higher there than on the surface [53]. This PM pollution may come from a variety of sources such as the connection between rail and wheel, the friction on the brake-pads of trains, and the wind in the metro tunnel kicking up dust and debris. This is displayed by the fact that the PM pollution present in the air increases when trains arrive and during peak-traffic hours [53].

A comparative study of subway/light rail systems in major Canadian cities supported this conclusion. The study found that the pollution levels at above-grade train platforms was around half of that found at below-grade platforms [52]. It also found that the type of wheel and brake designs used had a large impact on the amount of PM pollution produced and its composition. For example, the commuter PM exposure levels in the Toronto metro system was substantially higher than those in the Montreal system, despite the later being completely below-grade. This is likely due to the steel wheel-steel rail rolling stock used by the Toronto system, which likely emits substantially higher amounts of PM pollution compared to the rubber wheel-concrete rollways used in Montreal[52].

Since the below-grade platform PM levels are much higher than those above-grade, it might be expected that the PM levels inside the train cars may also be high. This is actually the opposite of reality, where the PM levels in the rail cars are substantially lower than those at both above and below-grade platforms. In fact, the commuter UFPs/NP levels experienced by subway users are much lower than those experienced by individual car drivers, most likely because the combustion engines used in cars are a huge producer of UFPs [52]. This phenomenon is similar when bus transportation is analyzed: nearly all of the PM exposure during the commute occurs during the wait at the platform[51]. This will be further covered in the final finding.

4.1.5 Finding 4: TOD and Urban development strategies

A study of air pollution levels across major cities in Europe including Prague during the Covid pandemic found that the reduction of traffic during this time caused a sharp decrease in air-pollution levels in the cities [54]. This study serves as proof that a reduction in the usage of Internal Combustion Engine(ICE)-driven vehicles has the potential to drastically reduce the levels of PM pollution in cities like Prague. Another report focusing on assessing the potential for Transit Oriented Development (TOD) in Edmonton, found that currently the city is extremely poorly laid-out in terms of TOD [55]. Only around 14% of people utilize the public transit there.

Perhaps this inefficient design of public transit is the reason that a 2020 study found that an analysis of transit strikes in Canada actually found that NOx pollution decreases when public transportation is halted[45]. While PM2.5 levels are not significantly affected, it is important to note that NOx is also a longer-term source of secondary PM2.5. It is speculated that the reason for this relationship is that Canadian public transport often relies on diesel-powered busses which emit large amounts of pollution when compared to electric counterparts. This is supported by the fact that reports done in Europe - where public transit is more often electrically powered - often have the opposite findings[45].

Other considerations when developing public transit were touched upon in Finding 3: the discrepancy between commuter PM exposure at above and below-grade

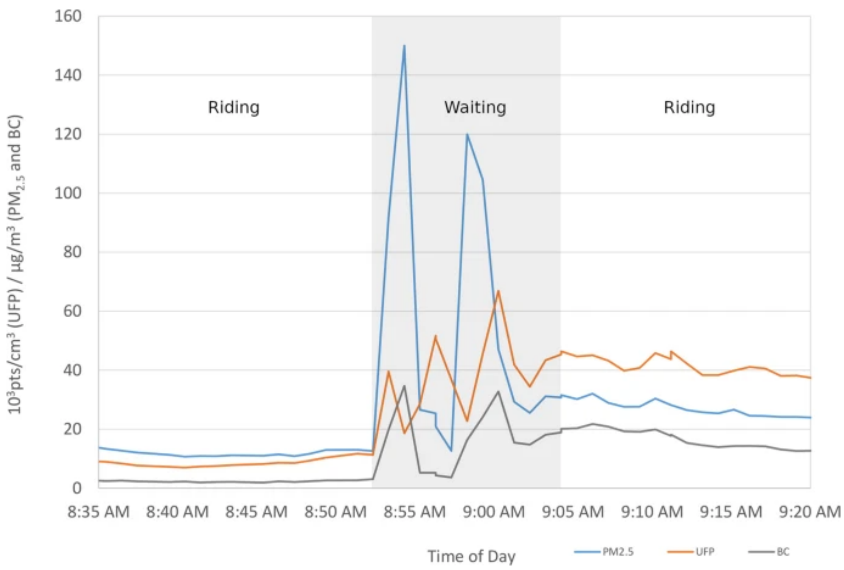


Figure 4.5: "An example of the impact of elevated bus station exposures on riding exposures: a time series plot displaying the minutely PM2.5, UFPs, and BC concentrations of a bus ride to an enclosed bus station, a 12-minute waiting period at the enclosed bus station, and the subsequent ride."[51]

platforms, and between exposure inside and outside the vehicle [52]. As mentioned, the time spent waiting at the platform contributes a majority of the commuter PM pollution exposure for both subway systems and bus systems, both above and below-grade, as depicted in Figure 4.5 [52, 51]. Thus, the waiting times of both subway and bus transit systems are of top concern if the commuter PM exposure is to be reduced.

In summary, Finding 4 displays the positive impacts of organization and optimization of transit systems, particularly in the case of Edmonton, Canada. The simple scaling of its current bus-oriented transit systems could actually have the potential to increase harmful pollutants. Instead, optimization tactics and development factor have proven to have the potential to reduce PM pollution.

4.2 Final concept

The final concept that was chosen is not a single version of the concepts that has been presented previously. It is rather a combination of the concepts that performed the best during the concept evaluation phase. It saturates the particles by letting them pass through a wet cellulose sponge, it's equipped with a one-stage virtual impactor, a silica gel dryer and a single front panel inspired by the "open box" concept. A sketch of the final concept that describes the different parts can be seen in Figure 4.6.

