Development of a high flow aerosol sampling device

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Abstract

Small biological airborne particles (aerosols) reside in the atmosphere and can influence human health, the climate and the environment. Whereas aerosol sampling technology is well-known, there is currently no satisfactory high-volume flow impinger for health and atmospheric monitoring applications. The aim of this thesis was to design and construct a working prototype of an impinger, a sampling device that collects aerosols from high air flows. It was to be based on a prototype impinger taken from the water of an Kärcher DS 5.800 vacuum cleaner.

The designing methodology used here was based on The Ulrich & Eppinger Generic Product Development Process. A 3D CAD-model of the water tank of the vacuum cleaner was created in Creo Parametrics, and thereafter imported in fluid simulation software (Autodesk CFD 2017) to predict fluid interactions inside the mixing chamber of the tank. Based on results from CFD analysis of the water tank and demands derived from interviews, specifications for the product were established and three main solutions concepts for the impinger were developed. Changes were made in an iterative process, and small adjustments were made in a CAD model for each concept, which were later simulated in CFD and evaluated. Two prototypes were developed. A 3D prototype was made to convey the visual design intention of the final product. A physical prototype was 3D printed and on which tests were performed to visually examine air and water mixing, water losses during operation and ergonomics.

The developed impinger prototype worked as well as the simulations, had higher inlet efficiency than the original prototype impinger and was far more ergonomic. However, water losses remain high and this needs to be addressed in further work.

Keywords: Bioaerosol sampling, impinger, high-volume flow, aerobiology, airborne bacteria, bioaerosol sampler, aircraft-borne sampling

Sammanfattning

Små biologiska luftburna partiklar i atmosfären kan påverka människors hälsa, klimatet och miljön. Tekniken kring aerosolprovtagning är välkänd men det finns för närvarande ingen tillfredsställande högvolymsprovtagare för luft i atmosfären och i sjukvårdsapplikationer. Syftet med denna avhandling var att designa och konstruera en fungerande impingerprototyp, dvs en luftprovtagningsanordning för att samla aerosoler från höga luftflöden. Designen skulle baseras på en prototyp som bygger på vattentanken i en Kärcher DS 5.800 dammsugare med vattenfilter.

Den designmetodiken som använts här baserades på The Generic Product Development Process så som den är beskriven av Ulrich & Eppinger. En 3D CAD-modell av dammsugarens vattentank skapades i Creo Parametrics, och importerades därefter i ett fluidsimuleringsprogram (Autodesk CFD 2017) för att förutsäga fluidernas beteende inuti vattentankens blandningskammare. Baserat på resultat från CFD-analysen av vattentanken och användarkrav från intervjuer, fastställdes kravspecifikationer för produkten och tre lösningskoncept för impingern utvecklades. Arbetet utfördes i en iterativ process där små ändringar gjordes i en CAD-modell för varje koncept, som senare simulerades i CFD och utvärderades. Resultatet blev två prototyper. En 3D-prototyp gjordes för att visa slutproduktens visuella design. En fysisk prototyp var 3D-printades och på vilka tester utfördes för att främst visuellt undersöka luftflöden fluidblandningen inuti blandingskammaren, men även vattenförluster och ergonomi hos impingern undersöktes. Lösningsförslaget på impingern fungerade snarlikt simuleringarna, hade högre uppsamlingsförmåga än den ursprungliga prototypen och var mycket mer ergonomisk. Vattenförlusterna visades sig emellertid höga och denna förlust måste tacklas i fortsatt arbete.

Nyckelord: Bioaerosol provtagning, impinger, högvolymflöde, aerobiologi, luftburna bakterier, bioaerosol sampler, flygplansburna provtagningar

Preface

This report is the result of a master thesis in Mechanical Engineering carried out at the Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Faculty of Engineering LTH, Lund University in collaboration with Department of Environmental Science, Aarhus University.

We would like to express our gratitude to our supervisor Jakob Löndahl and assisting supervisors Ulrich Bay Gosewinkel and Olaf Diegel for all their valuable input, patience and persistent support along the way. We would also like to thank PhD Aneta Wierzbicka and Lovisa Nilsson for their humility, helpfulness and being additional resources for ideas.

It is our great hope that the work we've put into developing this device will be useful in further advancements related to bioaerosol sampling.

Lund, June 2017

Hamza Licina & Saman Souzani

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1 Introduction

1.1 Background

Small biological airborne particles such as bacteria, pollen, fungal spores, allergens from organic residue and viruses, are omnipresent in the atmosphere (Kulkarni, Baron and Willeke, 2011). Due to their small size, they can reside in the atmosphere for a long time and be transported by wind over long distances. It has been suggested that these particles can influence the environment, climate and public health over large areas. For example, bacterial presence in the air can influence cloud formation by acting as ice nuclei and cloud condensation nuclei. Another example is diseases from virus and bacteria being spread through the atmosphere over small distances. It has also been reported that storms of yellow sand dust containing microbiological material, caused detrimental effects to the respiratory system (Burrows et al., 2009). To understand the behaviour of these particles, they must first be collected in aerosol samplers.

Aerosol sampling technology is nothing new. One of the first particle collection devices was laid out by Pouchet in a presentation to the Academy of Sciences in Paris on April 16, 1860. While he provided no sketches, the description implied that the sampling instrument worked by pumping air into a tube that contained a glass plate with a sticky coating. Airborne particles would stick on the glass plate allowing analysis in a microscope (Marple, 2004).

Even with over 100 years to mature, some challenges with aerosol sampling technology remain. The need to sample certain environments, which contain a low concentration of microbiological cells, is not adequately met by current equipment. The atmosphere, with very low bacteria concentrations, put serious restrictions on sampling equipment. A sampler working in such environment needs to accommodate either high air flow rates or very long sampling times, to obtain enough particles for analysis.

1.2 Problem statement

Aerosol and microbiology scientists at Lund and Aarhus University have expressed a need for a new kind of sampling device. It should collect aerosols from high air flows. The aerosols should be preserved in the liquid for later analysis. The sampling device should be user friendly, accurate, and allow later biological analysis.

1.3 Aims and limitations

A prototype impinger exists and has been tested and found satisfactory overall. This prototype is based on the water tank from the Kärcher DS 5.800 series vacuum cleaner. The prototype has good particle retention ability and can work with the required high flows. But there are some remaining challenges with the prototype. The objective of this thesis was to:

- Perform a CFD analysis on the water tank and identify trouble spots.
- Establish the required functional demands on the instrument.
- Provide solutions to the required functions.
- Select the most promising design solution and present a working prototype. The solutions will be presented as a comprehensive 3D prototype and focused physical prototype for testing.

Limitations of this work are the simplicity of the tests conducted on the physical prototype. Biological analysis of samples taken by the prototype was not made due to the early stage of the product. Challenges that remain with the proposed solution will mark as recommendations for further development. The scientific contributions of this thesis are the CFD simulations on the flows in the prototype and how well these correspond to the flows in the physical prototype. This work will not consider how the aerosols will be drawn from atmosphere and transported to the impinger inlet. This is a separate problem that would require full attention.

2 Theoretical background

This chapter will present a short introduction to aerosols and their properties, strategies to collect them, technical instruments used for their collection, as well as the technologies used in the design process of the prototype during this work.

2.1 Collection of bioaerosol particles

An aerosol is a mixture of liquid and solid particles suspended in a gas. In the context of this thesis, that gas will be air. Aerosols can be of various shapes and sizes. In the technical sense, the term aerosol is much broader than droplets from a spray can. A subset of aerosols is the so called bioaerosols, which have a biological origin (Vincent, 2007). This group includes viruses, pollen, bacteria, fungal spores and their fragments (Kulkarni, Baron and Willeke, 2011). When bioaerosol sampling is concerned, the bioaerosol particles could be grouped into:

- Single spores, pollen grains, bacterial cells or viruses.
- Massed clumps of spores, cells or biological material such as allergens.
- Fragments or parts of spores, cells or other biological material.
- Biological material carried by nonbiological particles.

The particle size is an influential factor for aerosol measurement. This property determines the behavior of the particle in a gas. For bioaerosols, the size range is typically between 0.01 - 100 µm. The size of a spherical particle can easily be specified by a single dimension, such as the geometric diameter. Since most aerosols are not spherical, they can be approximated by an equivalent particle size, for which there are several options. One method is *equivalent volume diameter* (d_v)*,* which is the diameter of a sphere with the same volume as the particle in question. For particles, larger than 0.3-0.5 µm in engineered devices such as cyclones and impactors, the *aerodynamic equivalent diameter* d_a (equation 1.1) is the most common approximation. It is defined as the diameter of a spherical particle of a unit density having the same gravitational settling velocity as that of the particle in question.

$$d_a = d_p \sqrt{\frac{\rho_p}{\rho_0}} \tag{2.1}$$

Here ρ_0 is standard density of 1000 kg/m^3. There are many other methods to describe non-spherical particle size, but that topic is beyond this work. The aerodynamic equivalent diameter of the particle influences the collection method as particles with d_a lower than 100 nm are prone to a certain way of moving due to collision with gas molecules. This movement is called the Brownian motion and the smaller the particle is, the greater the movement and the more likely that the particle will diffuse, meet a surface and adhere to it. Once this occurs, the other suspended particles will occupy the space left vacant by the particles that has adhered to the surface. Because of this phenomenon, filtration is an efficient method to collect small particles. Particles with higher aerodynamic equivalent diameters are less influenced by Brownian motion and have higher inertia (Verreault, Moineau and Duchaine, 2008).

As for bioaerosol collection, (Vincent, 2007) suggests two common sampling strategies when occupational hygiene is concerned. In such cases, sampling can either be performed on an area or on a personal basis. Area sampling is static and involves the measurement of aerosols in the working environment, showing the concentrations that are representative of those locations. Personal sampling involves measuring bioaerosols close to the human body, by placing samplers near the human respiratory apparatus. Another way to characterize bioaerosol sampling is with passive or active sampling systems. Active sampling systems usually involve mechanical components that transport air through the device (C.W Haig et al, 2016). Active and passive systems will be discussed in detail later. However, when sampling in non-industrial environments, the sampling strategies become more complex as no single sampling method can collect all of the bioaerosols in a certain environment (Kulkarni, Baron and Willeke, 2011).

There are additional classifications that are used when bioaerosol sampling is concerned. Organisms in an aerosol sample can be either viable or nonviable. Viable organisms are metabolically active and may be either culturable or non-culturable. Culturable organisms are growable and may reproduce when subjected to nutrients and a fitting environment. On the other hand, nonviable organisms are not metabolically active and are not capable of reproduction. They are therefore not culturable.

In the terms of sampling, this can mean that culturable organisms are to be collected into a medium that allows them to survive and later grow. Usually that medium is agar supplemented by buffers and nutrients. For some modes of sampling, the organisms can be collected in a suitable liquid medium. This medium must be compatible with the organisms sampled, but prevent them from multiplying.

Typical liquid media are distilled water or buffered salt solutions. As for the non-culturable organisms, these may be collected on an inert surface such as a greased flat surface and later subjected to light microscopy observation (Vincent, 2007).

2.2 Aerosol samplers

Aerosol sampling technology depends on the aerodynamic diameter, inertia and adhesion properties of the airborne particles bit also Brownian motion and thermal gradients. Aerosolized particles can attach to any surface that they encounter. Adhesive forces such as electrostatic forces, van der Waals and surface tension may partly explain this adhesion (Verreault, Moineau and Duchaine, 2008). Most of the sampling devices presented in the following section are based on these principles.

According to (Kulkarni, Baron and Willeke, 2011), a device that collects bioaerosols can be evaluated according to three factors:

- The inlet sampling efficiency
- The particle removal efficiency
- The biological collection efficiency

The first factor depends on the inlets ability to collect particles from the air environment. This is influenced by the size, shape and aerodynamic properties of the particles being collected. The second factor is based on the collector's ability to remove particles from an airstream of its inlet and deposit them into a collection medium. The third factor requires the collector to sample biological particles without changing their viability or biological activity. To satisfy these three factors, the collector should avoid long tubing between the inlet and collection medium, in order to avoid particle losses the tube walls. The inlet should be turned towards the airflow and the inlet air velocity should be equal to the ambient air velocity. As discussed earlier, devices that collect bioaerosols are classified into passive or active samplers. This will be described in the following section.

2.2.1 Passive samplers

Passive samplers are the cheapest, easiest and least obtrusive systems to use when sampling bioaerosols. The method is based on the particles settling on a collection plate, by the means of gravity. The collected particles, are commonly quantified in the number of colony-forming units (cfu) within the area of the settling plates for a specified time period, for example in units such as $(\frac{cfu}{m^2}h)$. Since no mechanical equipment such as pumps is used, passive samplers do not disturb the surrounding air and they make no noise. The speed of particle as it descends in still air (settling velocity) is dependent on particle size and density. Small and light particles can remain airborne for longer times than larger ones, and in a situation where the air speed exceeds the settling velocity, the particle will remain suspended in the air (Haig et al., 2016). A basic example of passive sampling is a cylindrical container with a hole at the top and collecting medium in the bottom. This device collects aerosols by simply letting them fall inside (Vincent, 2007). Attempts of standardizing passive sampling exist and one method described is the 1/1/1. This is done by placing Petri dishes at a height of 1 m above floor level, 1 m from a wall during 1 hour of exposure to measure microorganism contamination in a hospital. While simplicity and low cost are advantages of passive sampling, it is an inaccurate method and it is impossible to determine the sampled air volume (Haig et al., 2016).

2.2.2 Active samplers

However, not all organisms can be collected with by utilizing their own inertia and gravity. In some cases, a more useful approach is by drawing a particle laden air stream into the collector, then detaching particles from the airstream and lastly depositing the particle in a liquid or a collection surface. The detachment could be made by accelerating the air stream through small holes and slits and then abruptly changing the flow direction. The inertia of the larger particles forces them to deviate from the air flow and impacts them on a surface. (Vincent, 2007). This principle is utilized in the active samplers such as the impactors, cyclones and impingers described in sections below.

2.2.3 Impactors

Impactors use the inertia of the particles to facilitate collection (Haig et al., 2016). Examples of impactors include the Rotorod, Andersen sampler, slit to agar sampler. The simplest impactors employ the inertia of particles moving in the air relative to a stationary surface, which causes the particles to be deposited to the surface. In such cases, the air is moving slowly relative to a collecting surface. Instruments using this principle are the Rotorod sampler (Vincent, 2007). This instrument has two collecting surfaces in the shapes of arms which rotate rapidly in slow moving, almost stationary air. The particles are discharged onto sticky tape found on the collecting surfaces of the arms. The sticky tape with the particles can later be removed and studied. The drawback of the Rotorod is that the sampling flow rate cannot be measured. It also requires unobstructed airflow to function.

An ideal impactor should work like a sieve and collect all particles above a certain size, called the cutoff size. Particles under the cutoff size are let through. This makes impactors particularly suitable as particle size classifiers as they separate particles greater than a given size from the air flow (Haig et al., 2016). The ability to sort particles according to size is exploited in the Andersen cascade impactor (Figure 1). These devices are divided into several stages through which the airstream must pass and each successive stage collects particles of smaller and smaller size. The separation is done by each stage accelerating the incoming particles. The first stage induces moderate acceleration so that only the largest particles are detached. The second stage accelerates the smaller remaining particles even more, and it keeps going in this manner until the air reaches the last stage. And here lies the main advantage of the Andersen sampler, the ability to determinate the size of the particles and sort them accordingly.

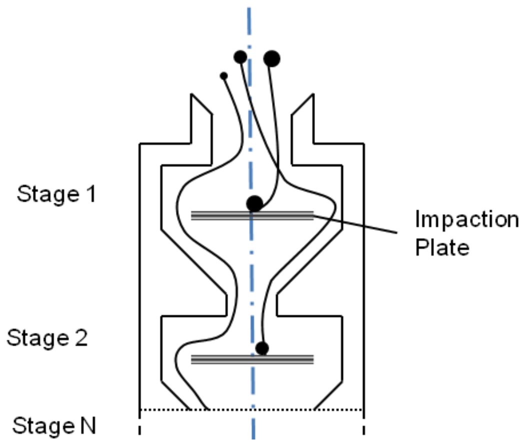


Figure 1. A schematic sketch of an Andersen sampler on the left (Benjamin Haywood, 2015). As an impactor, it works by forcing the air stream to change direction quickly. Because of their inertia, particles over a certain size cannot follow along and impact on the collection plate (Image: Benjamin Haywood, 2015). A physical copy of the Andersen sampler is seen on the right.

Another impactor variant is the slit sampler (Figure 2). Bioaerosol slit samplers are usually used to determine aerosol concentration of bacteria as a function of time. In this type, the accelerated particles are impacted on a slowly rotating petri dish containing a culture medium. This makes it possible to determine the time when each particle was sampled.

The collection efficiency of impaction samplers is usually higher for larger particles. However, some samplers, such as the Andersen cascade sampler, can collect particles with size down to the 0.65 µm range (Verreault, Moineau and Duchaine, 2008).

Figure 2. In a slit sampler, bioaerosols are impacted on a rotating disc seen here on the top.

2.2.4 Cyclones

Another principle of aerosol collection is using centrifugal forces to detach particles from the air stream and impact them on a radial geometry. This is used in the cyclone samplers (Figure 3). The walls where the particles are to impact are usually wetted surfaces and in some cases covered in a nutritional medium. In similar way to cascade impactors, cyclones can lead the air stream into multiple stages and separate particles by size. The cyclones can work with higher airflow rates than the other samplers (up to 1000 L/min), but according to some studies, they are less efficient than other samplers to recover low concentrations of airborne bioaerosols. This might be due to the physical stress caused by the cyclone as it presses bioaerosols towards the walls, where bioaerosols can get damaged or destroyed (Verreault, Moineau and Duchaine, 2008). As cyclones are effective in removing larger particles, they are often used as precleaners for a final collection device (Wierzbicka, 2008).