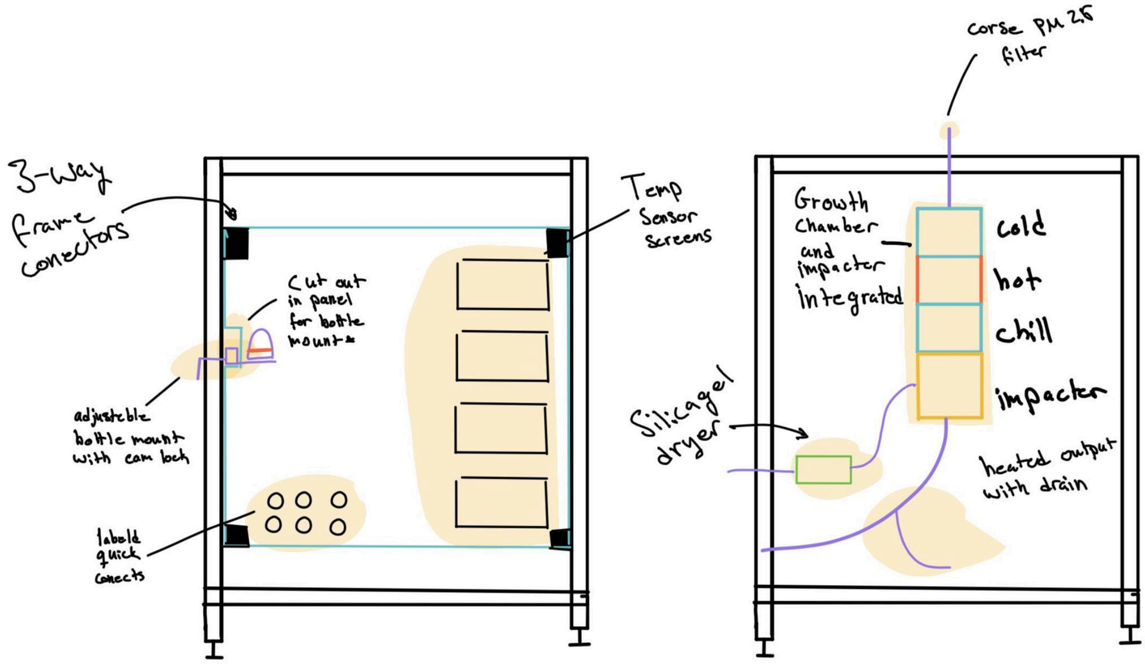


Figure 4.6: The final concept

4.3 Simulations

The simulation registered a maximum concentration factor of 2.12, observed under conditions of a major flow rate of 25 L/min and a minor flow rate of 1.5 L/min. It is essential to note that the simulated concentration factor may not accurately mirror the performance of the prototype, as elaborated upon in section 5.3.

4.4 CAD

This subsection describes the completed CAD model as well as its various sub-assemblies. All CAD work in this project was performed using Solid Edge 2023.

A full featured CAD model was created successfully. All assembly relations were applied correctly, and movable parts such as the water bottle holders move as expected. Figure 4.7 below shows a render of the final concentrator CAD model.

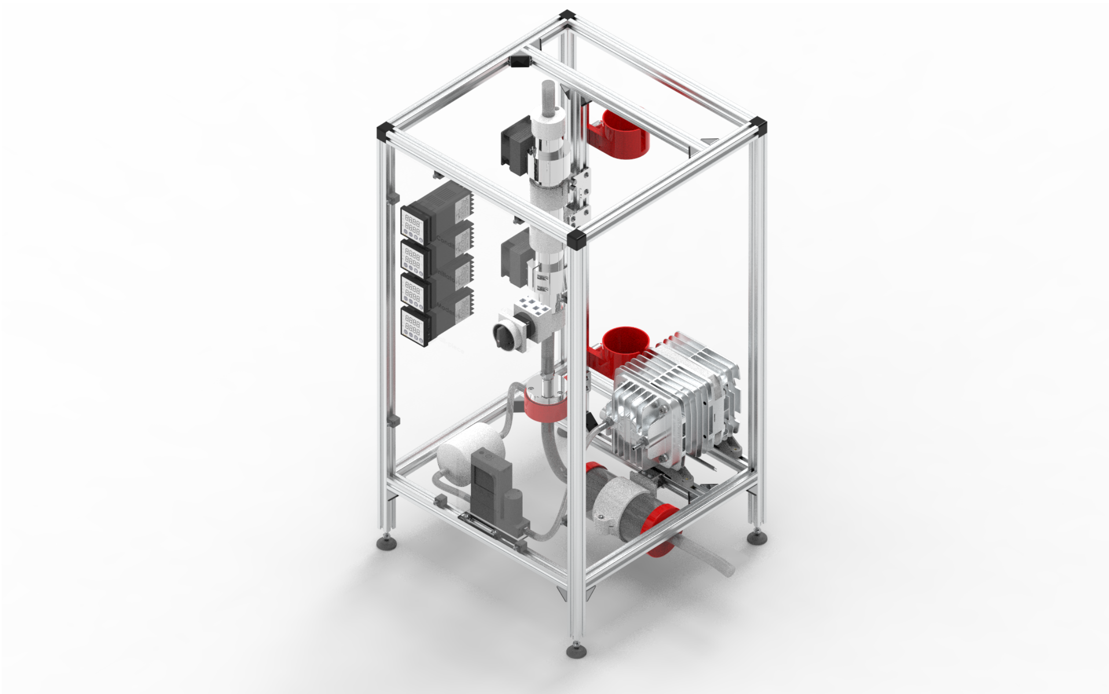


Figure 4.7: Final render of the concentrator CAD model

Parts which required regular updates throughout the duration of the project (e.g., the parts of the virtual impactor), were modelled in such a way that key dimension values were easily changed; i.e., best CAD practices were followed.

Standard parts like screws and nuts were inserted into the CAD model using the Standard Parts menu in Solid Edge. CAD models of teh mass flow controller and the vacuum pump were graciously provided by the respective manufacturers, Alicat and Nitto. These provided CAD models allowed us to design the other components more effectively.

Finally the Pack and Go feature was used to create regular back-ups of the CAD throughout the project's timeline.

4.5 Manufacturing

The 3D printed components met the specified expectations, demonstrating compatibility with their intended locations. The final parts exhibited appropriate fits, and the brackets effectively supported the designated components. The press-fit parts on the growth tube functioned as anticipated, requiring no additional external constraints for retention. Notably, parts intended to endure elevated temperatures, primarily those on the growth tube, were printed using PETG to accommodate the thermal requirements.

Parts cut with the abrasive water jet conformed to specifications and remained within the specified tolerance limits. However, it's worth noting that the water jet process left some burrs on the cut parts, necessitating manual removal to achieve the desired finish.