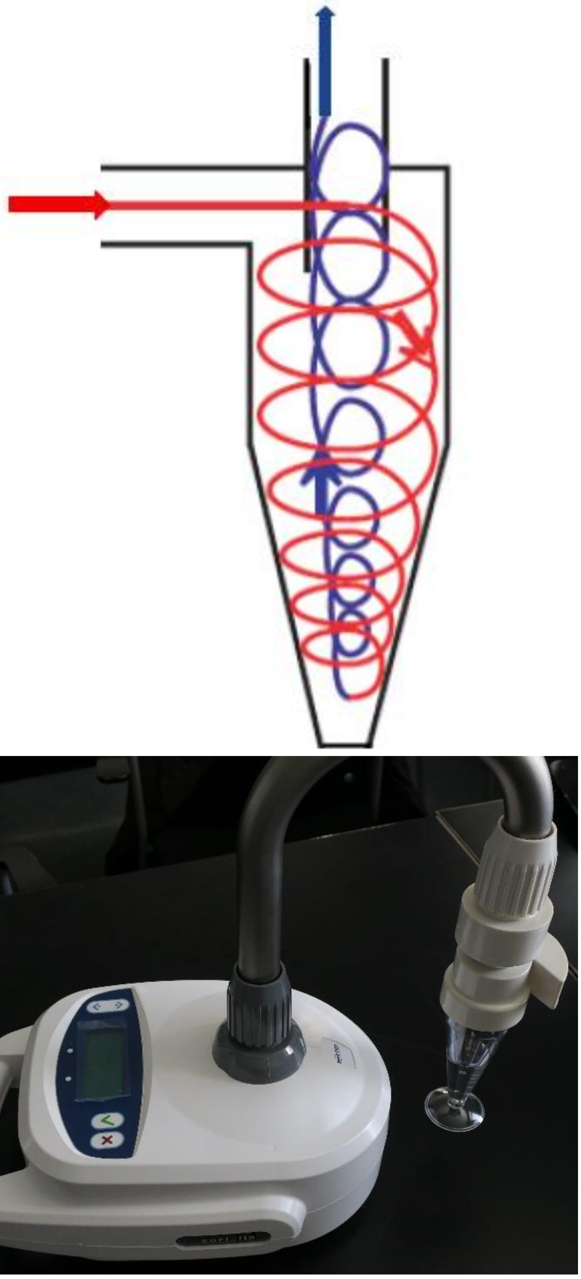


Figure 3. The cyclone works by using centrifugal forces to impact particles from the incoming air (red) into the walls. As the conical bottom decreases in radius, smaller and smaller particles are separated. The air at the narrow end (blue) is led into the center of cyclone to the exit.

2.2.5 Liquid impingers

Impingers operate by forcing the aspirated air through a liquid medium (Figure 4). The particles are primarily collected by inertial impaction into the liquid but also by particle diffusion from the particle loaded air bubbles to the liquid. Liquid impingement is also the basis for the device developed during the work of this thesis.

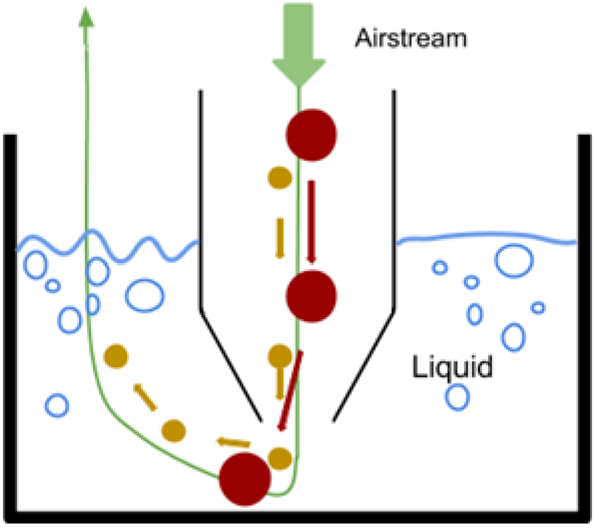


Figure 4. In liquid impingers, particle-laden airflow is channeled through nozzles into a liquid where they are collected.

A common impinger variant are the All-glass Impingers (AGI), also called Porton impingers. These work by accelerating aerosols through a narrow orifice placed at a fixed distance from the bottom flask containing a liquid. A pressure drop is created in the flask which forces the air to enter through the inlet of the impinger. The air enters horizontally through a glass tube inlet which curves to a vertical position, forcing the air to change direction and flow downward. The diameter of the tubing abruptly narrows down towards the outlet and accelerates the air passing through it. The flow in the impinger remains constant as long as the pump provides suction. The largest particles exiting the glass tubing are then impacted into the liquid. Small bubbles formed in the impinger can also cause particle deposition by diffusion. Sampling flow rates are around 30 L/min for the AGI impinger (Verreault, Moineau and Duchaine, 2008).

Liquid impingers can be made in a multistage configuration as well, commercially available as the Multi-Stage Liquid Impinger. In similar fashion to the Andersen sampler, these variants can sort particles according to their size. Sampling flow rate for this variant is between 30-100 L/min (Copleyscientific.com, 2017). A problem with this sampler is that it is made of glass so manufacturing it with correct tolerances can be difficult.

The AGI impingers have been further developed by changing the number and position of nozzles through which the air is forced into the liquid. Dubbed as the SKC Biosampler, the inlet glass tube ejects the incoming air tangentially to the bottom from three orifices, instead of having one tube forcing the air directly to the bottom of the flash. This new feature induces a circular motion in the sampling liquid, which has turned out to be a less violent and destructive way to sample bioaerosols. Sampling flow rate for the SKC Biosampler is 12.5 L/min.

The advantages of liquid impingers is that they are the least destructive samplers and have high sampling efficiency. The drawbacks are that there is a chance for reaerosolization if the particles collected are hydrophobic and latch on into small air bubbles formed in the sampling liquid (Verreault, Moineau and Duchaine, 2008). By latching on to the bubbles, the particles can avoid the liquid and escape the sampler through the outlet. If the liquid is water, condensation can probably affect the sample in some way. The AGI and SK Biosampler impingers are reported to have very low efficiencies in recovering particles in the 30 to 100 nm size range (Verreault, Moineau and Duchaine, 2008).

2.2.6 Other sampling systems

Most samplers have difficulties in trapping small particles with aerodynamic equivalent diameters less than 500 nm. For such endeavors, the method of sampling directly to filters is used. As other active samplers, filters require a pump to draw air through them and sometimes a cyclone is placed at the inlet to screen for particles of a selected size. Filters can consist of fine fibers or membranes with a pore like structure. They work by capturing particles that pass through them (Haig et al., 2016).

Filter collection is not commonly used in sampling airborne bacteria as it has several drawbacks (Cooper, 2012). Filter collection is known to cause structural damage in bacteria. It can also be difficult to remove the sample from the filter. There is a tendency of the filter to retain the sample so extraction could significantly reduce the amount of sample available for later analysis (Verreault, Moineau and Duchaine, 2008). However, in some attempts filter collection of bioaerosols proved to be successful (Haig et al., 2016).

Another method worth mentioning is electrostatic precipitation. On entering the inlet of an electrostatic precipitator, the bioaerosol particles become electrically charged. They then pass through an electric field where they are separated from the air flow and deposited on to charged plates (Haig et al., 2016). A particularly interesting case is the *Litton Large Volume Electrostatic Air Sampler (LVEAS)*. This device can work with flows up to 10 000 L/min. In this sampler, the collection surface is a rotating metal disk, in the centre of which a liquid medium was pumped in. As the disk rotates rapidly, the liquid spreads out as a film that covers the whole surface of the plate. The LVEAS is complicated to operate and it produces ozone at high relative humidity. It is unclear if this combined with the intense electric fields, can damage bioaerosols (Vincent, 2007).

2.3 Psychrometrics

Psychrometrics is the field which describes the physical properties and relations in gas and vapor mixtures. During the design work here, it was important to find out the properties of the atmospheric air entering the impinger. Of particular interest is how the air stream could reduce the amount of sampling liquid during operation of the impinger. Atmospheric air can be described as a mixture between dry air and water vapor. The amount of water vapor in air can be specified as mass of water vapor present in a unit mass of dry air (equation 1.2). This is called the specific humidity and is denoted by ω or:

$$\omega = \frac{mass_{water}}{mass_{dryair}} \tag{2.2}$$

By this definition, 1 kg of dry air has no water vapour and therefore the specific humidity is zero. As water vapor is added, the specific humidity increases until the air can’t hold more moisture and any moisture added above this limit will condense. Another important concept is the relative humidity ϕ which describes the moisture level at the current pressure and temperature. The relative humidity (equation 1.3) is defined as the amount of moisture in the air (m_v) relative to the amount of moisture the air can hold at the same temperature (m_g). This can be expressed as:

$$\phi = \frac{m_{vr}}{m_g} \tag{2.3}$$

A steady stream of air with lower relative humidity can pick up more water from its surroundings than an air stream with higher relative humidity. To describe the state of the atmospheric air at a specified pressure, a psychrometric chart is used which incorporates the relative humidity, specific humidity and temperatures and displays them graphically. If two independent properties in the chart are known, then others can be determined from these (Cengel and Boles, 2010). Without the chart, numerous laboursome calculations must be made. During the experimental part of this project, the psychrometric chart was used to calculate the mass of the sampling water lost to these phase mixing effects.

2.4 Water filter vacuum cleaners

As the prototype impinger is a water tank taken from vacuum cleaner, a quick explanation of how these works might be in place. A vacuum cleaner consists of a driving electric motor and a centrifugal blower working on a common shaft. In cases where dry suction is used, the principal task of the blower is to produce enough pressure rise and flow to suck dust particles from the floor and transport them into a collection canister. The airflow produced should also pass through the motor and provide cooling. The main difference between dry systems and water filter systems is that the former uses a bag to collect dust particles. Certain dry systems do not use bags but remove the dust by centrifugal motions of the inlet air, a similar principle to cyclone impingers. The water filter system on the other hand, leads the particle-filled inlet air through a water tank before the air is exhausted. Wet dust becomes heavy and it doesn't stay airborne easily, meaning it stays in the water tank. Water filter systems can also work as air humidifiers (Cudina and Prezelj, 2007).

2.5 Prototyping technologies

There are hundreds of different production technologies that are used to create prototypes (Ulrich and Eppinger, 2012). In this thesis, a number of CAD models representing the design solutions to problems, will be generated. Fluid mechanic analysis will be performed on the models with CFD and then they will be produced with 3D printing or AM technology.

2.5.1 Computer Aided Design

CAD, short for Computer Aided Design, is a software developed and used for design and drafting. It allows a computer to develop, analyze and modify a design, the main benefit of this being that since it is software-based, changes can be implemented easily and cheaply. By keeping the design in the software format for large proportions of the product development cycle, changes will be made on the software itself. In 3D CAD software, the model is constructed from basic geometric shapes that are combined in different ways to make more complex forms. For many familiar engineered products, this is enough but there are limitations in the software when advanced shapes are needed.

Early CAD systems in the mid-70s were extremely limited by the display technology of the era, they could hardly produce anything but numeric text output.

Some early computers had special graphic output devices that could display graphics separately from the text commands needed to drive them. These displays were however monochrome and it was difficult to show 3D shapes. The early CAD technology required several workstations, usually a giant mainframe and several minicomputers. As components for memory and procession were costly, utilizing early CAD systems required ample resources.

Today's CAD software can run on PCs as a result of improvements in computer technology (mainly processing power and graphics capability) but also because of advancements in the way CAD data is presented, manipulated and stored. Most CAD systems today utilize Non-Uniform Rational Basis-Splines or NURBS, a mathematical model to define the curves and surfaces that represent the outer shell of a designed product. A NURB is a function that uses two parameters to create a surface in three-dimensional space, the shape of the surface being determined by control points. The control points are easily manipulated by the user (Gibson, Rosen and Stucker, 2010. In the scope of this thesis, Creo 2 was used as it represents shapes accurately while maintaining physical fidelity.

2.5.2 2.5.2 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) are used to predict either gas or liquid fluid flow. This is achieved by a software tool that utilizes Finite Element Analysis to predict how the velocity, pressure, temperature and other properties of a fluid or gas inside the product will behave. With CFD, the flow of gas or liquid can be visualized, along with how the flow affects the objects it passes.

CFD is a valuable tool in the product development phase. The changes in for example heat or velocity of a fluid can be simulated and necessary adjustments made in the software, before developing the product. The more properties that are known about a product before it is built, the more effective is it going to be. Problems noticed after the product is manufactured can be very costly to address. However, the more complex a product is and the more performance is related to success of the design, it gets more difficult to gain sufficient insights by using only virtual methods. The CAD model imported into the CFD software carries with it tremendous amounts of information to provide design interaction, fast graphics, mass properties and interfaces for other software tools. When a model has large numbers of surfaces, it can be challenging to import from one software to the other. The software used during this project was Autodesk CFD. It could provide information about material properties and utilize these in the simulation.

2.5.3 Additive Manufacturing

One way of quickly creating a prototype from CAD is through additive manufacturing. Additive manufacturing (AM) or 3D-printing as it is sometimes called, is a manufacturing method in which parts are fabricated by an additive approach. Material is added in layers, each layer is a thin cross section of the part derived from CAD data. AM uses the output from the 3D CAD solid modelling software. However, not all CAD systems will provide suitable output for layer based additive manufacturing as it focuses on reproducing geometric form. CAD systems that produce such forms (i.e. solid and enclosed ones) in the most precise way are therefore more desirable. Before being sent to the AM machine, the CAD data is converted into the public domain STL (Stereolithography) format which describes the original surfaces and forms the basis for calculation of the slices. STL uses triangles to describe the surfaces to be built. Each triangle contains three points and a normal vector indicating the outer surface of the triangle.

AM technology simplifies the production complexity as it can produce artefacts directly from CAD data, without a detailed analysis of the part geometry in order to determine in which order different features will be created, what process, tools and fixtures are to be used and so on. In this way, a lot of time is saved and that explains why this manufacturing method is particularly suitable to build prototypes quickly.

Initially, AM technology was only used for Rapid Prototyping (RP), which is quick creation of a system or part representation before final release or commercialization. As capabilities of the AM machines increased, the output from them had much closer links to the final product in terms of performance and form. The technology was at birth developed to work with polymers, waxes and paper laminates. This has now been extended to composites, metals and ceramics.

Commercial AM machines differ from each other in respect to what kind of materials they use, how the different layers are created and how the layers are bonded to each other. These three different factors in turn determine the accuracy, mechanical and material properties of the final product. One way to classify of AM technology is by a two-dimensional method. The first dimension relates to the method the layers are constructed. Early on, a single point source drew across the surface of the base material. Later, the number of sources increased by droplet deposition technology. The second dimension is what kind of raw material the process uses. This could be liquid polymer, discrete particles, and molten material or laminated sheets. According to some authors, this two-dimensional classification method prevents dissimilar processes from being grouped together (Gibson, Rosen and Stucker, 2010).

Going through the different techniques is out of the scope for this work but the device used to print the prototype was the Formiga P 110. It uses selective laser sintering (Eos.info, 2017), a technique where layers of powder are spread across the build area and heated to a temperature slightly under the melting point or glass transition temperature. A laser beam is directed into the powder bed and thermally joins the powder material to form the desired cross section. After a layer is finished, the build platform is lowered by one layer of thickness and a new layer of powder is laid and levelled. The laser beam joins a new set of powder and the process repeats itself until the entire part is created.

Laser sintering is one of the earliest AM processes to be commercialized. The technology has had time to mature and is now able to compete with injection-molding. An advantage of laser sintering is that there the surrounding powder is loose and serves as support for subsequent layers, eliminating the need for secondary supports during the process. Among the drawbacks is that laser sintering is a comparably slow process, even with elevated temperatures involved.

There are three ways sintering can affect the properties of the final product. Firstly, powder particles can begin sinter to one another, increasing the size of the powder particles and changing their properties each time the powder is recycled. Secondly, the temperature difference between the thermally-induced fused part and the rest of the powder can become large leading to that un-melted powder next to the part can be fused into it and grow on it like a second skin. Thirdly, porosity is always a feature in parts made from powder based sintering. This detrimental to the properties of the end product. There are methods to reduce the percentage of porosity and increase material density, one example is by post production temperature manipulating methods (Gibson, Rosen and Stucker, 2010).

3 Method

In this section, the methodology used during the thesis will be described.

3.1 Ulrich and Eppinger product design methodology

The design methodology used are based on the ideas described by Ulrich and Eppinger (2012) as the authors are most familiar to their design theory. It is a sequential method of activities that lead to the realization, design and commercialization of a product. The Ulrich & Eppinger design methodology contains three parts, consisting of how marketing, design and manufacturing can be best be combined to make products that meet the required needs, in short time for a low cost. To accomplish this, the authors suggest concrete plans of actions that are based on industry experience, that link the different aspects together and to ensure that the ideas developed don't forget critical issues. According to the authors, their method is aimed at creating discrete engineered products and is less suitable for creating new software or services.

3.1.1 The Ulrich & Eppinger Generic Product Development Process

The product development method used will be the one described by Ulrich & Eppinger (2012). The process is divided into 6 successive steps seen in Figure *5*.

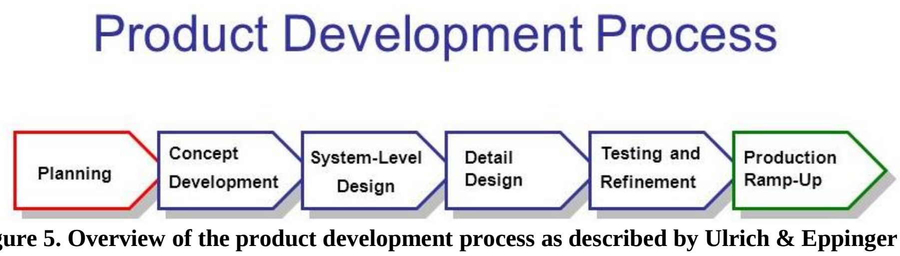


Figure 5. Overview of the product development process as described by Ulrich & Eppinger

1. Planning: The generic process begins with a planning phase which is linked to research and technology but also identification of market opportunities. The output from it is a mission statement. The mission statement should contain the target market for the product, the business goals, assumptions and constraints.

2. Concept Development Phase: With the market statement as guide, the process then continues into the concept development phase. Here the market needs are identified, and product concepts are generated and evaluated. Finally, one or more concepts are chosen for further development and testing. A product concept should contain a rough sketch and description of form and function. Results should also be a set of specifications for the product, a comparison with similar products and an economic justification for the project.

3. System-level design: This phase includes the definition of product architecture and initial plans for the production system and final assembly.

4. Detail design: This phase leads to the complete specification of all the geometry, materials and tolerances of all the unique parts in the product. The tools used in the production are designed. Issues concerning material selection, production cost and robust performance are finalized.

5. Testing and refinement: At this stage, the products undergo construction and evaluation of multiple versions of the product. The prototypes are tested to determine if the product works as intended and satisfy key market needs.

6. Production ramp-up: The product is created by the intended production system, small manufacturing problems are ironed out, the workforce is trained and products supplied to selected customers. Hopefully, any remaining flaws are identified and the transition to ongoing production begins. At some point in the transition, the product is launched.

3.1.2 The Front-End Concept Development Process

The concept development stage is the usually the most demanding step. The Ulrich & Eppinger design methodology used here is based on the generic concept process. Their generic method, also called the *front-end process,* is divided into 7 sequential steps. These are as follows:

1. Identifying customer needs: The objective is to investigate the customer needs and to convey them to the development team. The output from this step is a list of ranked customer need statements.

2. Establishing target specifications: The customer needs are translated into technical terms that provide a precise description of what the product has to do. The specifications are done two times. They are set to represent the broad aspirations of the team based on customer needs early on, called the target specifications. As a concept gets selected, the specifications are revised to be more consistent and precise, these are called the final specifications.

3. Concept generation: The goal of this phase is to thoroughly explore the design space of possible solutions to the consumer needs and specifications. This step includes creative problem solving and results in a number of solutions sketched with a short description.

4. Concept selection: This phase is about evaluating product concepts based on customer needs and other criteria. Each concept's strength and weaknesses are compared with each other. In the end one or more concepts are selected for further testing and development.

5. Concept testing: The output from the last phase is tested partly to verify that the customer needs are met, and party to identify any potential shortcomings.

6. Setting final specifications: The target specifications from step 2 are revised after a concept has been selected and tested. Broad ranges of values are refined and expressed as precise metric ones.

7. Concurrent processes: At every stage during the process, various forms of prototypes and models should be involved. Some should demonstrate technical feasibility or the form while others evaluate ergonomics and style. Competitive benchmarking should also be performed at all stages to provide a source of ideas and understanding of the product. And finally, an economic analysis should be performed to justify trade-offs.

3.2 Thesis methodology

The methodology used in this thesis was a modified form of the Front-End concept development process seen in Figure 6. The main modifications are the inclusion of literature study after the planning phase. The purpose of it was to gain a deeper understanding of bioaerosols, methods of sampling them and what products are utilized. The results from the literature study can be seen in the theoretical background chapter and in the benchmarking section before product specifications. Secondly, an initial phase of analyzing the prototype impinger through CFD was made to gain understanding of the performance of the device.

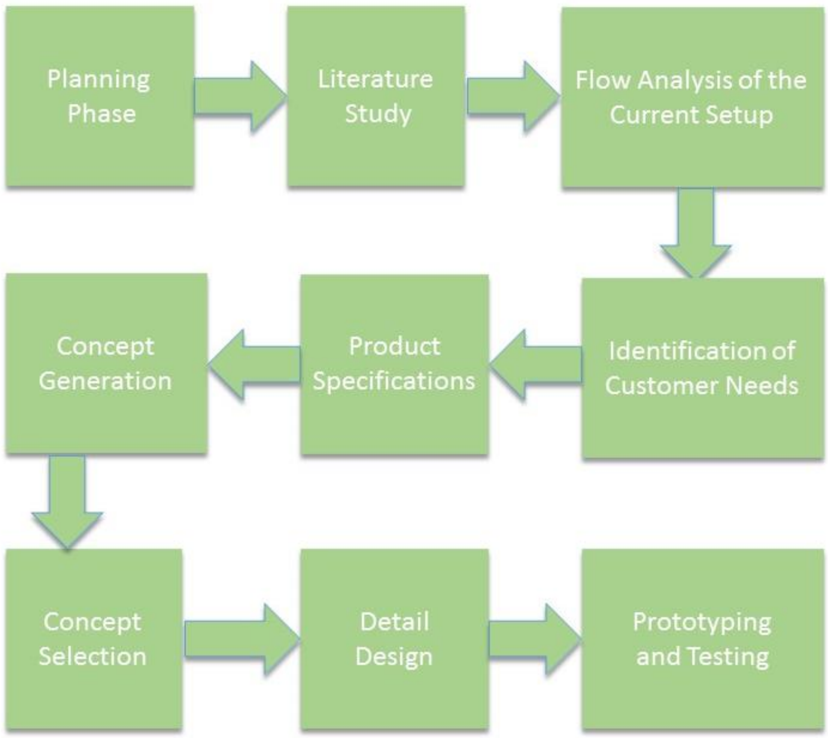


Figure 6. Overview of the method used.

3.3 Planning phase

The first step in the planning phase, was to complete a mission statement which included a brief description of the product, the reasons why anyone should buy the product, the target markets, stakeholders for the product, and assumptions for the development process. The main difference from the original method was the omittance (exclusion bættre ord?) of Key Business Goals. Since the project is handled by the university research departments, there are no corporate strategies involved. During this thesis, the managerial aspects of the Ulrich & Eppinger design methodology, will not be implemented.

3.4 Analysis of the Kärcher Prototype Impinger

To perform improvements on a product, some comprehension of its functions is required. To achieve this, a 3D model of the water tank for the Kärcher DS 5.800 that the biology team used for sampling, was created. This will be termed as the Kärcher Prototype Impinger (KPI). A 3D prototype was made in two steps as its main tasks were to visualize the geometric structure of the KPI and to analyze the mixing and flow of air and water during operation. In the first step, a CAD-model of KPI was made. The model was created in the software using a top down design technique, meaning that the KPI was broken into 3 sub-assemblies which were based on the 3 separate parts that the KPI consists of. The parts are assembled simultaneously and they are made to reference to each other, meaning a change made in one part will automatically update the dimensions of others.

Before a part was created in Creo Parametrics, some rough sketches of it were made by hand, containing the actual measurements and shapes of the KPI. Each feature and detail on the product was measured with a caliper or a ruler. Measuring by hand raises some concerns about accuracy but the focus is to gain understanding of the functions not to make an exact copy. For copyright reasons and the limitations when importing 3D CAD to CFD-software, an exact copy was not desired. The precision of the measurements was restricted by the capability of measuring things by hand or a caliper/ruler in this case.

Some restrictions of the fluid analysis software were considered when designing the CAD model. To smoothen the required simulation process, the intricacies of the CAD model had to be reduced as more details lead to slower speed of the simulation process. Certain features of the KPI that we deemed not critical to the air and water flow, were simplified or removed. This was especially true for the top cover of the water tank.

The second step of the modelling process was to import the CAD model into a fluid simulation software. The aim of the fluid simulation was to locate trouble spots in the flow and to predict fluid interactions inside the mixing chamber of the tank during operation. The simulation was intended to be done in two steps. First, only air flow was simulated inside the KPI without any liquid involved. The next stage was to perform a complex multiphase air and water simulation. However, this proved to be problematic. To gain insight in the mixing capabilities, a physical prototype was developed instead.

3.5 Identification of customer needs

To establish product specifications and compose concepts that will solve the design problem, customer needs should be identified to serve as guidelines for further development work. The term “customer” is a misleading in this case, as those who acquire this impinger might not be the ones using it, nor are they costumers in a traditional mass market sense.

To find out latent and explicit needs, interviews were conducted with end users of the Kärcher DS 5.500 in the field of sampling, usually scientists in aerosol and microbiology departments. The interviews were done in two parts. Firstly, a continuous dialogue with our supervisors, and secondly, interviews with selected end users of the KPI. Interviews were conducted in either a semi-structured way or an unstructured way. Semi-structured interviews were preferred with users of the previous model of the high-volume sampling device. Questions used in our interview can be found in Appendix A3. Our questions were based on examples found in Ulrich & Eppinger, with small modifications.

However, since the number of bioaerosol impinger users is limited, some interviews were also conducted with other experts in the fields of aerosol and microbiology, who weren’t involved in sampling. Unstructured interviews were suitable for those without direct experience in sampling, as asking more open questions and providing topics of conversation was more useful in getting information. Especially since the authors weren’t fully familiar with the interviewees’ field of expertise beforehand, and it can be difficult to find common ground and understand the technical jargon and terminology. Notes were taken during all interviews but the following transcription cannot be considered word-for word accurate. Interviews were done with both authors of this thesis present.

Once the customers’ needs were collected, they were organized into a hierarchy to increase overview for further activities. The needs were put into groups based on what we perceived, were the main desired functions. Redundant statements were eliminated and some need statements were rewritten. As some interviews were conducted at later stages in the development process, the needs and hierarchy were revised accordingly. A compiled list of the customer needs can be found in Appendix A4.

3.6 Product specifications

Based on interviews, discussions with experts and lead users, technical and manufacturing demands a list of specifications was established. These are a set of measurable requirements that the product must accomplish to be considered successful.

3.7 Concept Generation

To describe working principles and form of the possible solutions, sketches with short descriptions were made. The concept generation was inspired by the Ulrich and Eppinger method, but there was a strong push for certain alternatives from the stakeholders. To explore what kind of solutions were available, a five-step method was used. The steps are the following:

1. Clarification of the problem
2. External search
3. Internal search
4. Systematic exploration
5. Reflection on the process and solutions

In the first step, the problem was clarified and broken down. This breakdown was done by considering what the customer needs and product specifications were. The impinger is a complex device with many functions, and the relation between input and output isn't obvious. The decomposition helped to understand the key working principles of each subproblem, and then it was possible to scope out available solutions for each subproblem. After solutions were developed, they needed later to be integrated in the overall design.

In the next step, an external search was conducted. This was done by searching online sources, conducting field trips, acquiring similar products aiming to find possible solutions for each subproblem. The initial search was expanded and then narrowed down, and for certain subproblems, the authors were advised to pursue certain promising leads. Afterwards, some of the possible solutions were sketched down. To understand certain complex subproblems, such as water losses during impinger operation, experts were consulted at the Engineering Fluid Mechanics department of LTH.

3.8 Concept Selection

In the design method proposed by Ulrich & Eppinger, concept selection is done in a two-step process. The first stage of concept selection consists of a concept screening which can be described as a rough preliminary comparison. A screening matrix is prepared and the different concepts are rated and then ranked. After the screening, a more refined version is repeated, this time called concept scoring. Usually, the concepts are compared relative to different reference concept points for the various criteria.

Using matrices was not suitable for this project as it was not possible to predict how satisfactory the concept would meet various important criteria concerning the flow in the mixing chamber. Instead, a two-stage iterative process was chosen for the mixing chamber, where the three basic concepts were selected early on and developed, analyzed in CFD and then developed again. After each concept was developed to a satisfactory level, the authors together with the supervisor and stakeholders, compared the strengths and weakness of the three mixing chamber concepts against each other. The winning idea was then developed further to correct some design weaknesses appearing thus far.

Areas of the impinger design that were deemed less important for the mixing and flow capabilities, went only through a concept screening process to produce a dominant concept. There was no need for additional concept scoring.

3.9 Prototyping and Final Design

Two prototypes were made. One 3D model to visualize the look and feel of the selected concept. A second physical prototype would then be built to learn as much as possible about the properties and capabilities of our selected concept concerning water retention and to visually examine air and water mixing. The physical prototype was also made in 3D to perform airflow simulations. There is a notable difference between the 3D model that was developed to visualize the design intention and the 3D model used for CFD analysis. This was done to speed up the CFD process. Due to cost, only one prototype was manufactured at the end and it was intended for testing only.

3.10 Test of prototype

The main purpose of the prototype testing was to visually examine the flow of the air and water inside the mixing chamber. Secondary purposes were to examine:

- the ergonomics and functionality of the side handle
- function and strength of the insertion holes
- water losses during operation
- how tilting the impinger affects the operation

The experiments were initially setup by connecting the impinger to a pump. The flow of the pump was measured with a flow meter. The air flows used in the testing was $1{,}4\ \mathrm{m}^3/\mathrm{min}$. Since only half of the impinger volume is used in the manufactured physical prototype, it was deemed acceptable approximate to divide the initial flow by half and use about half the amount of water intended for the end product. During the prototype testing, the impinger was filled over the recommended water limit. The reason for the additional water was to examine if there was an unforeseen optimal water volume that for this design could limit water losses. It could be possible that for example, higher water volumes gave better retention and mixing abilities.

Four tests of the impinger were done in total. In the first test, the overall capabilities of the impinger were examined. The amount of water inserted was 750 g and the impinger ran for 10 min. In the second test, the purpose was to examine water losses and to find out whether the amount of water inserted affected the flow and mixing capabilities. These tests were done when the impinger started running with 850 g water. The prototype tests were run in ten intervals of five minutes. The mixing chamber was filmed and photographed in the beginning of each interval. After each interval, the impinger was weighed to determine the losses of sampling water.

In the third test, the procedure above was repeated with the only difference that the impinger was tilted forwards 30 degrees. This meant that the angle between the inlet and the horizon increased to 45 degrees.

In the fourth prototype test, the aim was to examine the insertion ports and handles. This was done by testing the crimping tool used for similar products, but also by adding and removing liquid while looking for leaks. The handles were also tested by pulling and dragging. The handles were tested with dry and wet hands.

3.11 Method discussion

The Ulrich & Eppinger design methodology has the advantages of being explicit, i.e. made sure that everyone involved in the project is understanding the basis for the design decisions taken. Another advantage is that the ideas are presented in a checklist which hopefully prevents key issues being forgotten. The downside is that the method demands intensive documentation. If not careful, more time could be spent on documenting the process than developing the product. The method is split into many steps to ensure commercial viability in a competitive market, and to go through all the steps would require a lot of information about the product and the market which was unavailable this time. In this project, ensuring that the product could meet the requirements of basic functionality while limiting cost was deemed satisfactory. One of the hardest aspects of this project was the uncertainties, as the different effects concerning inputs and outputs of the impinger were not easy to elucidate.

One of the things done correctly was keeping the prototyping limited. As soon as the prototype was produced, there was immediately plenty of work that could be done to improve it. Some fixes and re-fixes had to be done, especially since the prototype fell apart in the first test. However, spending time on perfecting the prototype can be a time drain and fixes on the prototype do not automatically make the end product better. Not everything went according to plan, the authors were at times too quick to get working on details. This lead to certain aspects of the processes being carried out too quickly, leading to some unforeseen negative consequences encountered later on.

4 Results

This section will describe the results from the CFD analysis of the KPI and the results from each of the steps undertaken in the Ulrich & Eppinger design methodology. The final design solution and the results from the prototype testing will presented in the next chapter.

4.1 Planning phase

During the planning phase, a time schedule was developed and as well as the mission statement. The compilation of the mission statement can be seen in Table 1.

Table 1. Mission statement of the project.

Mission Statement: High volume impinger	
Product Description	A device that collects aerosols from stream of air into a liquid.
Benefit Proposition	It will extract aerosol particles from very high flow rates
Primary market	Aerosol Science departments Environmental monitoring agencies
Secondary market	Healthcare institutions Food industry
Assumptions and Constraints	Product is 3D printed Perform analysis on the current prototype
Stakeholders	Users and purchasers Lund University Aerosol Department Aarhus University Aerosol Department

4.1.1 Discussion of the planning phase

The planning phase makes more sense from a business and managerial perspective than from a design one. That is because it involves project staffing, leadership, management of budgets and resources. In the scope of this project, the most useful thing from this step are the reflections regarding available secondary markets. This is something that should be examined more closely at if the product is to be developed further.

4.2 Results from fluid analysis of the Kärcher Prototype Impinger

To gain understanding of the flows and behavior, the KPI was analyzed by running air flow simulations. The results of CAD and CFD simulations can be seen below. The air simulation (Figure 7) shows that there is an initial impaction at the bottom of the tear shaped bubble seen on the left side on Figure 7. The bubble lies under the water surface when the KPI is used. The air is then pushed upwards towards the roof of the mixing chamber (Figure 8), and then pressed back into the water once more. On the mixing chamber, there are two points for impaction and as the air moves along its roof, it is forced down in the water a second time. In this way, a swirling vortex is created. On its way to the exit, the air moves upward and changes direction because of the baffling plate seen in the middle of Figure 9, which is assumed to collect water droplets. The KPI in its entirety can be observed in Figure 10.