The virtual impactor machined by "Metallic AB" adhered precisely to the specifications outlined in the provided drawings. Additionally, an assembly drawing was submitted, prompting Metallic to conduct a thorough test fit of all components. This verification process ensured that each part aligned as intended, confirming that tolerances were appropriately sized and avoiding any instances of overly restrictive fits.

The cooling block was internally fabricated by the staff at the KTH Prototype Center. The received part aligned with the specifications outlined in the submitted drawing. However, discrepancies were noted in the tolerances of this drawing compared to the measurements of the intended mounting pipe. The identified issue stemmed from a smaller-than-required hole in the part. Subsequently, a resolution was implemented at the IIP workshop, involving the use of a lathe to enlarge the inner diameter and rectify the size mismatch.

4.6 Testing

The following section will describe the results and procedures of the tests that were conducted on our particle concentrator. Because the parts for the virtual impactor arrived much sooner than those in the growth tube assembly, we started the testing with the virtual impactor.

4.6.1 Spark discharge + CPC

The first experiment that was conducted used a spark discharge to create particles and a Condensation Particle Counter to measure the particle levels. The spark discharge particle generator aerosolized metallic particles of the a size range of approximately 60-154 nm. The CPC has the ability to measure particle sizes ranging from approximately 16-600 nm. The CPC also had an inlet flow of 0.3L/min. To maintain the same ratio of major to minor flow as expected in our use-case, we scaled the major flow down accordingly to be a range of 1-3.5 L/min. The setup of this test rig is displayed and explained in Figure 4.8.

Figure 4.8: Photo of the first test rig with spark discharger machine in the top right, Condensation Particle Counter in the left, and the virtual impactor and flow controller in the bottom right

When testing the virtual impactor, no major changes in size distribution or concentration was noticed between the control and the various experimental trials. The suspected reasons for this will be further addressed in the Discussion section.

4.6.2 Particle suspension + OPC

The second experiment that was conducted used a particle suspension and aerosolizer to create particles and a Optical Particle Counter to measure the particle levels. The particle suspension is made of polystyrene plastic particles with sizes of approximately 1, 3, or 5 microns. The OPC has the ability to measure particle sizes ranging from 0.25-32microns. The OPC also had an inlet flow of 1.2L/min. The aerosolizer was originally designed for an inlet flow of 3.9L/min. In order to accommodate for the desired virtual impactor combine flow of 16.5L/min in our system, the critical orifice in the aerosolizer was switched with an adjustable valve to allow for a higher flow during experimental trials. Thus, the particle concentration of the combined flow during these trials was lower than the control. The flow into the OPC, however, is constant. A blow-off valve is also used to make sure that the air pressure entering the OPC didn't become too high.

During the control trial, the concentration of the desired particle size (3micron) did not peak as expected and not substantial readings were obtained. This did not change when a particle size of 5 microns was used, or when the virtual impactor was used. Thus, the results of this test were completely inconclusive as no baseline measurements were achieved. The setup of this second test rig is displayed and explained in Figure 4.9.

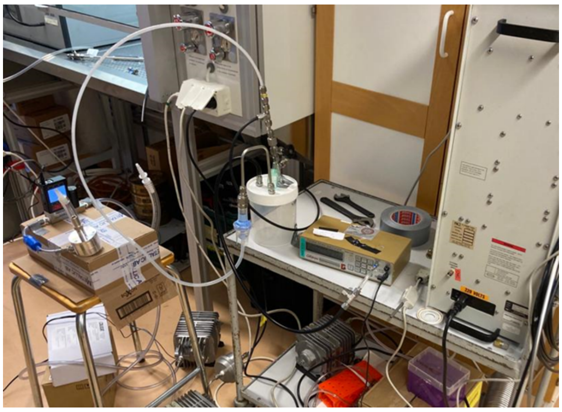


Figure 4.9: Photo of the second test rig with the flow controller, virtual impactor, particle suspension aerosolizer, and Optical Particle Counter from left to right

4.6.3 Smoke pen + OPC

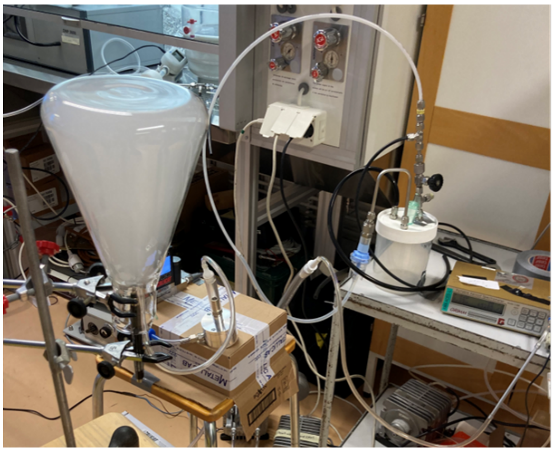


Figure 4.10: Photo of the thrid test rig with the smoke pen and chamber, flow controller, virtual impactor from left to right. The OPC is out of frame to the right of the photo

The third experiment (Figure 4.10) that was conducted used a smoke pen to create particles and a still used a Optical Particle Counter to measure the particle levels. The particles created by the smoke pen are make of soot and the sizes very widely from the nanoparticle range to over 5 microns. Similar to the second experiement: the OPC can measure particle sizes ranging from 0.25-32microns with an inlet flow of 1.2L/min. The smoke from the smoke pen was collected in an upturned 2L flask with the inlet tube placed near the mouth of the flask. When running the control, the input of the system only pulls 1.2L/min from the flask. This allowed the smoke pen to replenish the smoke pulled by the inlet. During the experimental trials, however, the virtual impactor must also pull the major flow, for a combined inlet flow of over 8 L/min. Because the supply of smoke was only

2L maximum, and the smoke was unable to replenish at the same speed as it was pulled, the results of the experimental trials showed an immediate reduction in PM which continued as the quantity of smoke in the flask decreased. This rendered the results inconclusive because the experimental trial results were incomparable with the control.

5 Discussion

5.1 Secondary Research

This section discusses the findings from the secondary research conducted during this project. The findings which were introduced during the Results section will be discussed in more detail. The research focuses on Edmonton, Canada and Prague, Czechia's PM air pollution levels and transit design and the comparison between the two. The findings are titled: Finding 1: Comparing PM levels in Edmonton and Prague, Finding 2: Scope and Pollution Studies, Finding 3: Subway tunnel pollution levels, Finding 4: TOD and Urban development strategies.