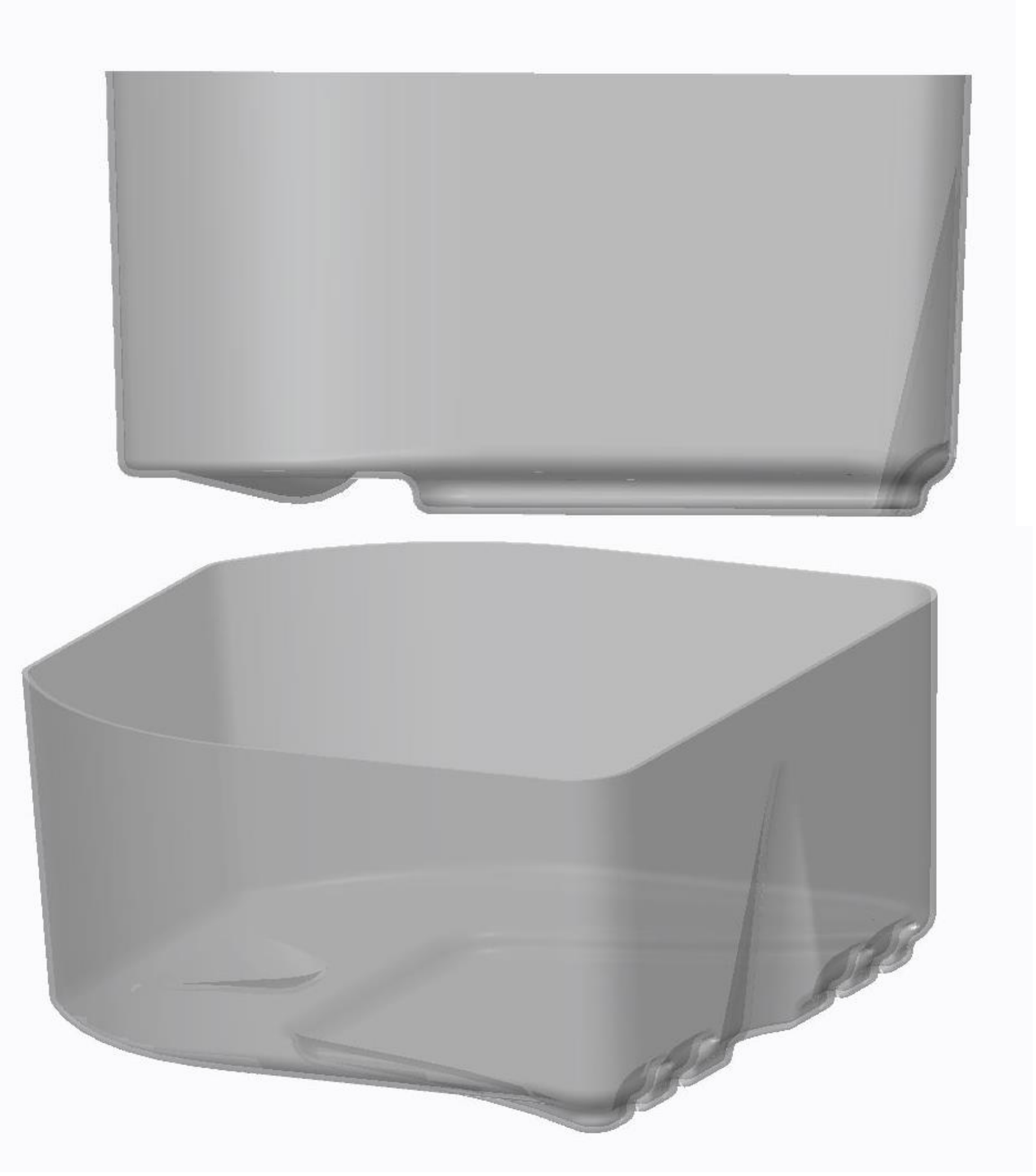


Figure 7. Bottom part of the KPI

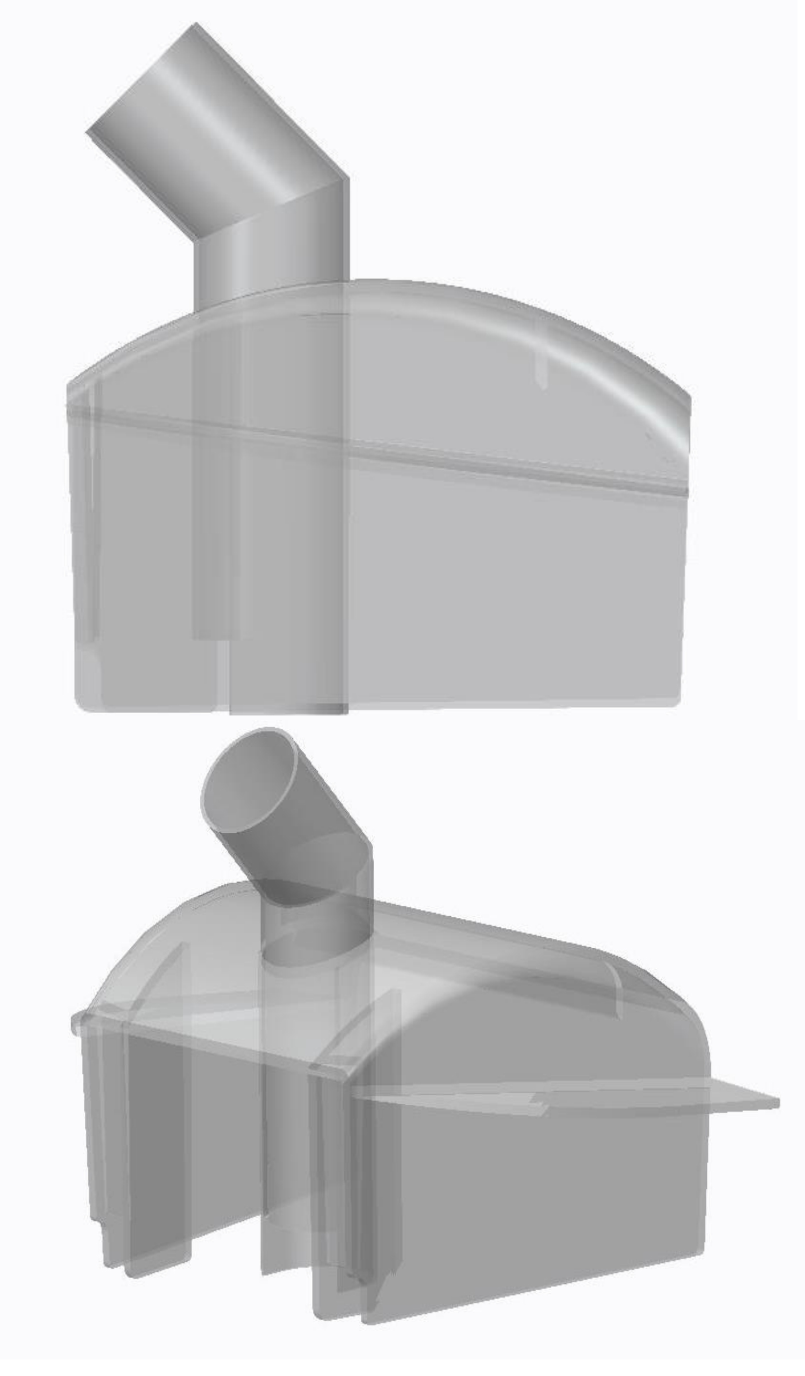


Figure 8. Mixing chamber of the KPI

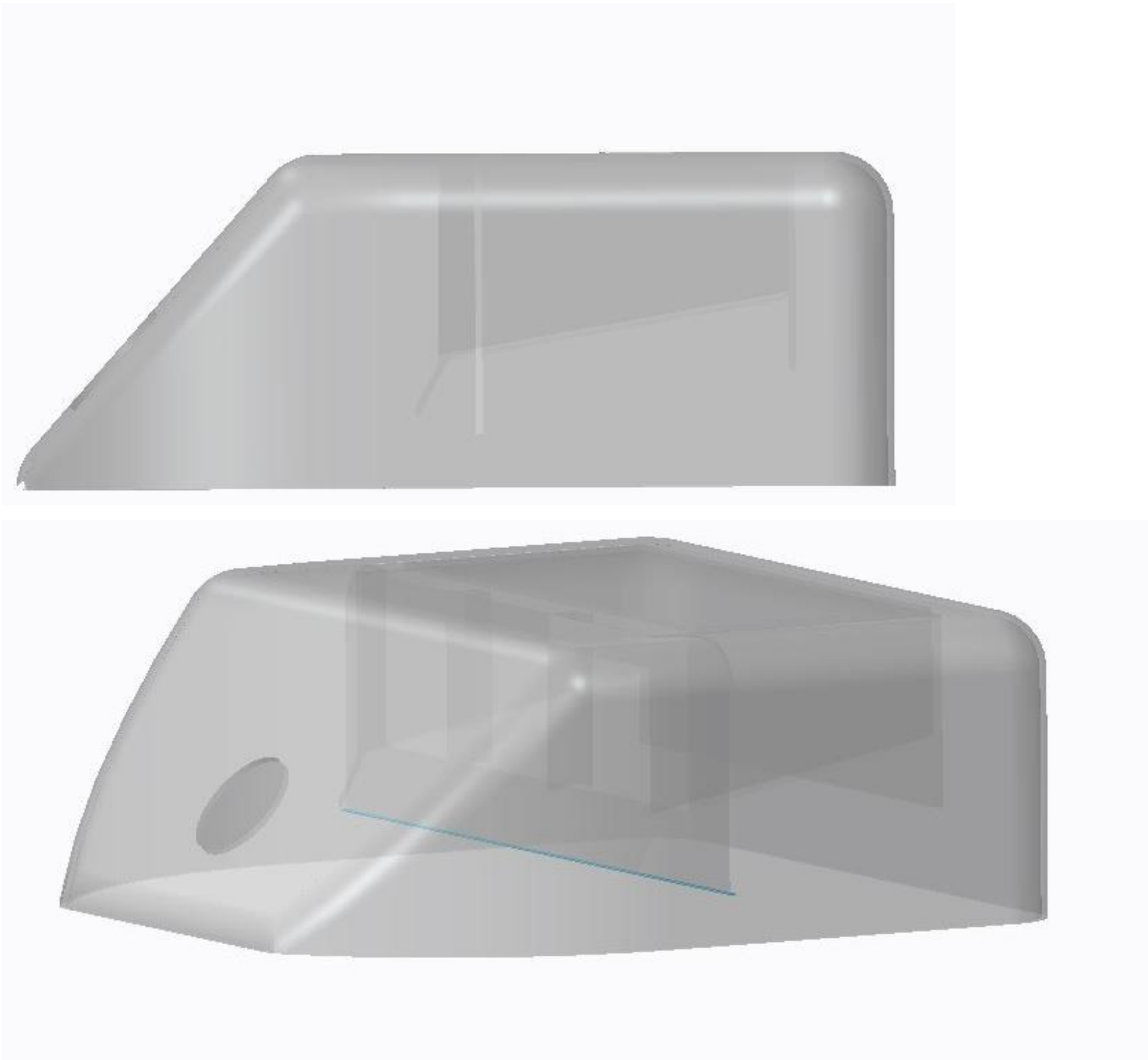


Figure 9. Top enclosure of the KPI. The baffling plate can be seen inside and its thin edge is highlighted in blue.

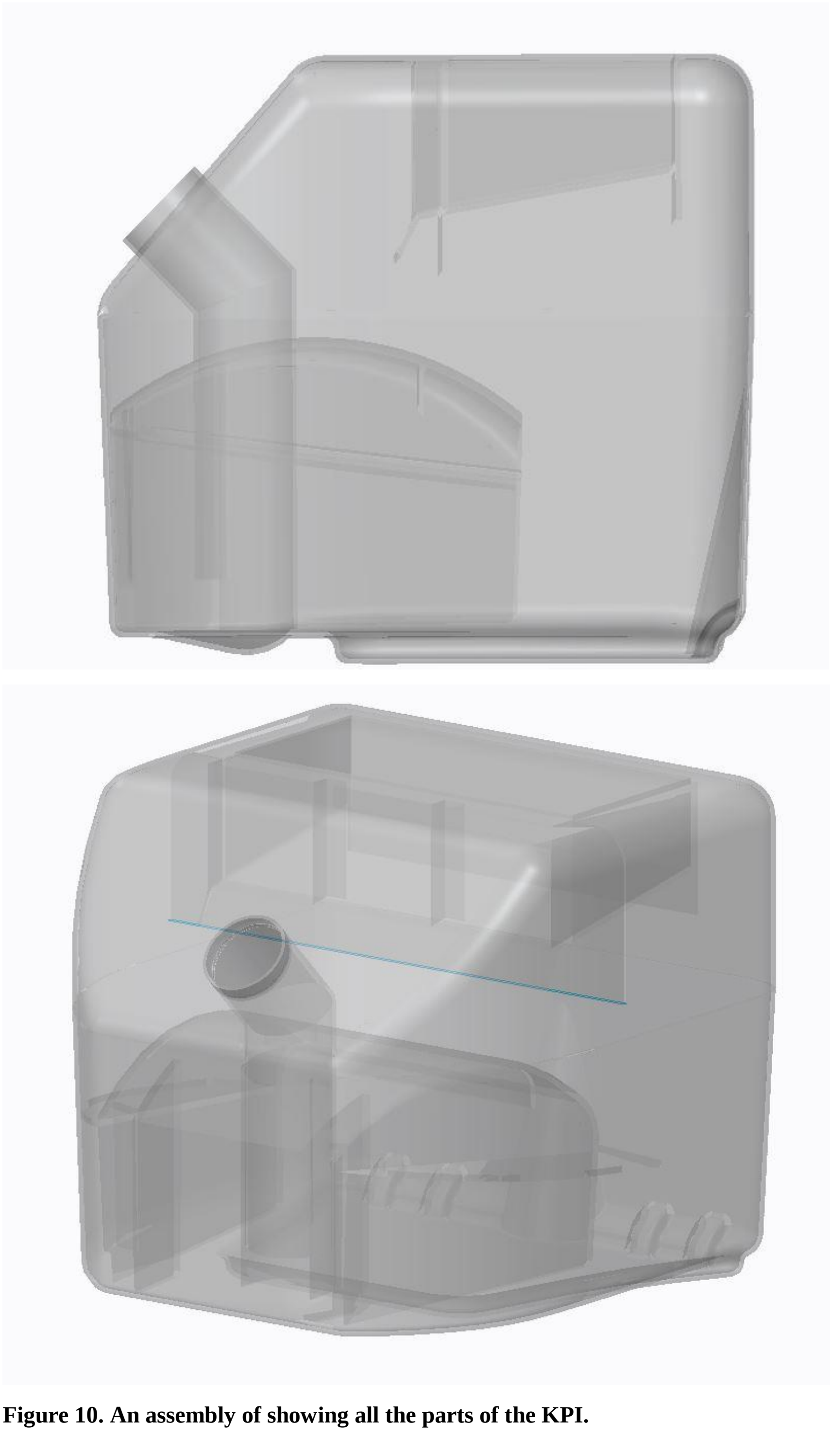


Figure 10. An assembly of showing all the parts of the KPI.

The material selected for the flow simulations was acrylonitrile butadiene styrene (ABS) as it has similar properties to polypropylene (PP) in terms of density and strength of which the KPI was made. During this flow simulation, material properties are of small importance. The boundary conditions for the simulation were based on volume flow measured during aerial sampling. For the inlet, a volume flow rate of 3000 L/min was used and for the outlet 0 gage pressure was set. A finite element mesh was created and the simulation ran for 100 iterations to reach convergence. The pressure drop from inlet to outlet was calculated to be 8100 Pa. The movement of the air stream can be seen in Figure 11.

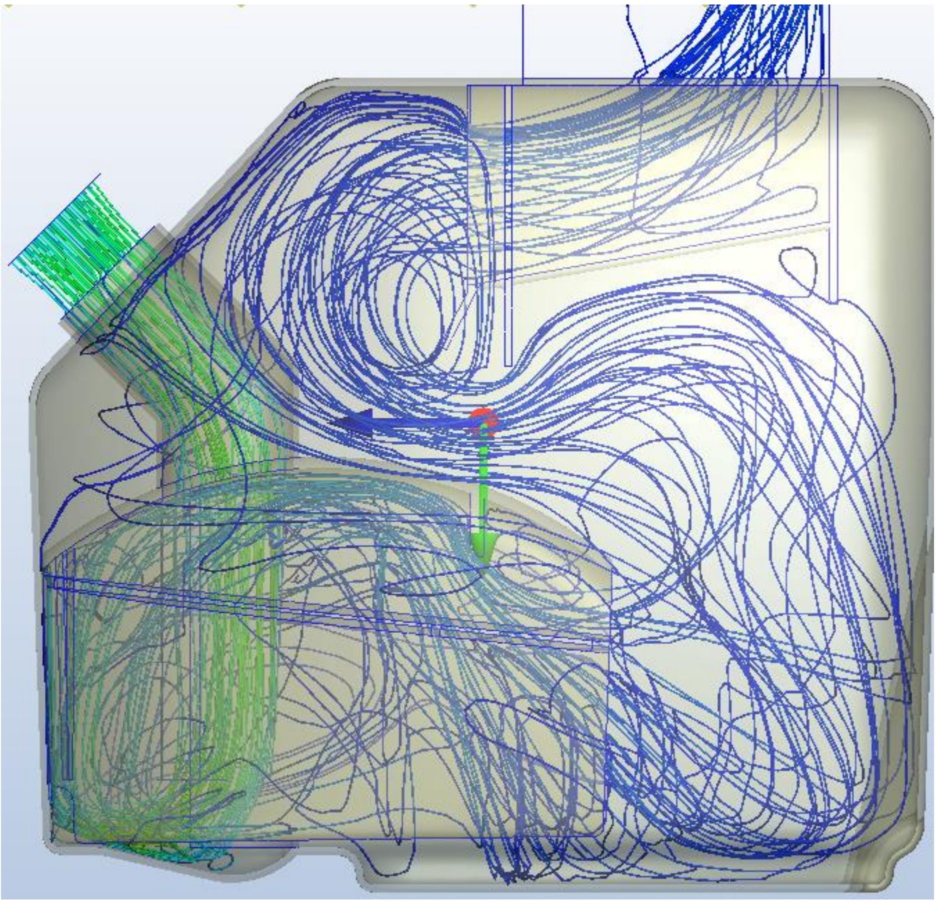


Figure 11. The flow path of the air in the impinger. The green initial velocity is higher than the blue exit velocity.

4.3 Identifying Customer Needs

The customer needs gained from interviews were collected and rewritten in the table found in Appendix A3. To gain an overview, the needs were put into hierarchical list. In the list there are labels, and each label is a statement that generalizes all of the needs in that group. The purpose of this was to increase clarity and reduce redundant statements. Also, the relative importance of each need was established. From the interviews conducted, it was possible to make an educated assessment of which customer needs were more important than others. The more important ones are marked with **.

Sterilization

- Easy to sterilize in lab. **
- It can be sterilized under a fume hood. *
- Easy to sterilize in the field. **
- Short amount of operations from the user when sterilizing in field conditions. **
- The sample is protected from contamination. **
- The impinger can be fully sterilized *
- The impinger is autoclavable or able to be sterilized in an oven. *

High sampling efficiency

- Particles should not get stuck or destroyed in the bent inlet. **
- Particles are retained in the sampling liquid for 5 hours. **
- Particles should not leave the impinger during use. **
- The impinger works with high volume flows. **
- Large volumes of particles are collected. **
- The sampler works with other liquids than water. *
- The sampler has low losses of liquid. **

Sterile during operation

- The sample is protected from contamination. **
- The impinger is well sealed after sterilization. **
- Easy to fill up in the field without contamination. **
- During use in aircraft, water can be added to the impinger without compromising the sample. *
- Easy to remove liquid without contaminating the sample. **

Adding and removing liquid during operation

- The sample should be easy to remove from the impinger. *
- It is easy to insert liquid in the impinger. *
- The liquid sample can be removed with a small hose. **

- Liquid is tapable with simple operations. *
- It is hard to handle the lid and prevent contamination when inserting the liquid. **
- The lid holds itself in place whenever handled. *

Easy of handling and transportation

- Short assembly time for aerial use. *
- Short assembly time for ground use. *
- Weight and size is reduced. **
- Maintenance time during use should be reduced. *
- Automatic regulation of sampling liquid. *
- Automatic regulation of sampling temperature. *

Measurement

- The impinger can separate particles after size. *
- The impinger can measure flow. **

4.3.1 Revision of customer needs

The customer needs were presented to the microbiology experts. They deemed the inlet and the mixing chamber the most critical parts concerning sampling efficiency. The bending on the inlet pipe found on the KPI, was considered especially troublesome. Bioaerosols could impact on it, and remaining there without ending up in the collection fluid. The impact on the plastic walls could potentially destroy the bioaerosols as well. For this reason, the mixing chamber had to be redesigned. Another desire was to be able to visually inspect the water and air in the chamber during use. The reason for this was that since multiphysics simulation could not be conducted, understanding the air-water interaction had to be developed.

Heating was deemed less important, internal heaters (heaters put directly in the water chamber) could affect the flow and mixing properties inside the chamber. Since the entire impinger will be made from an autoclavable material, it can be heated by placing it on a hot plate, or cooled for that matter if it has a flat bottom.

4.3.2 Customer Needs Discussion

Unfortunately, good design practice requires the designer to observe the product in use. As no airborne aerosol measurement was carried out during this period, this was not possible. Fortunately, there were private videos showing a similar sampling device used on a ship. However, these cannot substitute the amount of insight gained from observing the real deal in action in the proper product environment. As the project went on, it became clear that certain needs turned out to be less important than what was initially considered. Sterilization for example was more of a question of picking a suitable material, than a design issue. A few important needs were missing, such as other sampling liquids than water being used and how this could lead to sodium from such liquids clogging the impinger components.

There is also a very limited number of users available for interview, but this is understandable given the very specific nature of the sampler. The nature of product is not mass production for the consumer market.

On the positive side, the interviews were carried out with both authors present, immediately afterwards, a transcription session was conducted. The direct access to sources widened the understanding of the problem among the authors and no time was wasted retelling what had interviews had said. The interviews were important to discover what latent needs exist that are beyond the capabilities of the existing KPI.

4.4 Benchmarking

Before compiling specifications and generating concepts, different types of water filter vacuum cleaners, high volume impingers and aircraft-based bioaerosol samplers were examined. The reason for this was to draw inspiration and gain understanding of products that are similar or used in a similar way.

4.4.1 Benchmarking of water filter vacuum cleaners

Benchmarking of a few different water filter systems was done by downloading user manuals for the different types and searching through webpages of the retailers. The aim for this was to do a quick investigation of comparable products, mainly the shape of the water tanks used, opening mechanisms and other features. A more thorough study was done on the Kärcher DS 5.500 water tank as a physical copy was acquired. The capabilities of vacuum cleaners in household appliances were examined, only the water storage, peculiarities concerning the shape of water tank and power required during operation.