5.1.1 Finding 1: Comparing PM levels in Edmonton and Prague

As mentioned in the literature review, it was expected that secondary sources of PM2.5 would be a significant percentage of the total PM origin. This was true for both of the locations, with both having secondary sources contribute to over half of the PM2.5 mass. In fact, the proportions for each source are relatively similar with the exception that a larger percentage of PM2.5 in Edmonton originates from biomass burning.

Beginning this research process, the expectation was that the PM2.5 levels would be higher in Edmonton, due to its poorer-performing public transit and higher dependency on individually-owned cars, however this proved to be false. As shown in the results, the average PM2.5 levels in Edmonton were found to be approximately one third of that in Prague. This indicates that the general air pollution is less directly connected to transportation planning decisions than originally thought. This notion is also supported by the fact that the PM2.5 emissions attributed to traffic causes are very similar percentages in both locations.

As mentioned in the results section, some discrepancies may have arisen from the different grouping methods chosen by the reports. While the Edmonton report does not have a category named "road dust", some of the PM2.5 under its "soil" section would likely be classified as road dust in a different study. Since the PM2.5 attributed to soil in the Edmonton study is less than 10%, it still doesn't make a large difference even if it did originate from road dust.

One factor that may largely impact the PM2.5 levels in both cities which was not considered strongly during the selection of the cases is the population density of both cities. Edmonton has a population density less than half of that of Prague. Since the individual people in Edmonton have more space available to them per-capita, it also implies that the sources of PM2.5 pollution are also more spaced out. This would explain the the lower levels of PM2.5 present in the air in this location. Another related issue with measuring air pollution levels is that air pollution sources are not strictly local. Similar to other environmental issues such as acid rain, it is possible for the PM2.5 pollution in one city to be caused by another. This is mostly relevant to the secondary PM caused by chemical reactions in the atmosphere. This is pertinent this case study because Edmonton is a much more isolated city, with a vast wilderness to the north, and only one major city, Calgary, within close proximity to the south. Prague, on the other hand, is surrounded by major cities with Berlin, Munich, and Vienna a similar distance away. The higher density in both Prague and the country of Czechia, and Prague's proximity to other major cities may be possible explanations for the larger amount of PM2.5 pollution present in the location.

It is also worth mentioning that functional transit planning often comes hand-in-hand with more dense city planning. This concept is covered more in-depth in finding 4 which discusses Transit-Oriented Development. It makes the objective of reducing regional air pollution even more difficult, because denser cities allow for reduced travel distances and more efficient usage of transportation resources, which are thought to decrease overall PM pollution levels, but it also condenses the sources of this pollution into a smaller area, therefore increasing the regional PM pollution levels.

5.1.2 Finding 2: Scope and Pollution Studies

Finding 2 focuses on the important difference between PM pollution levels present in the air and the amount of PM pollution taken in by the average person. Of course, in the context of human health impacts, it is more important to measure the amount of pollution being inhaled by each person, rather than just what is present in the air. This, however, is much more complicated to measure since one must also account for the breathing rate of the person. It is especially pertinent when forms of active transportation (i.e. walking, biking) are compared to passive forms of transportation like driving, as mentioned in the results section. This is because different forms of active transportation involve different levels of increased breathing rates. It becomes more complicated still when mixed transportation routes are considered, such as those involving public transportation. The walks to and from stations, and the waiting times at these stations are often when nearly all of the PM2.5 pollution intake occurs, as discussed in findings 3 and 4. Because of this incredible complexity, it is much more practical to simply measure and compare the PM pollution present in the air, but it remains an important factor to consider.

Another important factor is the composition of PM and NP pollution. As mentioned in the results section, it has been found that different modes of transportation produce different compositions of PM and NP/UFPs. This can be seen in Figure 4.3 in Section 4.1.2, where the "Industrial mixture" category represents only a small percentage of PM2.5 mass, but a huge proportion of the health risks presented by PM2.5. This means that even though two transportation layouts may have similar quantities of PM2.5 or UFPs, the toxicity in these two scenarios may widely vary. This is the research niche that our particle concentrator and SU's ALI system hope to fill. By studying the way which lung cells react to specific types of NP concentrated on-site, we can build a better understanding of the impacts of different types of PM/NP. In conclusion, the context of PM emissions is vital to consider when studying PM emissions in the transit sectors. This allows for a full understanding of the impact of airborne PM and NP pollution.

5.1.3 Finding 3: Subway tunnel pollution levels

The results in Finding 3 highlight the large effects that platform design can have on on the local airborne PM2.5 levels. It shows that below-grade platforms have substantially higher PM2.5 levels than above-grade designs, a result which is consistent in both scenarios studied. These particulates are caused by multiple sources such as dust which is kicked up by the wind of passing trains, brake dust, and PM from the contacts between the trains' rollers and the rail. Perhaps the most prominent issue, however, is the lack of free ventilation which would normally disperse the airborne particulates. Therefore, one possible improvement that could be made for underground platforms is increased ventilation of the underground portions of the systems. Such modification and improvement upon ventilation systems has been tried and is shown to be capable of improving platform air quality while also improving energy efficiency, such as in these two Korean government-funded reports [56, 57]

Another key aspect of this finding is the impact of differing types of rail technologies. The example given shows that steel wheel-steel rail rolling stock, while extremely energy-efficient, appears to produce substantially higher quantities of PM2.5 than rubber wheel-concrete rollway technologies. This, like many other aspects of air pollution research, presents yet another dilemma. Does the increased efficiency of steel wheel technology outweigh the negative aspect of substantially higher particulate production? Or does a combination of technologies allow for a best-of-both-worlds scenario? Steel wheel-steel rail technology may be better suited for above-grade scenarios where the PM production could be better ventilated and the efficiency capitalized upon, and rubber wheel-concrete rollway technologies could be better for underground subway lines which benefit from its low PM2.5 production.

Finally, it was also discovered that the PM2.5 levels inside subway cars and busses are substantially lower than the train platforms. This may come as a surprise, since they are enclosed spaces much like below-grade subway platforms, however the area is separated from prominent sources of particulates, and issues with dust being aerosolized rarely occurs due to the stable and slow moving ventilation systems used. Because of the low PM levels inside the cabin, this means that almost all PM2.5 exposure during an average commute occurs during the waiting time at the platform, both with rail and bus travel as described in the results. With this in mind, it becomes clear that lessening PM2.5 exposure during platform waiting times would be the most effective focus. This leads into the discussion of the final finding, which covers the Transit-Oriented Development and how issues of particulate air pollution can be addressed using transportation planning strategies.

5.1.4 Finding 4: TOD and Urban development strategies

It has been shown that there is massive room for improvement in terms of the air quality and the particulates coming from the transportation sector. The first study mentioned displays how a sharp decrease in car usage could lead to a rapid recovery of air quality. It is also worth mentioning that this study was conducted in many European cities which currently are thought to have high-quality urban public transit infrastructure. If one considers Edmonton, which as mentioned has alarmingly low ridership in its public transit sector, it is clear that the system could be improved greatly. This is supported by the fact that transit strikes in Canada have actually shown to reduce many pollutants, clearly indicating an inefficient current transit system. Before any scaling of the Canadian transit system, it is evident that improvements to its efficiency emissions standards are necessary. Since the current widely-used diesel engine busses emit large amounts of PM and UFPs, these improvements could come in the form of investment into cleaner, electric busses, or efficient rail systems. The issue with this, is the massive amount of up-front investment required.

As touched upon in Finding 3, the majority of PM2.5 exposure during the average commute occurs during the period waiting at the platform (Figure 4.5 in Section 4.1.5). This means that a great reduction in commuter PM2.5 exposure can be achieved if the average time spent waiting on the platform is reduced. Since it is an extremely expensive measure to update the busses used in transit, and even more so to develop a less-polluting electric subway system, optimizing the transit timing to reducing commuter waiting times may be a more viable option. Instead of a costly technological solution, the strategy would instead be shifted to one of optimization, which would entail much less up-front costs. In the case of Edmonton, the optimization of existing transit infrastructure would allow for reduced commuter PM2.5 exposure while also providing incentive for increased ridership in the city. This can serve as a first step in the direction of Transit-Oriented Development in Edmonton. Larger, more expensive or complicated projects like rail line expansions and zoning law adjustments would be easier to do after an increase in ridership has been demonstrated. In the case of Prague, it is evident that the public transit options are already performing at a high level, however the higher levels of PM2.5

there make it all more important to minimize time spent waiting on platforms, especially in subways where PM concentrations are even higher. Many studies have confirmed that reductions in total transit traveling and waiting times reduce users' PM exposure, however no examples of optimization for the purpose of air pollution exposure reduction were found [58].

In conclusion, aerosolized particulate matter pollution and its connection to the transit sector is a complex issue without a clear consensus on its solutions. Findings 1 and 2 indicated the somewhat unintuitive correlations in local PM levels which indicate a need for in-depth PM studies. Finding 3 showed the intense, localized concentrations of PM which can be caused by infrastructure decisions. Finally, Finding 4 mentioned potential plans that may address these issues. In general, it is clearly vital to develop a better understanding of the effects of different types local PM and NP air pollution to address the prominent health and environmental impacts. This secondary research has clearly demonstrated the need for of our particle concentrator design (as detailed in the following sections) in conjunction with the Air-Liquid Interface developed by Stockholm University. Because PM is made up of extremely varied materials from numerous sources, the toxicity of PM also widely varies. Our system will allow for a better understanding of the toxicity, and therefore the impact, of nanoparticle pollution from the transit sector.

5.2 Final concept

The final concept was based on the best performing concepts from the concept evaluation phase. It was decided that the saturation should be performed using a wet cellulose sponge and not a water tank containing hot water since the sponge requires less parts and lowers the complexity of the entire device and contributes to maintainability of the device.

The device is equipped with a single one-stage virtual impactor. This decision was greatly influenced by the researchers from the university of Tampere. During a meeting with them we were told that using several virtual impactors was unnecessary unless the device was supposed to achieve a concentration greater than 30.

The device includes a silica gel dryer that removes moisture from the particles after the virtual impactor. Drying the particles without loss of particles is extremely challenging. The sharp turn with a tap solution does mean that some particles will be lost, this information was also acquired during the same meeting with the researchers from the university of Tampere. A silica gel dryer is a common method of removing moisture from air. However, it can also remove particles. To avoid this a tube of fine stainless steel mesh is used to provide a clear path through the silica gel dryer and minimize the loss of particles. Since this modification is possible and currently being used by researchers from SU, it was decided that this was the method to move forward with.

To avoid a potential problem with cooling it was decided that the device only should have one panel. This is beneficial both for cooling purposes, maintainability and ease of use since it gathers all controls and displays on one side of the device.

5.3 Fluid Flow Simulations

A limitation of the simulation model lies in its exclusive reliance on 2D models. Enhancing the robustness of the simulation necessitated the inclusion of simulations incorporating 3D geometry. However, due to time constraints and guidance from Tampere University researchers to shift our focus, the planned 3D simulations were not completed.

Following discussions with researchers from Tampere University, the decision was made to discontinue simulation efforts and shift attention towards finalizing the machine, emphasizing tuning aspects. This resulted in an immediate cessation of simulation-related work, with a concerted effort directed towards optimizing the design of the virtual impactor for manufacturability. The design process was informed by thorough research considerations, and the pertinent ratios informing the design were explicitly delineated, [33].

Encountering challenges in identifying a suitable manufacturer for the virtual impactor according to the original specifications, as well as facing difficulties in sourcing a pump capable of handling the simulated high flow rate, hindered the replication of the simulated conditions. Modifications were made to address manufacturing and part-sourcing issues, rendering the simulations non-representative of the final product. A planned simulation incorporating the final design of the virtual impactor and the selected pump's flow characteristics could not be executed due to persistent challenges in procuring components and unforeseen assembly issues within the project's time-frame.

5.4 CAD

5.4.1 Aluminium extrusion profile

A few minor details were omitted from the parts and assemblies of the final CAD model. One of these details is the intricate details of the aluminium extrusion profile. Only the necessary details like the slit gap and the width/height of the profile were added to the model.

5.4.2 Wiring

Electrical wiring was omitted for the final CAD model. This was for two reasons: 1. for the sake of time and 2. it would have made the CAD model overly complex and the file-size too large. However, the electrical routing feature in Solid Edge was used to model the various pieces of tubing for the major and minor flows. These routing paths were not nearly was complex or numerous as the electrical routes.