In the rectangular water tank of the Kärcher DS5.500, the air is led vertically into the water from an inlet pipe, after impaction it moves upwards along a bent, almost scoop-like baffle plate that ends before the edges of the tank, forming a cavity. The air is sucked through the cavity, and exits the tank from the opposite direction through an exhaust, located at the tank cover which contains the HEPA filter. According to the manufacturer, the water tank holds 2 L of water and the Kärcher DS 5500 requires 1400 W of power.

Manuals were examined for the Thomas Pet Family Aqua, Thomas Anti-Allergy and the Polti Vaperotto series. The Tomas variants are allegedly able to store 1.8 L in the tank and require 1700 W of power. Polti Vaporetto Lecoaspira has a 1.5 L water tank and requires 1300 W of power, and this variant has the additional ability to dispense steam from the nozzle where the telescopic tube is inserted. According to the manufacturers, all of these water filter systems create a vortex in the water tank which collects the particles. From the basic drawings of the water tanks found in the user manuals, nothing particular stood out.

The vacuum cleaner tank used in this project, the DS 5.800 has according the manufacturer, a 2-litre water tank where a high swirling vortex is formed. When adding water from a measuring jug, the water tank limits allowed no more than 1.6 L of liquid to be inserted. It is believed that the swirling vortex created is what allows the vacuum cleaner power requirements to drop down to 900 W, far lower than the competitors.

4.4.2 Benchmarking of high volume bioaerosol collectors

In this section, high volume impingers will be examined by a literature study. As high-volume air sampling is a developing technique used by small number of specialists, the number of products to benchmark was found to be limited. In certain literature, a definition for high volume sampling is a device that can sample rates of 40 L/min or higher (Cooper, 2012). Since the Kärscher Impinger used as reference can sample up to 3 m^3/min, the search was narrowed down for devices that could sample flows of at least 500 L/min.

In a study by Casey W. Cooper in 2012, two types of high volume impingers are examined. The DFU-1000 and the XMX/2L-MIL, the latter being available for civilian use under the name XMX-CV. According to the manufacturer, XMX series has a low liquid volume of about 5 mL and can sample 530 L/min. It collects particles between 1 - 10 µm . Drawbacks of this device is the weight of about 17 kilograms and the short sampling period. As the XMX/2L-MIL was designed for detection of airborne biological warfare agents, sampling times are therefore short. The device works by using a virtual impaction process to separate the incoming air flow into two streams. The separation is done by forcing the airstream to an accelerating nozzle direct towards a collection probe. Before the probe, there are 90 degrees' radial openings, through which majority of the flow will pass. Most of the smaller particles with low inertia will follow the flow streamlines. Larger particles with higher inertia will continue towards the collection probe with the minor flow. The sampled particles continue through a series of virtual impactors only to be impinged in a liquid during the final step. This arrangement allows the XMX series to concentrate particles in the inhalable range of 1-10 µm. The flow rate of the minor flow that leads to the liquid impinger is 12.5 L/min.

The DFU-1000 (Dry Filter Unit) is a high-volume air sampler that uses filter collection as a sampling mechanism. This device has much higher collection efficiency of particles under the 1 µm range compared to the XMX series and it can collect particles in the nano size range depending on the filter used . However, this advantage is offset by the difficulties of extracting the sample from the filter in suitable quantities. The DFU-1000 is capable of sampling for extended periods of time at flow rates up to 800 L/min. It is intended for indoor sampling but a modified variant for outdoor sampling exists, the DFU-2000 with a protective housing, a pre-separator to prevent debris from falling inside. These modifications allow it to operate in harsher outdoor conditions Cooper, C. (2012).

4.4.3 Benchmarking of bioaerosol collection from aircraft

Sampling for bioaerosols in the atmosphere has been conducted on multiple occasions with airplanes, balloons and rockets (Burrows et al., 2009). In the literature study, two similar examples were found. One of these was used when sampling for bacteria 3500 m over the Noto peninsula in Japan (Kobayashi et al., 2011). In this setup, a Cessna 404 aircraft was used and sampling was done through an inlet connected to a tube that poked out from a hole through the roof of the airplane. The inlet and tubing were made from autoclavable plastics. The tube was then fastened into a NILU filter holder and aerosols were collected in this filter. A diaphragm pump provided suction and the flow rate achieved was 17 L /min for 60 minutes of sampling. A control unit was connected to the pump and a pinch valve was placed at the inlet. The control unit can shut the valve when not sampling and thus preventing particles from contaminating the filter (Kobayashi et al., 2011).

A similar sampling setup was also when conducting bioaerosol sampling from a tethered balloon. In this case, as described by Iwasaka et al (2009), the balloon could collect various bioparticles transported by Kosa (Asian dust) from near the ground to 2300 m above sea level. The control unit, together with various equipment for determining particle size and concentration, humidity, temperatures, could be operated and monitored from the ground (Chen et al., 2011) (Iwasaka et al., 2009).

4.5 Product specifications

Product specifications are based on customer needs and are an interpretation of these in measurable and precise form. Since a completely new product was developed, there are many unknowns regarding what metrics and values were suitable. Therefore, the design method required some modifications. Since the product does not have any direct competitors (if it meets the demands for functionality), the competitive benchmarking step is omitted. Some values of what the impinger has to accomplish are however given below. The initial specifications are:

- The impinger works in -20 degrees and 40 degrees C.
- The impinger handles flows between 1.5-3.0 L/min.
- The temperature of the sampling liquid is kept at 5-7 degrees C.
- The impinger can sample for 5 hours.
- The impinger collect at least 10 000 bacteria.
- It must withstand 121 C and 105 kPa (gage) for 20 minutes.
- Outlet must be a round pipe that sticks out 5 cm and has a 5 cm outer diameter.
- The impinger will made from Nylon-12 by additive manufacturing.

The specifications were revised during the work as the relations between capabilities and functions of the impinger became understood better.

4.6 Concept generation

The most critical functions according to the specifications and customer needs for the impinger were:

1. Opening mechanism
2. Inlet
3. Outlet
4. Adding and removing liquid
5. Heating and cooling
6. Overall shape

By considering these six factors, all problems the customers voiced could be solved. Initially the most important ones were decided to be opening mechanism, addition and removal of liquid and overall shape. These were revised as the project went on as from the stakeholder's side of the project, it became more interesting to examine the flow and gain an understanding of the mixing capabilities instead of further development of usability and ergonomics. This meant that the sub-problems were revised to include the mixing chamber and water loss prevention.

1. Opening mechanism
2. Inlet and mixing chamber
3. Outlet and water prevention
4. Adding and removing liquid
5. Heating and cooling
6. Overall shape

An external search was conducted in the next step, where solutions to the opening mechanism, adding and removing liquid and heating and cooling were considered. When searching for opening mechanism, a wide range of lids and closing mechanisms for plastic boxes were examined. Benchmarking against other types of water filter based vacuum cleaners was made when exploring possible overall shape. The heating and cooling options were discussed with users who operated the impinger in arctic conditions. From these discussions, aquarium heaters were suggested and examined.

4.6.1 External search

Different lid designs were investigated by comparing various kinds of plastic boxes and heaters. Initially, searches on the internet were made for all kind of boxes and opening mechanisms. From gear-driven boxes carved out of wood to containers for overseas transport. The purpose of this search was to examine the entire field of what was possible to do, in order to gain inspiration. The search was later narrowed down to only look for:

- Tool boxes
- Ammunition boxes
- Plastic lunch boxes and Tupperware®

All of the boxes examined had to be plastic since the material characteristics are related to Nylon-12. A tool box is usually of the same size as the KPI, so those were deemed especially interesting. Tool boxes are designed to be sturdy and feel rugged, two aspects that should be incorporated into the impinger. Another interesting feature is their handles, which could be used for our design. The main flaw is that plastic tool box design doesn't take sterility into consideration. Plastic lunch boxes are interesting as they must prevent food from being contaminated from the outside. Similar functions are desirable for the impinger, after it is loaded up with sampling liquid and is transported to the sampling area, nothing should get in and spoil it. But plastic lunch boxes have some drawbacks as well, firstly they are smaller than the KPI, secondly give off a somewhat brittle and cheap impression.

Lastly, ammunition boxes for small arms were examined as they are designed to be durable with an interesting hinged lid design to prevent moisture from getting in. However, their main drawback was that the lid mechanisms or the box itself usually contains metal parts. Imitating their function in 3D printable plastic, was deemed to require extensive redesign.

Figure 12. A small selection of plastic lids and closing mechanisms examined.

Field trips were conducted to Biltema and Ikea with both authors present in order to investigate lid closure mechanisms of different sizes. A couple of boxes were bought as the intention was to measure their closing mechanism in greater detail and perhaps imitate it.

In discussions with biology experts, it was recommended to investigate lab equipment such as petri dishes as they are used for growing bacteria without contaminating them. The authors were also provided with Tupperware® deemed interesting.

For solving the addition and removal of liquid problems, a search was made for suitable products. The most interesting ones proved to be different types of rubber valves (duck-valves), medical injection vials and medical lopez valves. Medical injection vials together with rubber seals and metal fasteners, were also acquired and examined. The subproblems and the various solutions can be examined in Table 2. A patent search in the US Patent and Trademark Office, Google Patents was conducted based on the search words impinger and aerosol but they turned out unfruitful. There is a patent on the current KPI and it was studied to avoid copyright problems.

Table 2. Table for subproblems and their possible solutions.

Opening Mechanism	***Adding/removing Liquid***	***Heating and cooling***	***Overall Shape***
Sliding lid	Duckbill sampling port (insertion)	Electric immersion resistance heater and regulator	Cylindrical Drum
Clip on- lid	Insertion through inlet	Fish tank heater	Rectangular Box
Detachable lid with rubber side	Removal through outlet	Peltier electric water chiller	Sloped front and rectangular back
Hinged middle section cut through	Beer tap	Heat conductive bottom part	Conical flask shape
Revolving door lid	Rubber stoppers	Wallpaper steamer	
	Two round edged sliding arms		
	Medical Lopez Valve		
	Umbrella valve		

4.6.2 Internal search

To solve certain subproblems, a brainstorming session was made. Usually this meant that both authors drew about 10 solutions each to every problem by hand. Sketches were made for the overall shape of the impinger, closing mechanism, lid and various handles. The sketches were not made all at once but were made in turn as each problem appeared. Some of them can be seen in Figure 13. The critical parts such as the internal chamber and the inlet pipe were sketched out with microbiology experts. This was done during one meeting for about 2 hours

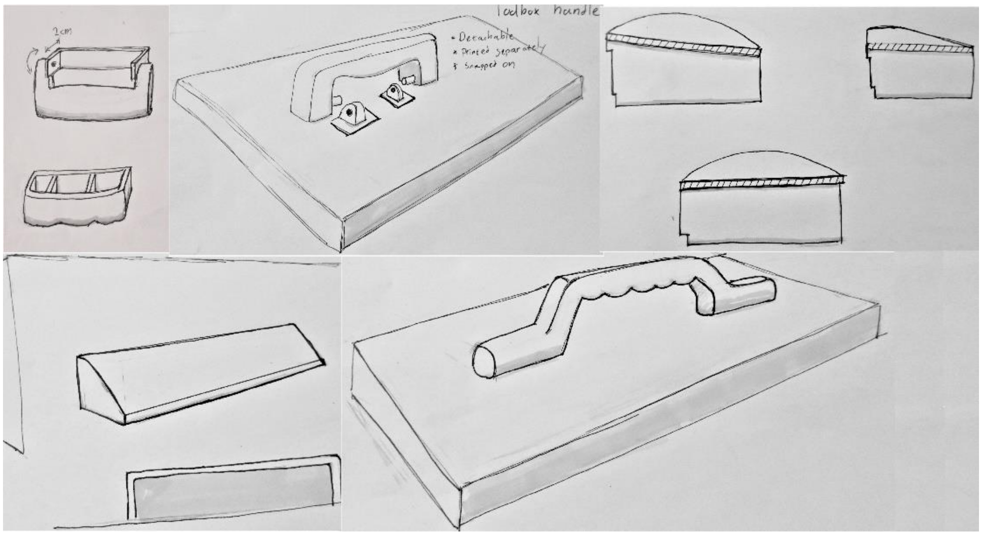


Figure 13. A selection of sketches covering the handles (left top and bottom) and the mixing chamber (right top).

As the concepts were presented to the microbiology experts, the inlet and the mixing chamber were deemed far more critical than other parts. The bending on the inlet pipe, was considered as especially troublesome. Bioaerosols could impact on it, and remaining there without ending up in the collection fluid. The impact on the plastic walls could potentially destroy the bioaerosols as well. For this reason, the mixing chamber had to be redesigned. Another desire was to be able to visually inspect the water and air in the chamber during use. The reason for this was that since no multiphysics simulation could be conducted, some kind of understanding about the air-water interaction had to be developed.

Heating was deemed less important, internal heaters (heaters put directly in the water chamber) could affect the flow and mixing properties inside the chamber. Since the entire impinger will be made from an autoclavable material, it can be heated by placing it on a hot plate. Or cooled for that matter, as long as it has a flat bottom.

4.7 Water loss and retention

The Heat transfer and Fluid department at LTH was consulted to look at solutions for the water loss prevention. From these discussions, it became apparent that to fully solve this issue, cooling of the exhaust air had to be undertaken. Cooling the exhaust air, would change the amount of water the air can contain, which would lead to reduced water losses. And when turning the issue around, if hot dry air enters the impinger, large water losses would follow. By examining different relative humidity for the exhaust air, a basic calculation of water mass loss was made. Assuming a temperature of 15 °C, relative humidity of 25%, a humidity ratio of 2 g of moisture per kg dry air, a volume flow of 3000 L/min, the impinger should lose 440 g of water per hour when running because of evaporation. This assumes an adiabatic saturation process, which means that unsaturated air gets in and then exists as saturated air. Because of the high air flow velocities involved, this might not be the case.

4.8 Design of internal mixing chamber

From the work done during concept development, a total of 3 main concepts for the internal chamber were developed. The main objective for these concepts was to remove bending of the inlet pipe. Changes were made in an iterative process, for each concept small adjustments were made in a CAD model which were later simulated and evaluated. Each concept will be presented in its initial form and its final form, where it attained the most desirable flow qualities. These concepts are shown are preliminary layouts of the inlet pipe and mixing chamber, without details such as lids and handles.

4.8.1 Concept P

In concept P (Figure 14), the main idea was to completely remove the bending of the inlet pipe. It allows for a small angle between the inlet pipe and the bottom surface. This is because of the distance between needed water level and the inlet, to prevent water from running out during handling and use. It retains the original air flow motions of the KPI. The incoming particles are being pushed upwards as they hit the mixing chamber wall and then follow a circling motion forcing the air to impact in the water twice (Figure 15). In the final version (Figure 16), a small bulge was added near the wall to better redirect the flow. The resulting pressure between inlet and outlet was measured to 5220 Pa (Figure 17). This was measured in the last iteration once all changes were in place.

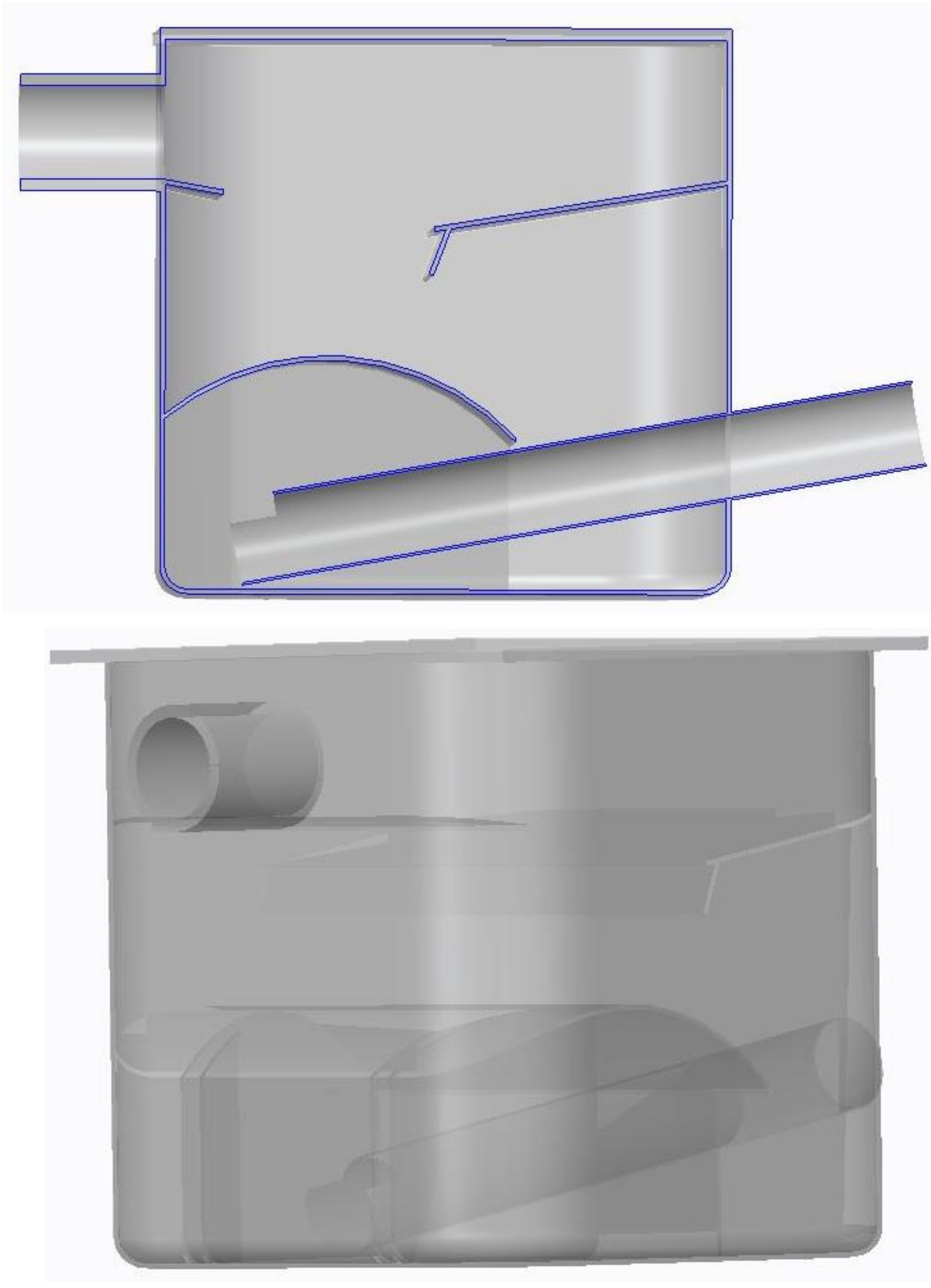


Figure 14. Initial variant of the P concept with reversed inlet.