5.5 Testing

The original plan for testing was to test the individual components on separate days as soon as they were completed, then to combine them into one completed machine and test that as soon as possible. The planned growth tube test date was November 27th and December 4th for the virtual impactor. Due to delays in the shipment of the PVA sponge/wick, which is necessary for the functioning of our growth tube, we were unable to test the growth tube on the desired date. On December 4th, we were able to conduct the following individual tests on the virtual impactor subsystem:

5.5.1 Spark discharge + CPC

Because of the specifications of the spark discharger and CPC, for this test we were forced to run the experiment with much smaller particle sizes and substantially lower flows than the virtual impactor was designed for. This is likely the reason that the different experimental trials did not show any meaningful difference when compared to the control. After this, we sought out to design an experiment for the device using the correct particle sizes and minor flow rate.

5.5.2 Particle suspension + OPC

The next experiment was designed to test with the appropriate particle size and minor flow. By changing the valve configuration and adding an additional blow-off valve, the particle aerosolizer was set up to take a combined flow of roughly 15L/min, which is similar to the planned use case. The problems that arose were that the particle suspension was never aerosolized properly, even in the control trial. We speculate that the reason for this is that the particle suspension that we used was old and had never been tested. The research group focuses almost solely on the nanoparticle size range and perhaps the aerosolizer may not work fro heavier particles which may collect at the bottom of the chamber. Even with the exactly flow-rates that are normally used in the machine, there was no noticeable increase in the desired size range.

Because the pump incorporated into the OPC was too weak, only major flows of less than 7L/min were able to be pulled. Otherwise, the minor flow would be drawn in the opposite direction; this has a chance of hurting the OPC machine so we sought to avoid this situation if possible. This was another potential source of error which rendered the tests inconclusive.

5.5.3 Smoke pen + OPC

In order to make sure that the issue with the previous experiment was related mostly to the particle suspension aerosolizer, we instead used a smoke pen to create particles. The control for this test successfully showed increased concentration of various particle sizes including the desired range of around 3-5microns. The issue is that the particle production is unstable and the distribution is unpredictable. Additionally, when the virtual impactor was plugged in, the initial combined flow of around 8-15L/min very quickly consumed all of the smoke in the 2L flask and the readings of PM continued to decrease from the start of the test. This prevented us from obtaining valuable test trials. This, combined with the issues regarding the OPC pump discussed in the previous tests led the experiment to also be inconclusive.

5.5.4 Barriers to further testing

While we had fully planned and allotted time for the further testing of the growth tube and full system, the delay of delivery of the PVA sponge/wick disrupted these plans. As a crucial part of the growth tube, we were unable to perform testing without this crucial specialize part. Attempts to create a temporary sponge/wick from the available samples were made, however the material was the wrong dimensions and did not respond well to machining or other modifications. The cause of this late delivery was a delay in payment approval from SU and a delay in shipping from the small company which we order from. The procurement process for this specialized item had been initiated over two months prior, so without these abnormal delays, the procurement process would have finalized much earlier.

Without the completed growth tube, we were also unable to test the complete system. Our plan was to use the setup of the first experiment (spark discharge and CPC) with a higher flow of 1.5L/min - something we later learned was possible - and including the growth tube. This would have allowed us to have the precise particle generation of the spark discharger and also examine the smaller particles at the outlet. It would have also been possible to instead use the OPC and study the particles at the output before they had been significantly dried at their larger size. These experiments would have given us the chance to truly assess the capabilities of our particle concentrator and tune the major flow amount to our exact desired particle size. Now that we are unable to perform them within the scope of this project, we suggest that these tests are the first step for the next researchers who take on this project.

5.6 Manufacturing factors

The initial design of the virtual impactor incorporated small holes with stringent surface specifications on their interiors. Preceding these holes were chamfers at non-standard angles. Following consultations with the Prototype Center at KTH, a decision was made to enlarge the apertures. Subsequent discussions with the manufacturer "Metallic AB" led to a modification in the chamfer angle and a transition to a material available in their inventory. The material switch aimed to expedite part manufacturing, ensuring adherence to project timelines for the timely initiation of testing.

Following discussions with the Prototype Center at KTH, a decision was made to alter the cooling block design from a two-part structure to a single part, as seen in Section 3.6.5. This modification aimed to enhance heat transfer between the aluminum cooling block and the aluminum pipe of the growth tube. Concerns were raised with the original split design, anticipating potential inefficiencies in cooling the pipe due to the disconnected section acting as a separate thermal entity, adversely affecting overall performance.

As outlined in Section 4.5, the specified tolerances on the drawing deviated from the intended range and did not align with the dimensions of the pipe as intended. This discrepancy could have been addressed if the pipe dimensions had been received prior to submitting the drawing to the Prototype Center for manufacturing. In such a scenario, measuring the pipe would have revealed a slight increase in diameter compared to initial expectations. Consequently, the tolerances on the drawing could have been adjusted to accommodate this change in pipe diameter and ensure a proper fitting part.

Numerous components of the machine were fabricated using 3D printing technology. Prototyping iterations were essential to achieve the desired fits and finishes for these parts. The 3D printers utilized were located in the KTH Prototype Center, shared among multiple students, leading to logistical challenges. Occasional unavailability of printers due to concurrent usage posed a constraint on our print scheduling. The standard material for these printers is PLA, but for specific prints, PETG was required. Switching between these materials posed complications, particularly when the transition back to PLA was not executed seamlessly, resulting in printer issues. Furthermore, variations in print quality emerged among different printers, leading us to favor those yielding superior results. Efforts were made to coordinate print colors, adding an additional layer of complexity in printer selection. Despite these challenges, the project timeline remained unaffected, and the prints were completed as scheduled, meeting the desired fit and finish criteria.

6 Conclusion

In this report, the motivation behind the development of a compact and portable particle concentrator was provided. Then, the design, manufacturing, assembly, and partial testing of the functioning first prototype the particle concentrator was detailed. Unfortunately, if the particle concentrator is fulfilling its performance requirements can not be stated at this moment. For that to be determined thorough testing of the device with all of its subsystems running has to be performed. All of the materials and instructions necessary to do these tests have been provided to the sponsors at Stockholm University, in addition to all of the supplementary materials and previous designs.

The sponsors of the project from Stockholm university are satisfied with the outcome of this project. The size and weight requirements that were determined in the beginning of the project were achieved with a focus on durability and modularity. Stockholm university now have a particle concentrator available for themselves which is an improvement compared to before when the particle concentrator that was used was borrowed for short periods of time.

The main obstacle that was faced during this project was complicated procurement processes and late deliveries. That is the sole reason why no testing was conducted for the particle concentrator in its entirety.

6.1 Maintenance and Repairs

The machine has a few areas which should be regularly checked and maintained:

- Growth tube water bottles - fill/empty
- PVA Sponge - hydrating
- Virtual Impactor - cleaning
- Dryer - silica gel
- Major flow water trap - empty

Growth tube water bottles - fill/empty

In order for the growth tube to properly function, the intake water bottle must be refilled as it drains. The water entering the growth tube will then be deposited into a second water bottle which should be emptied. This allows for the continuous hydration of the PVA sponge inside the growth tube.

PVA Sponge - hydrating

If the machine is not used for a long period of time, it made be useful to remove the PVA sponge from the inside of the growth tube and hydrate it by submerging it in luke warm water before the next use. This will occur much quicker than letting the water gravity feed through the tube as the sponge is extremely absorbant and therefore take a large amount of water to saturate.

Virtual Impactor - cleaning

Since large amounts of air and particles flows through the VI at high speeds, it is likely that dust will collect on the inside of the machine after prolonged use. It is good practice to therefore clean the inside of the device regularly to retain optimal performance.

Dryer - silica gel

The silica in the dry will gradually absorb moisture and change from Orange to clear. Once this happens, the silica gel must be taken out by removing one of the two caps, then it must be dried or replaced. Place the cap back on making sure that the inner mesh is properly seated, then reattach the tubing connections.

Major Flow Water Trap - empty

Similarly, the water trap/filter in the major flow must be routinely emptied as it collects moisture. This can be done by unscrewing the small cap next to the inlet and pouring the excess water out. The cap should then be replaced.

6.2 Future work

This project was conducted within the scope of the SU research group's goal of studying nanoparticle air pollution in subway tunnel platforms. In the future, this same setup could easily be used to test the toxicity of NP pollution in different locations and scenarios. This could be within the transportation sector, such as near highways or a busstops, or even outside the transportation sector (i.e. near incineration plants or industrial facilities).

A potential issue with the functioning prototype are the cooling modules of the growth tube. As of right now the cooling module only consists of one peltier module. It has been noticed that it takes a long time for the device to reach the cold working temperatures of the growth tube. This issue could potentially be solved in several different ways. More powerful peltier modules could be used, adding additional peltier modules could also improve the cooling efficiency or a combination of the two might also be possible.

Another part of the particle concentrator that could be optimized are the electronic components of the particle concentrator, some of the improvements that came to mind during assembling and initial testing of the device was that it would be better if the electronic components used the same voltage and amperage, this would result in fewer power supplies and less parts overall and also a lower total weight of the particle concentrator. Apart from the power supplies a custom circuit board would with the ability to turn on and off different subsystems of the particle concentrator. For example, it could be beneficial to be able to activate the growth tube before other subsystems since it needs some time to reach the different working temperatures of the cooling and heating zones.

The dryer that was designed for the particle concentrator is also something that could be improved for next iterations of this particle concentrator. The main concerns being that to refill the silica gel, much disassembling is required and the fact that it is unknown if the dryer contributes to any significant particle loss.

The part of this project which needs the largest form of improvement is the testing of the particle concentrator. This includes both a total system test as well as individual testing of the different subsystems such as the growth tube, virtual impactor and the dryer. Without these tests it is not possible to determine an accurate concentration factor for the particle concentrator, which is problematic since one of the performance requirements is that the particle concentrator is supposed to have a concentration factor equal to or greater than 5 times.

A long term test and on-site testing would also be helpful to recognize other potential improvements that are still unknown.

A subsystem test that would be crucial to optimize the concentration factor would be a comprehensive test of the virtual impactor and how different nozzle gaps affects the concentration factor of the virtual impactor and the particle concentrator as a whole.

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A Document Numbering

All CAD files/documents (parts, assemblies, sub-assemblies and drawings) each have their own unique document number. The document number has the following format.

KTH-HK-02-2023-xx-yyy

Where "xx" is the first level sub-assembly. "xx" is determined according to the following table, Table A.1. For assembly or sub-assembly files, the document number will omit the "yyy" portion. This is because the "yyy" portion is reserved for part files only.

Table A.1: Part number convention

Sub-assembly/Module	Number Series
Main Assembly	00
Structural Frame	01
Growth tube	02
Virtual Impactor	03
Electronics	04
Air equipment	05

If required, and extra number sequence can be added before the "yyy" section of the part number. This would be done if there is a sub-assembly within another sub-assembly.

A.1 Document number examples

The following table, Table A.2, shows some example parts and their part numbers.

Table A.2: Example document numbers

Part Description	Document Number
Main assembly	KTH-HK-02-2023-00
Structural frame weldment	KTH-HK-02-2023-01-01
A member making up the structural frame weldment	KTH-HK-02-2023-01-01-001
The bottom section of the virtual impactor	KTH-HK-02-2023-03-002

B Concept Evaluation

		Concepts		
Criteria	**Weight (1-5)**	**Concept 1: Water Bath**	**Concept 2: Saturated Sponge**	**Concept 3: Ultrasonic**
Reliablity	4	Reference	+	-
Manuverability (tilt)	4	Reference	+	+
Cost	1	Reference		-
Manufacturability	5	Reference		-
Adjustability	3	Reference		+
Complexity	3	Reference	-	-
Maintainability	4	Reference	-	-
Ease of use	3	Reference		
Integration	1	Reference		-
	Sum Positives (+)	0	2	2
	Sum Negatives (-)	0	-2	-6
	Sum Neutrals ( )	0	5	1
	Total Score	0	0	-4
	Sum Weighted Positive (+)	0	8	7
	Sum Weighted Negative (-)	0	-7	-18
	Total Weighted Score	0	1	-11
	Concept Ranking	2	1	3