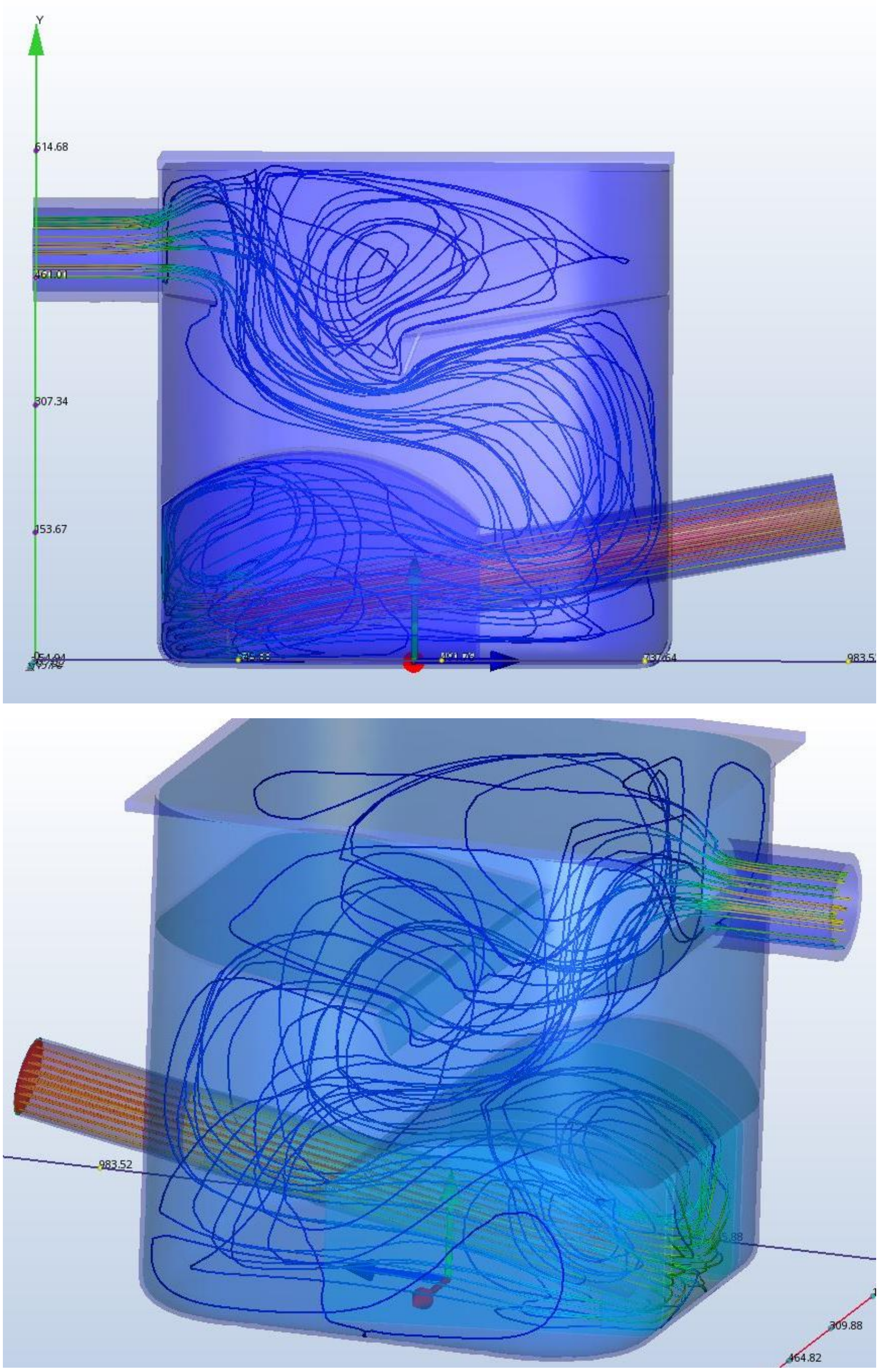


Figure 15. Airflow traced in the initial variant of concept P.

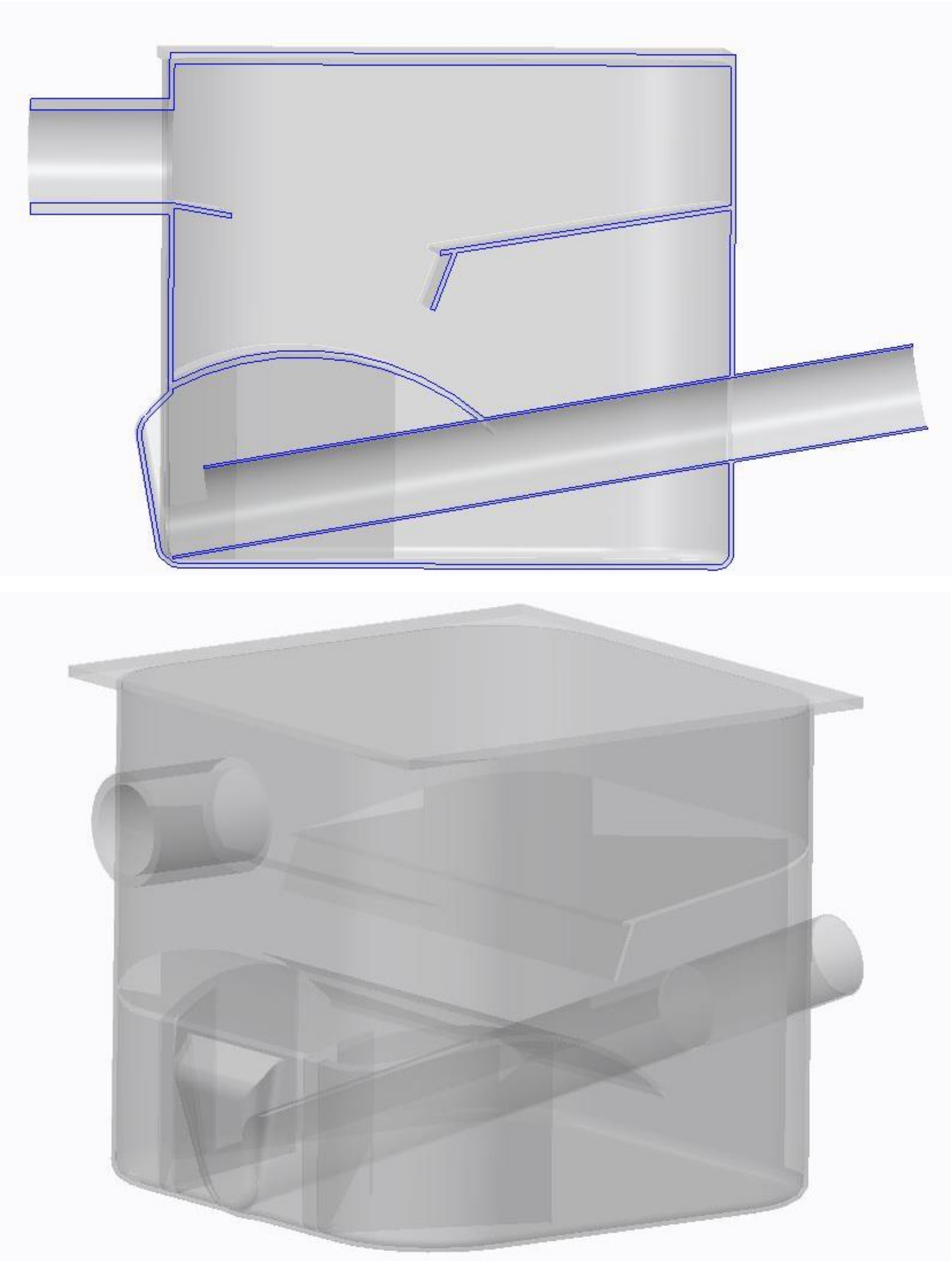


Figure 16. Final variant of the P concept with reversed inlet.

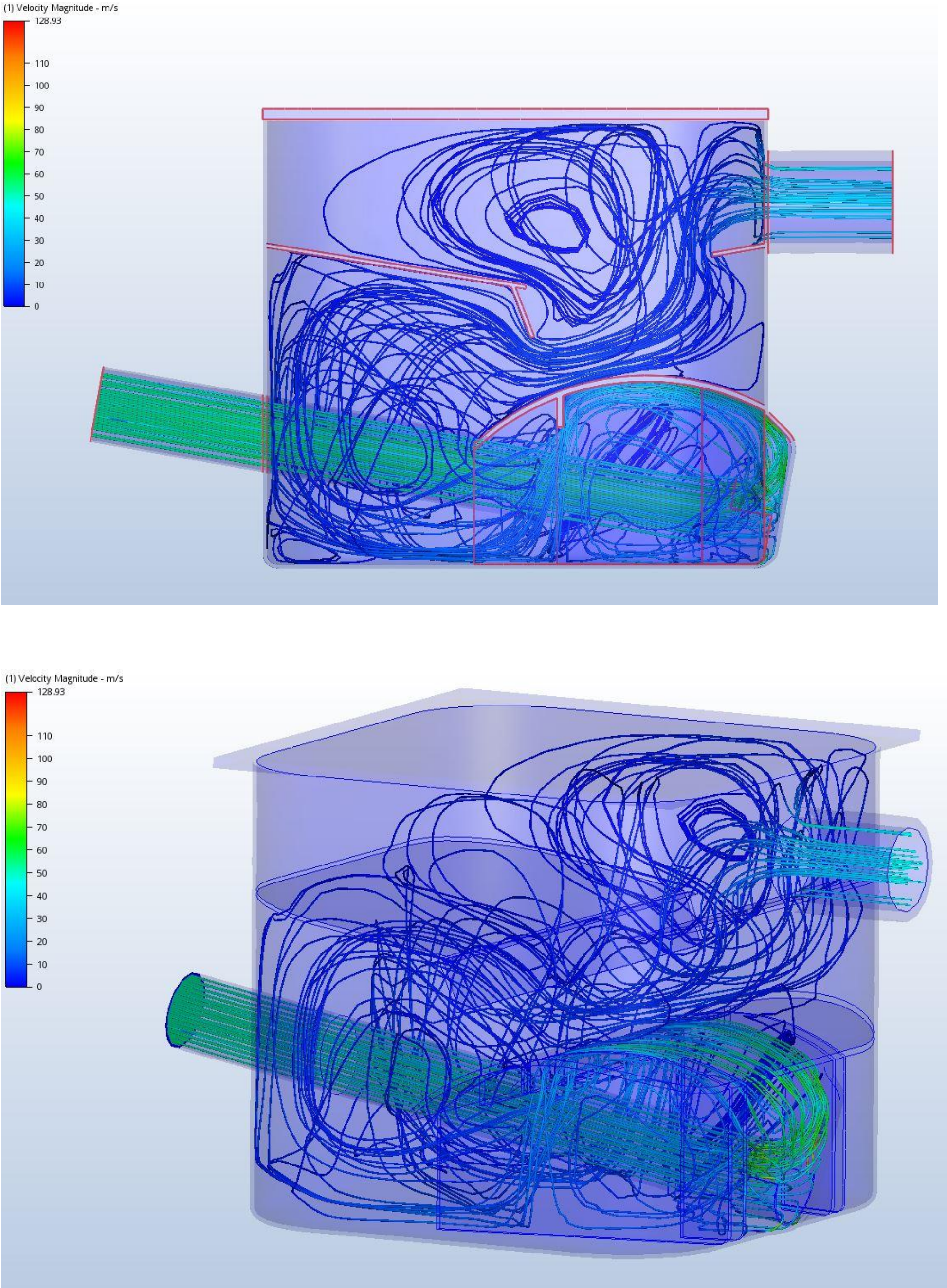


Figure 17. Airflow traced in the final concept P.

4.8.2 Concept Q

In concept Q (Figure 18), the main difference from the KPI is the elimination of the bending by placing the inlet pipe to one of the sides. To gain a circular motion, a wall was added close to the pipe exit to push the air flow upwards into roof of the mixing chamber. The mixing chamber then redirects the air into the water once again.

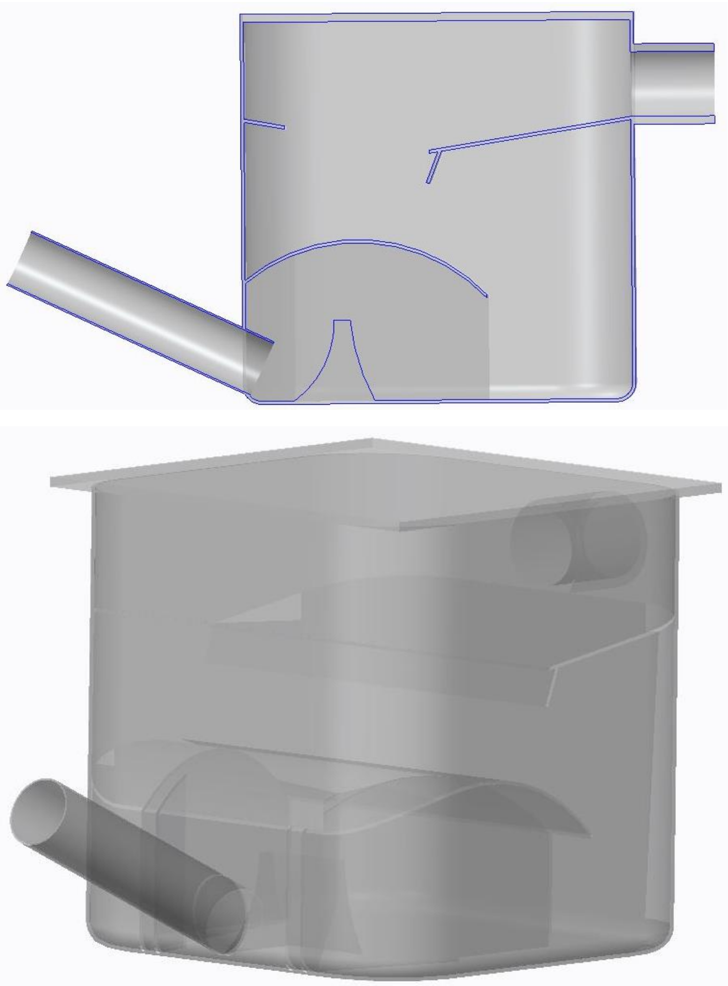


Figure 18. Initial variant of the Q concept with impaction wall.

4.8.3 Concept R

In this concept (Figure 19), the pipe is led into the mixing chamber from the front and it retains a bending in the end. But the bend is placed much further down, so that particles will impact in the water, before they impact at the pipe wall at the bend. The air flow can be seen in Figure 20. In the final iteration of concept R (Figure 21), the pipe is led into a bulge and the mixing chamber closely resembles the original configuration. The distance between the inlet and water level makes it harder for water to flow out through the inlet pipe. In the final iteration of concept R (Figure 22) the pressure between inlet and outlet was 8840 Pa.

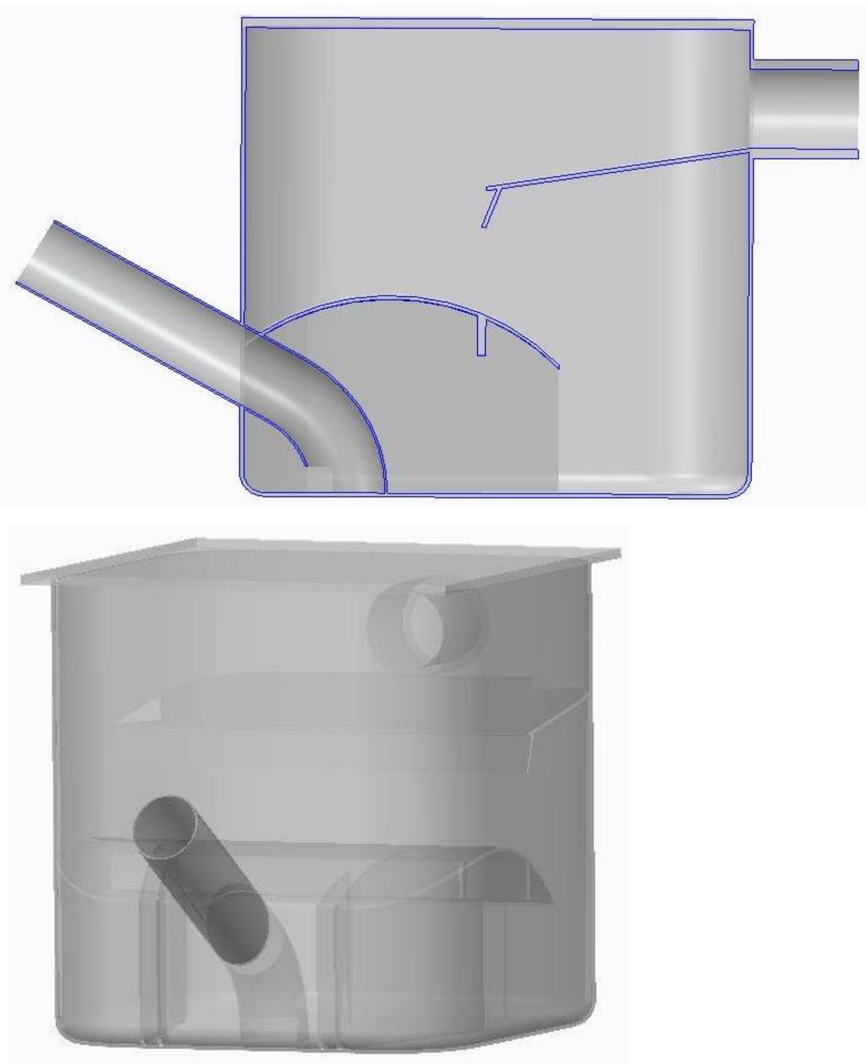


Figure 19. Initial variant of the concept R with a bent pipe configuration.