		Concepts		
Criteria	**Weight (1-5)**	**Concept 1: Water Bath**	**Concept 2: Saturated Sponge**	**Concept 3: Ultrasonic**
Reliablity	4	3	4	1
Manuverability (tilt)	4	2	5	4
Cost	1	5	4	2
Manufacturability	5	4	4	2
Adjustability	3	3	3	5
Complexity	3	4	3	1
Maintainability	4	5	3	3
Ease of use	3	3	3	3
Integration	1	3	3	1
	Sum	95	99	71
	Concept Ranking	2	1	3

C Project Charter

Project Name	Design of a concentrator for airborne particles	**Project code**	MF207X
Start date	09 February 2023	**End date**	19 December 2023

Sponsor	**Team members**
KTH	Erika Erdhage
Project manager	Jed Bramley
Joel Nilsson	Joel Nilsson
Support	Theo Zemack
	Lucien Wallace

Goals and objectives	**Scope**
• Design and manufacture a working particle concentrator.	• Team members will design and manufacture the device. • Testing will be performed with the team members and researcher from SU. • SU will use the device after the project.

Approach
• Concept generation. • Detailed design. • Manufacturing and testing.

Milestones
• Final concept decision. • Manufacturing drawings complete. • Fully assembled concentrator. • Testing and configuring complete.

Deliverable	Completion Criteria
• One fully operational concentrator. • Written reports. • Final project presentation.	• Particle concentration $\geq 5\times$. • Submitted written report. • Final project presentation complete.

Risk and Issues:
• Time scope. • Budgeting.

D System Overview

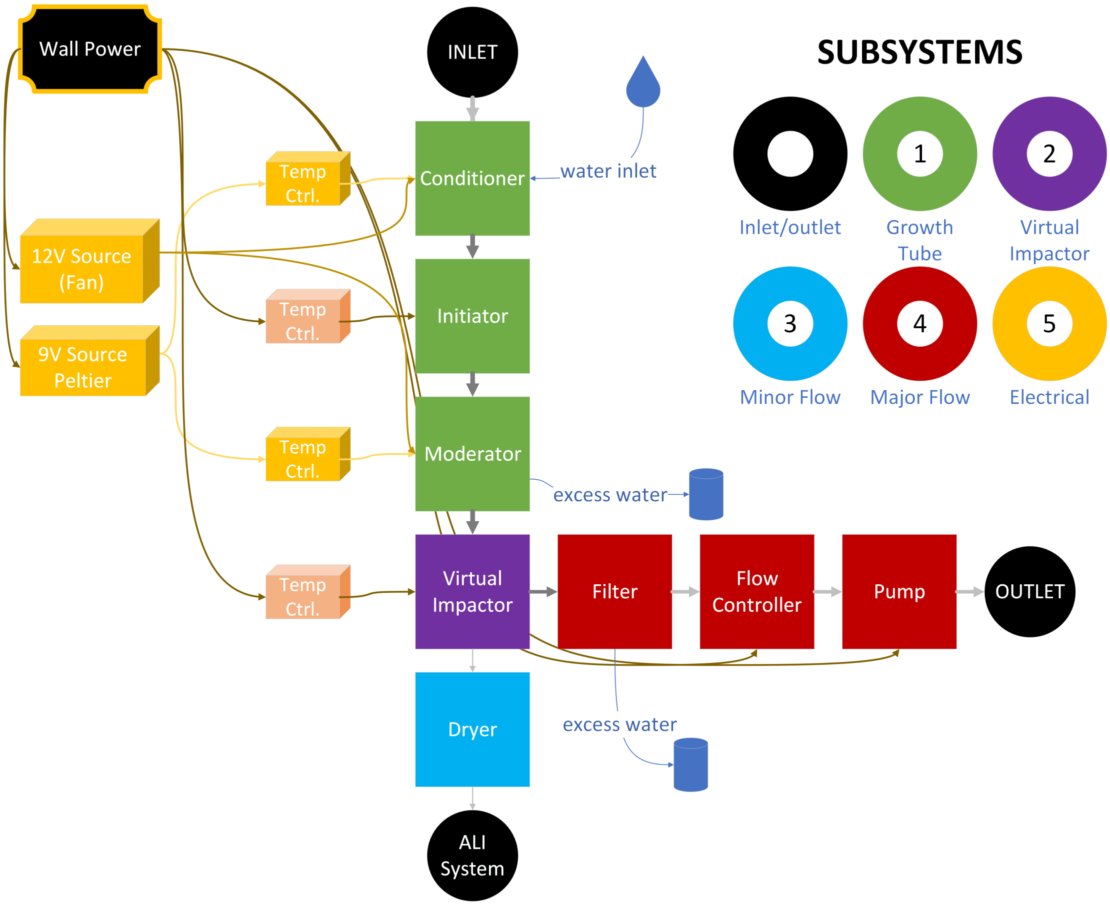

Figure D.1: Block diagram of the complete system

E Growth Tube Calculations

The following pages show the calculation steps of the growth tube's length. Calculations were performed using PTC Mathcad Prime. The length of the growth tube was based off of a CPC's wick material but scaled up. To to this the time required for air to pass through both tubes (growth tube and CPC) was kept constant. The length of the growth tube was the only free variable, the maximum flow rate and the inner diameter are fixed. As the diameter of the tube and the flow rate increased, the length had to increase in order to keep the transit time of the air constant.

Growth tube length Calculations

CPC Dimensions:

$Q_1 := 0.3 \frac{L}{min}$ Flow rate through CPC

$d_1 := 4.6\ mm$ Inner diameter of the CPC wick

$l := 112\ mm$ Length of the combined heating and cooling zones

$v_1 := \frac{4 \cdot Q_1}{\pi \cdot d_1^2} = 0.301 \frac{m}{s}$ Flow speed through the CPC

$t_1 := \frac{l}{v_1} = 0.372\ s$ Dwell time in the CPC wick tube

Sponge dimensions:

$Q_2 := 16.5 \frac{L}{min}$ Combined major & minor flow (maximum flow rate through the growth tube)

$d_2 := 20\ mm$ Inner diameter of sponge

l_2 is unknown Length of sponge

$v_2 := \frac{4 \cdot Q_2}{\pi \cdot d_2^2} = 0.875 \frac{m}{s}$ Speed of air flowing through sponge tube

$l_2 := v_2 \cdot t_1 = 325.864\ mm$ Length of sponge