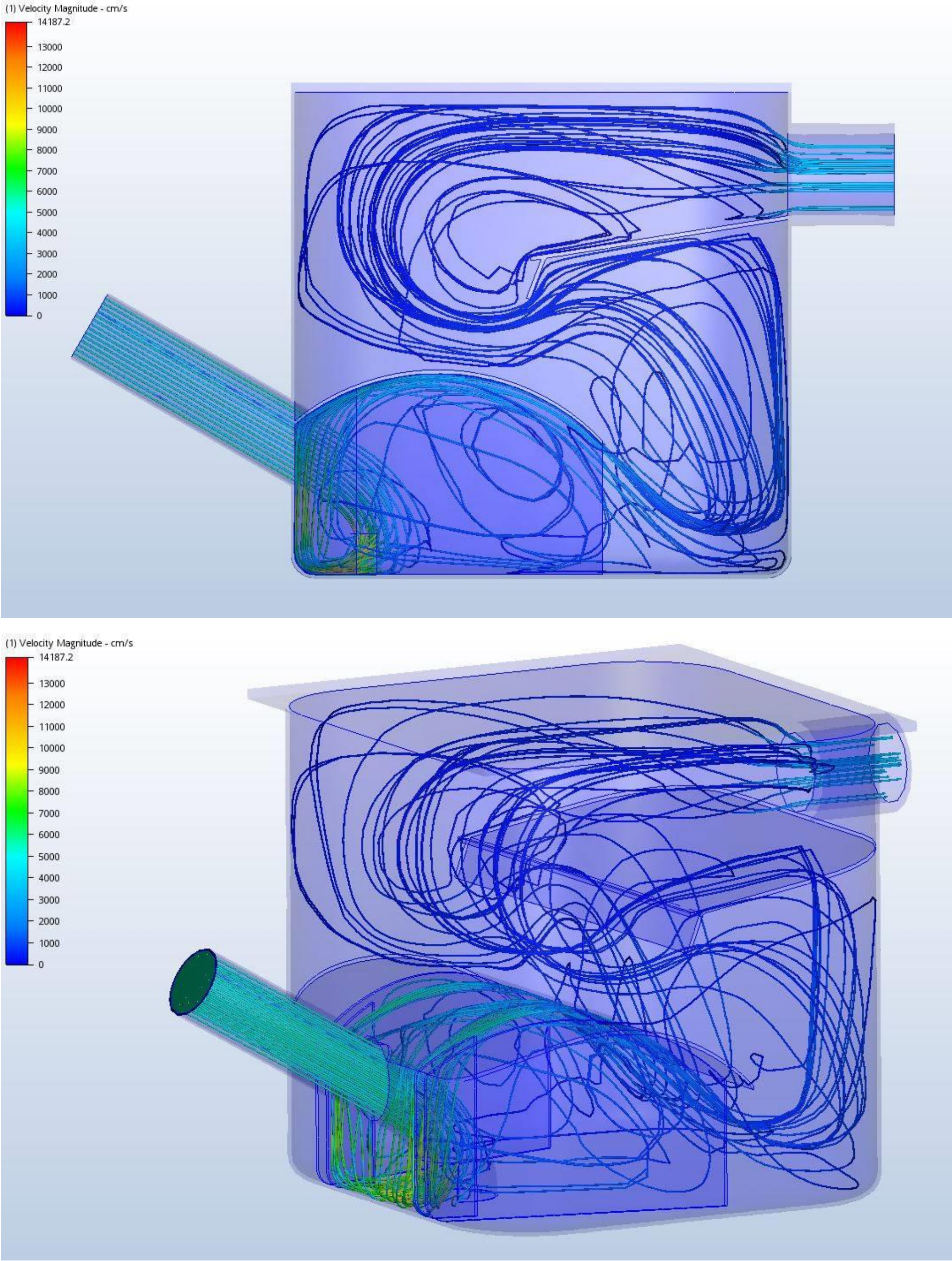


Figure 20. Airflow traced in the initial variant of concept R.

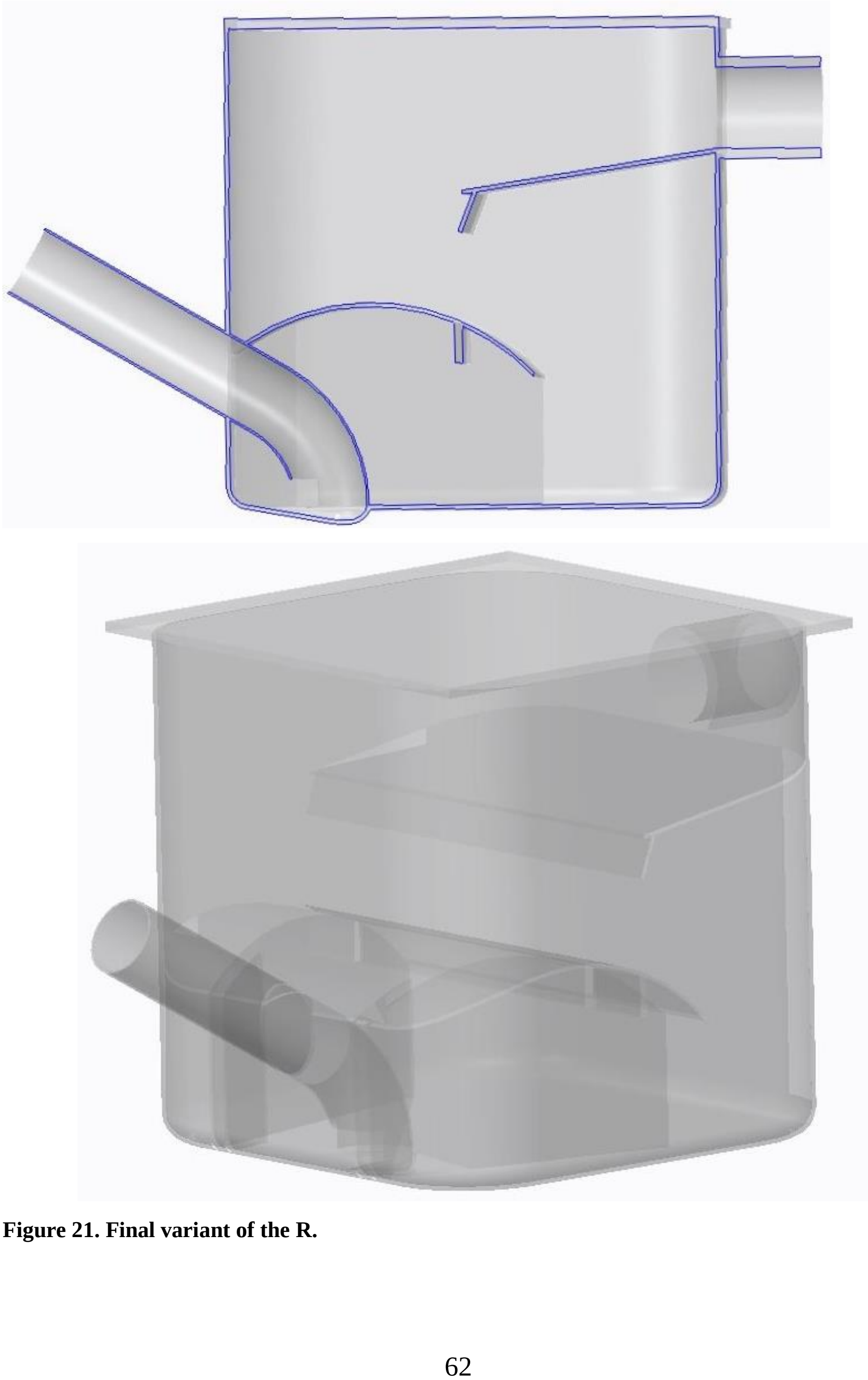


Figure 21. Final variant of the R.

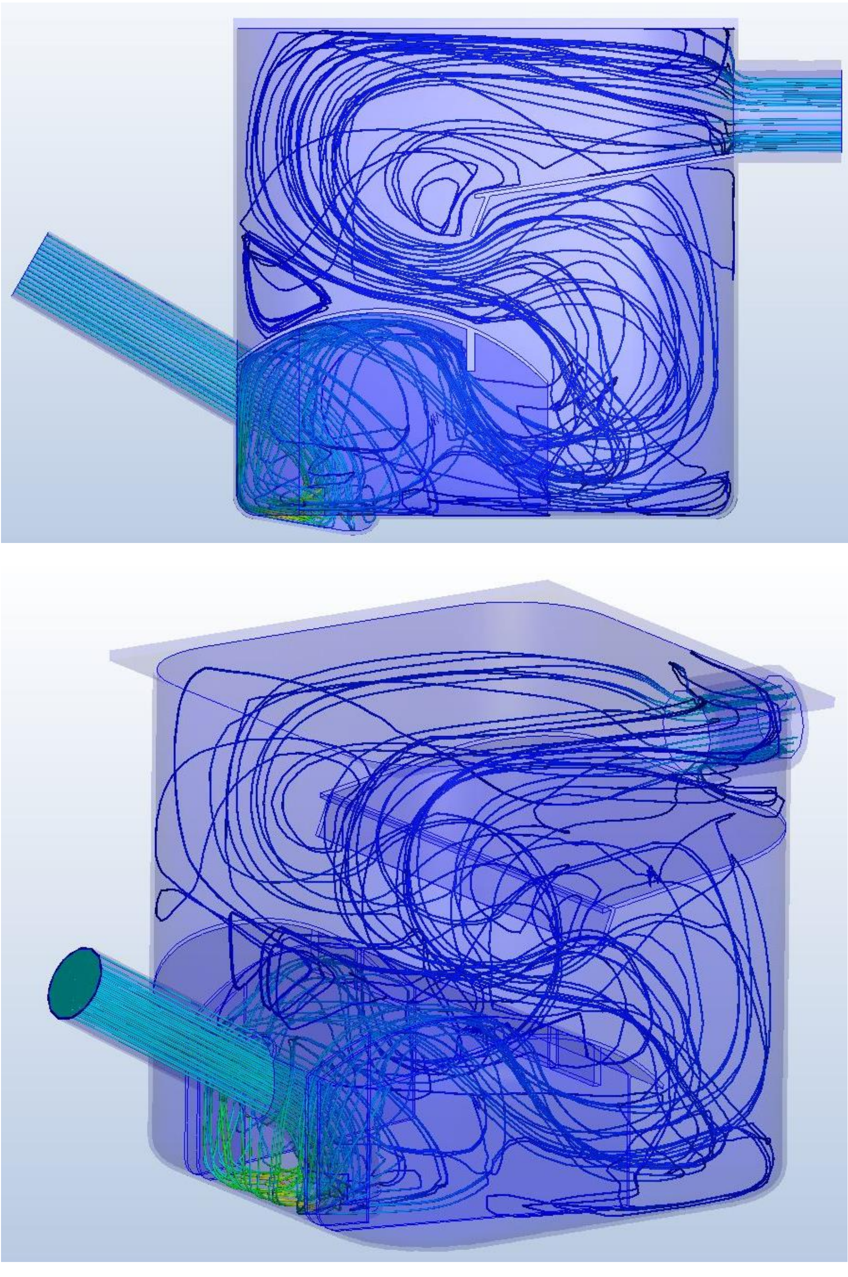


Figure 22. Airflow traced in the final iteration of concept R.

4.8.4 Concept Development Discussion

The purpose of this stage was to systematically explore the solution space available to solve the 6 critical functions described in the beginning of the chapter. Out of the 6 critical functions, the outer shape turned out to be less important. It depended mainly on the printing process and the configuration of the mixing chamber and pipe inlet. The outer shape of course affects how the final product looks but it was not a critical function.

Initially, during the concept development process, perhaps too much attention was focused on the design aspect of shapes, lids and handles. The decision for this was based on the initial assumption that the internal mixing chamber and inlet would not be changed because of the difficulties in accurately predicting and evaluating the behavior of the mixing chamber. Working from that assumption, correcting the many ergonomic deficiencies of the KPI was an obvious way to reach an improved overall product.

As the product was to be used as a measuring instrument, the importance of aesthetics for the final design were downplayed. It was deemed more important to focus on the mixing chamber and to focus on how to properly display the mixing capabilities. Therefore, task shifted from making a complete 3-D printed ready to use prototype, to one prototype for flow characterization and one prototype that conveys the intended look and feel. On another note, it was unexpected that the patent search yielded no useful results.

The authors used brainstorming as a method to generate ideas, however this fared somewhat poorly as the similar levels of experience and lack of stimuli made its impact. Most generated ideas were quite similar. Stronger results could have been produced by involving more people in the brainstorming sessions. However, one should not expect too much from brainstorming as the problems concerning the impinger are too difficult and complex to be solved with spontaneous ideas. A concept generation method that depended less on intuition could have been used as a complement.

4.9 Concept Selection

In this section results from the concept screening process will be described followed by the results from the concept scoring. As mentioned before, the screening and scoring in this case are streamlined compared to the theory of Ulrich & Eppinger.

4.9.1 Concept screening for mixing chambers and inlet

The concepts of the mixing chamber and inlet were evaluated on these criteria:

- The movement of the simulated air flow should be as similar as possible to the original KPI.
- The drag by comparing pressure drops in the simulation.
- Possible impaction areas are alike to the original KPI.
- Retains the shape of the original mixing chamber to preserve the known sampling efficiency of the KPI.

After many iterated flow simulations, the concepts were repeatedly refined until they gained an air flow path similar to the original KPI. However, some drawbacks remained for some concepts and they were hard to compensate for. Unlike generating ideas for handle, lid, the pipe inlet and mixing chamber, concept selection was deemed of critical importance and selection was conducted with more extensive cooperation with biology and aerosol experts.

Concept P has the advantages of not having a bent inlet pipe, which means the particles will impact directly in the liquid. There is also a low inlet pipe angle. As the inlet pipe enters the chamber from the opposite side, the sampling liquid is prevented from being completely spilled out if the impinger is tilted forward by mistake. The original shape of the mixing chamber is better retained in this concept, compared to concept Q. This will probably lead to better sampling efficiency. The main drawback of concept P is that the opening of the inlet pipe which leads into the mixing chamber, is slightly above the water level. There is a slight risk for some particles to follow the air flow and escape through the inlet pipe opening without impacting in the water.

Concept Q has the advantage of no inlet pipe bending. This advantage means the aerosols will impact directly in the sampling liquid. The disadvantages of it is the need to have a low inlet pipe angle, this increases the risk of water being spilt out from the inlet. In case of an accident where it is heavily tilted forwards, it is possible that the entire impinger is emptied off sampling liquid. This can be remedied by increasing the length of the inlet pipe but a long pipe is harder to handle and more expensive. The other disadvantage of this concept is that the shape of the mixing chamber changes greatly. This means it will be hard to predict the sampling efficiency if its internal arrangement is too different from the KPI.

By calculating the water level at 1.5 L, it was suspected that the exit of the inlet in concept R, could cause problems. The backside radius of the bent inlet would begin over the water level and there is a risk that aerosols would impact on its walls instead of the impacting in the liquid, meaning little improvement from the KPI. This concept also had the highest drag resistance compared to the others. The advantages of this concept are that it retains the impaction angle of the KPI and a similar mixing chamber layout is possible. Similarity with the mixing chamber of the KPI, increases the probability of the concept working properly.

The concept that was chosen for development was concept P. While it has some disadvantages, these were deemed the easiest to adjust and fix. The problem with the particles escaping could be solved by lowering the pipe further down into the chamber. The concept P was found to the best compromise between eliminating the bending of the inlet pipe and retaining the shape of the original mixing chamber. Concept P was also the most original design. It was also the concept with least amount of risks identified making it the best variant.

4.9.2 Concept screening for handles

The concepts for handlebars were evaluated on criteria based on checklist for handle design developed by (Patkin, 2001). Together with customer needs, the following evaluation criteria were developed.

- Proper size. To fit the width of the palm, length should be at least 10 to 15 cm. Thickness should be between 3 or 4 cm in diameter for an adult male.
- Signify function, how to use the handle should be easily identified and its effects predictable.
- Allow for bungie cords to latch into.
- Stick out as little as possible from the impinger to reduce manufacturing cost.
- Be stiff to allow a firm grip.

The concepts selected were a large round grip on the top of the impinger and two triangular ones on the side. The top handle is designed to be sturdy and allow for a powerful grip so that the impinger could be comfortably carried while fully loaded. The triangular handles chosen would be narrower as they protrude outwards and therefore directly influences the cost of 3D printing. The side handles are wide enough to be used with gloves and there is a small wall on the inside to secure the grip.

4.9.3 Concept screening for lid and closing mechanism

The lid design concepts were evaluated on criteria based on:

- Open and closable with one hand.
- How secure it is.
- Tightness of seal.
- The outer lid edges overlap and cover the bottom part.
- Carriable with one hand.
- Can be fastened in place with a bungee cord.
- Manufacturing cost.
- Minimum interference with flow.

Most of the lid concepts could not pass the criteria in a satisfactory way. Many of the concepts would either interfere with the flow or require multiple different materials for manufacturing. Two of the suggestions were deemed most successful. Firstly, the plastic lunch box design where a rubber seal fastened the lid in place and enclosed it. Secondly, the toolbox design latches were selected because the latches make the locking mechanism durable and secure. These two were combined to get the final lid design.

4.9.4 Concept screening for insertion and removal mechanisms

The concepts for liquid insertion and removal, were evaluated on criteria based on:

- Compatibility with common laboratory equipment
- Minimum of interference with flow inside the mixing chamber
- Manufacturing cost

Because of the compatibility requirements with existing laboratory equipment, the only concept that could be selected was the injection vial with rubber bungs. If something happens with a rubber bung, it can easily be replaced. There was strong desire from the biology expert to use this type of arrangement.

4.9.5 Concept refinement

After selecting concept P, it was decided to develop a simpler prototype for testing, in order to see how well the CFD analysis predicts the behavior of the internal mixing chamber. The refinement was done in two steps. In the first step, a cost reducing design process was initiated and in the second step, additional designs of the internal mixing chamber were made and evaluated.

Because of the 3D-printing process being cost dependent on size, some features were omitted to reduce manufacturing costs. The lid was deemed not to be necessary for the flow tests and by removing it, the manufacturing cost could be reduced by 30%. The cost was calculated by importing the CAD-models in Shapeways and getting an estimation. The height of the concept could be reduced without impacting the air flow. It is assumed that once the air passes the wall above the mixing chamber, there are no changes introduced to the air flow. The position of the outlet has been changed to the top to reduce the overall height.

The part of the inlet pipe that sticks out is removed to keep the overall size down. This part is mandatory in the final product but is not necessary for the functional prototype test, because the test will not be conducted in the tubing used in aircraft sampling.

For the functional tests, 3 ports for addition/removal of liquid are added. That is one more than is necessary for the final product. The reason for the additional port is to dye to the liquid during the functional tests. This port should not be used on the final product. In both refined concepts, care was taken to ensure that the internal structure of the mixing chamber corresponds as close as possible to the KPI.

4.9.6 Concept P1

In this variant (Figure 23), the inlet pipe is lowered further down in relation to the liquid surface. This is to prevent particles from escaping impaction in the liquid by following with air stream. This concept P1 differ from the others by having a 90-degree angle between the pipe inlet and the impaction wall. The wall was designed by an iterative process where small incremental changes were introduced after several air flow simulations were made (Figure 24). The pressure drop between inlet and outlet was 5130 Pa.

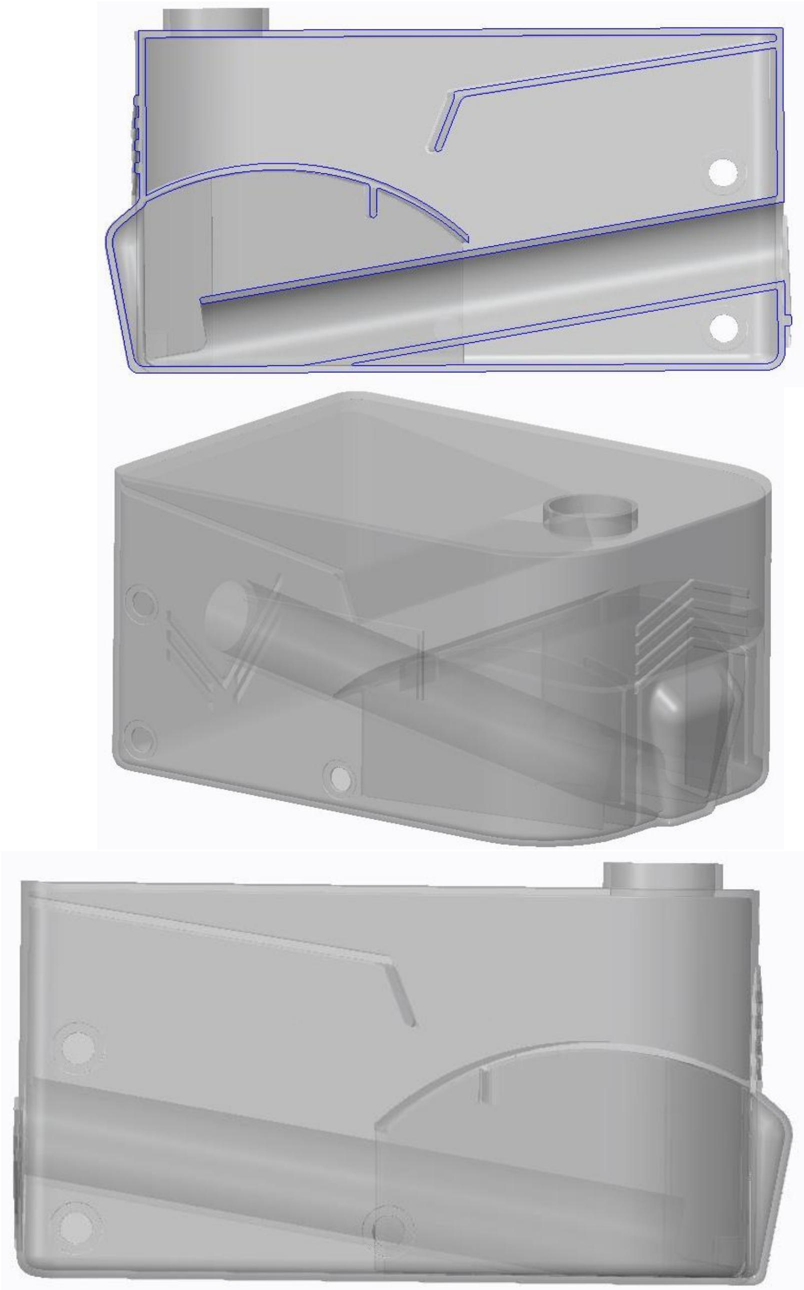


Figure 23. Different views of concept P1.

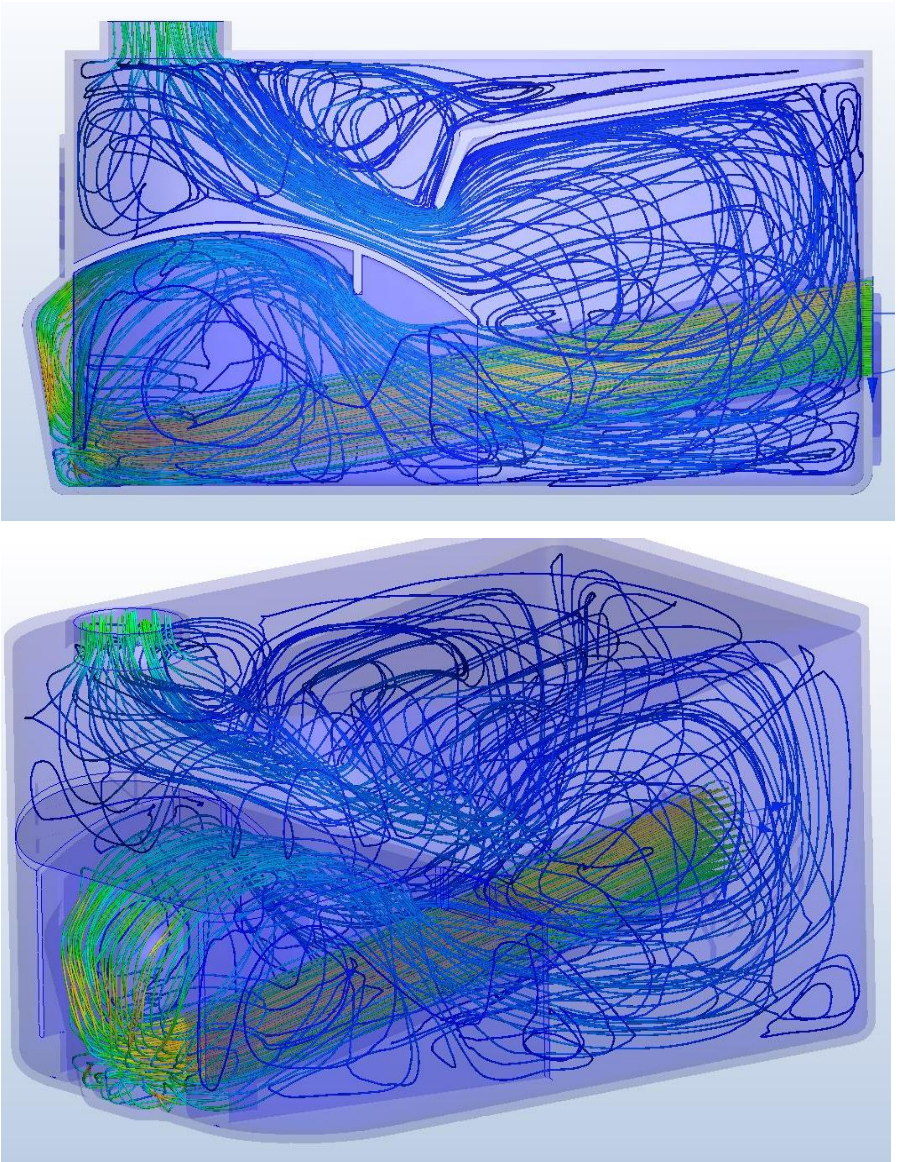


Figure 24. Airflow traced in the final iteration of concept P1.

4.9.7 Concept P2

In this concept, the idea was to reduce the pressure drop by introducing a more circular wall (Figure 25). This would reduce the drag resistance which would lead to lower power consumption in field sampling conducted on the ground. Another feature of this concept is that the inlet protrudes into a lump, which leads to the inlet pipe opening being further down the liquid surface. After several iterations, the pressure drop was reduced to 4200 Pa. The motion of the air can be seen in Figure 26)

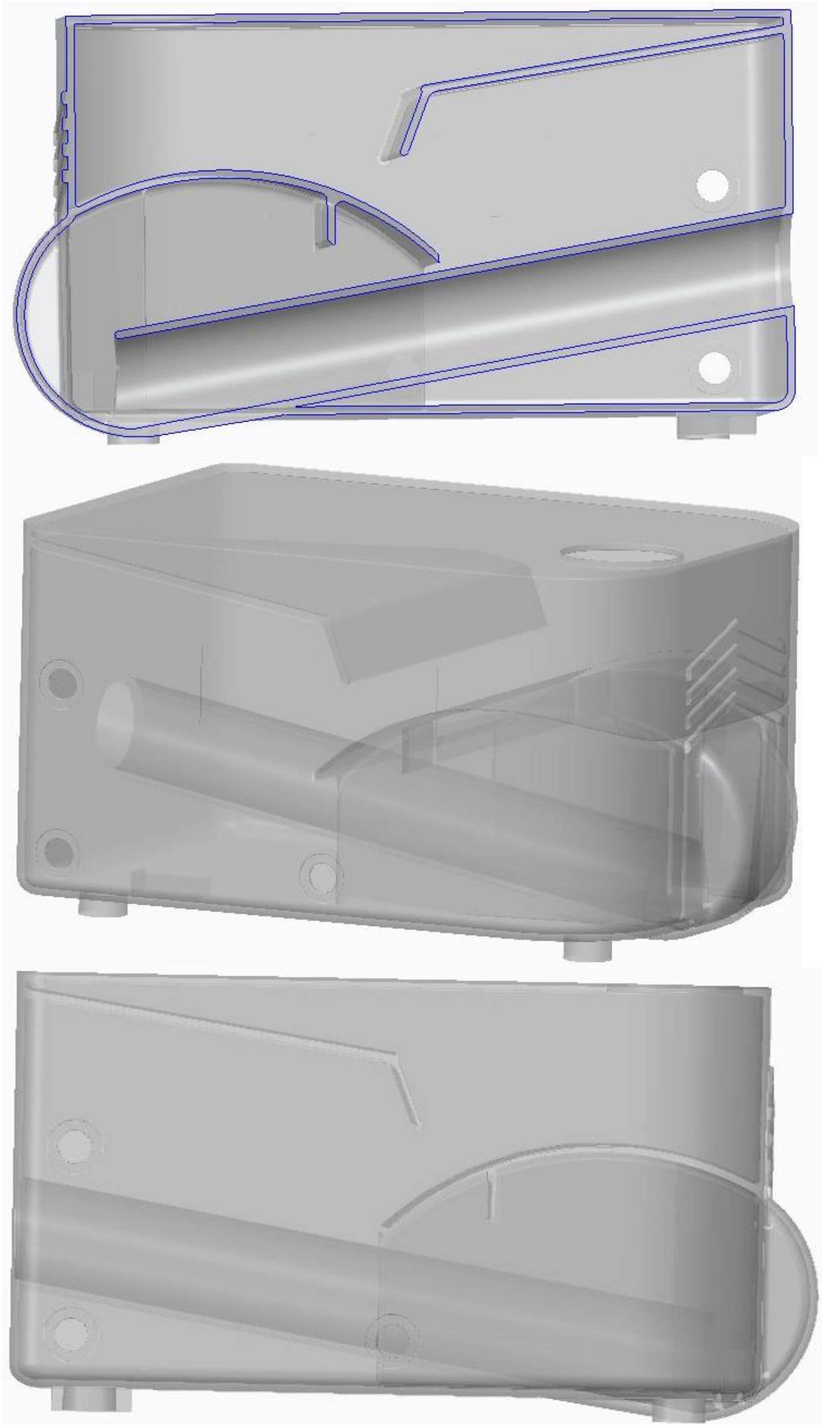


Figure 25. Different views of concept P2.

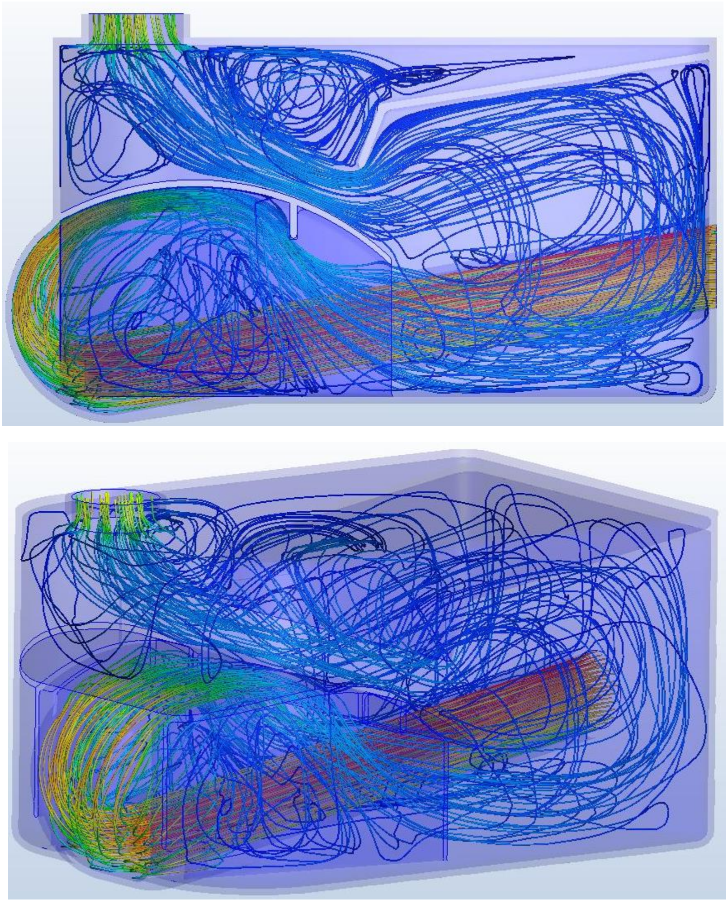


Figure 26. Airflow traced in the final iteration of concept P1.

4.9.8 4.Concept scoring

This final evaluation of mixing chambers corresponds to what Ulrich & Eppinger call concept scoring. After this the point of no return for the concept development phase is passed. The two mixing chambers concepts evaluated are in most aspects quite similar. It was however decided that the increased turbulence of concept P1 was more desirable than the lower pressure drop in model P2. The assumption was that the increased turbulence would improve the mixing capabilities between water and air. The bulge in concept P2 allowed the pipe opening to be lowered further down the water surface and it was considered desirable. In the final concept, the bulge from P2 was combined with the 90-degree impaction wall from P1.

4.9.9 Concept selection discussion

In this step, suitable criteria to compare the different internal mixing chamber concepts was selected. Initially the concepts were compared by visual examination of the simulated air flows and how similar these flows were to the KPI. We are confident that the eliminated concepts during the screening process, do not satisfy the overall sum of criteria better than the winning concept P. However, during the concept scoring process, the evaluation was more difficult and the selected concept P1 is not obviously better than the other one P2. To reduce uncertainties, building both type of mixing chambers and then compare them by testing would have been preferable.

The concepts for lid, handle and liquid insertion/removal were not developed enough to receive a extensive selection method. It would have been advantageous to have developed them further before doing a proper concept screening and scoring. But since lid, handle and liquid removal were deemed to have a limited impact on customer needs and satisfaction, time was better spent simulating and developing better inlet and mixing chambers. Therefore, no concept scoring was made for the lid, handles and liquid insertion/removal. The end result is still deemed satisfactory.

During the screening and scoring of the critical inlet and mixing chamber, the authors of the thesis received consultation from the supervisors when deciding the outcome. Selection of the liquid insertion/removal was done by authors with consultation from the biology supervisor. The selection of lid was done by the authors alone based on customer needs.

Most of the criteria used in the screening are based on customer needs but some such as manufacturing cost are not. However, somebody must pay for prototype and keeping costs down is important for the stakeholders of this project.

The criteria for concept selection, were themselves diverse enough, except for the lid criteria where similarities exist between them. Some of them, such as how secure the lid is, are more subjective than the others. To reduce uncertainties, most of the lid designs were based on products that were easy to acquire similar and evaluating them the different factors. The most durable one found, was used for our design.

5 Prototyping and final result

In this section, the prototypes selected will be presented as well as results from the prototype tests.

5.1 Final result, the analytical prototype

This prototype is a 3D rendering and its aim is to describe the feel and intent behind the chosen design. The final design for the impinger includes a lid with an ergonomic handle sticking out on top. The detachable lid features two latches on the side. While the latches have not been tested, the dimensions of their working parts are based on an existing plastic tool box. The handle on top is made with a comfortable round grip (Figure 27). The top handle sticks out and has room for bungie cords to be tied around it, to secure the entire impinger in place. The inside of the lid features a rubber cord to better seal when the lid is closed during transport (Figure 28). The outer wall of the lid envelops the bottom part of the impinger when it is closed, this feature makes it harder for particles to enter from the outside and contaminate the impinger (Figure 29). The lid also features several ribs on the outside for stability and visual appeal. The inspiration for the rib design came from radio equipment from the military. Two inlet ports are featured on the side so that liquid can easily be inserted and removed (Figure 31). Water that gets on top of the mixing chamber should be able to drop back into the bottom by small holes located where the maxing chamber connects to the front wall of the impinger (Figure 32). A rendered version of the final design is seen in Figure 34.

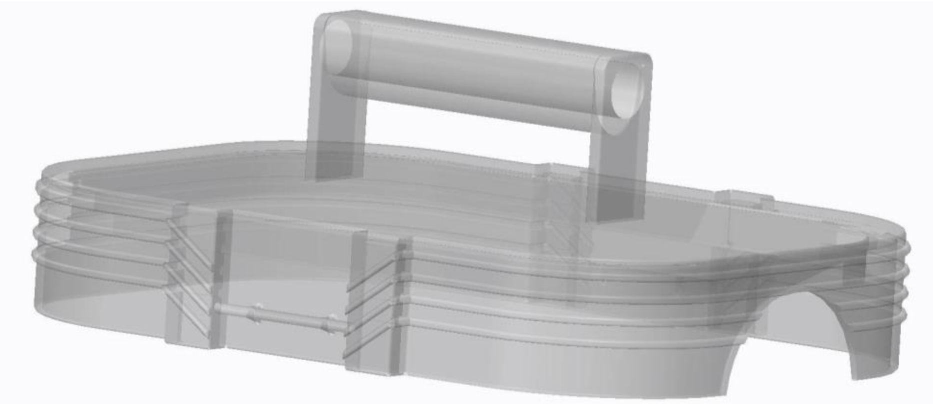


Figure 27. Side view of the lid design.

Figure 28. The bottom of the lid, where the rubber seal should be placed.

Figure 29. Latches and the side handle are illustrated here. The cylinders with dimensions specified for the aircraft piping system are attached on the inlet and outlet of the impinger.

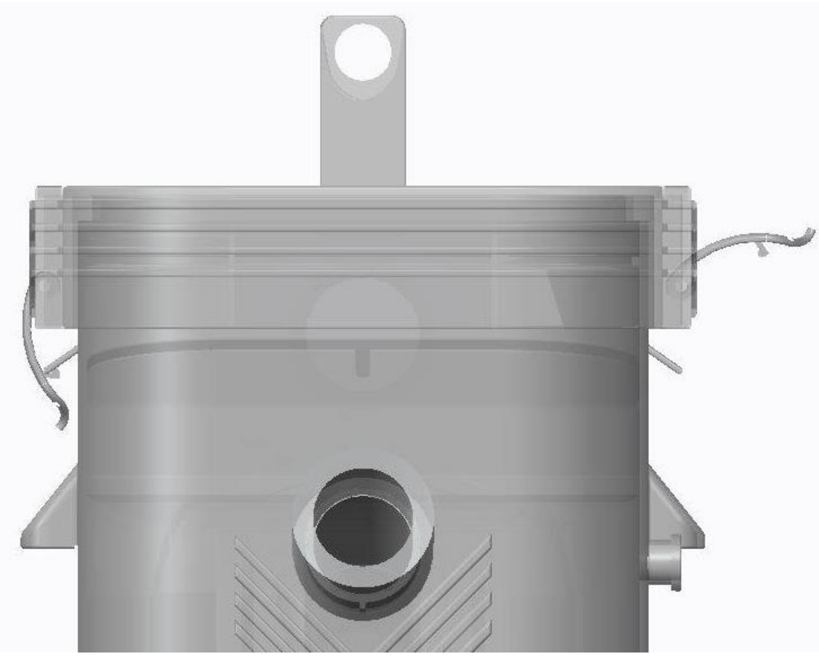


Figure 30. Latches in closed and open position. The side handles are beneath the lid. Right bottom shows the ports for liquid addition and removal.

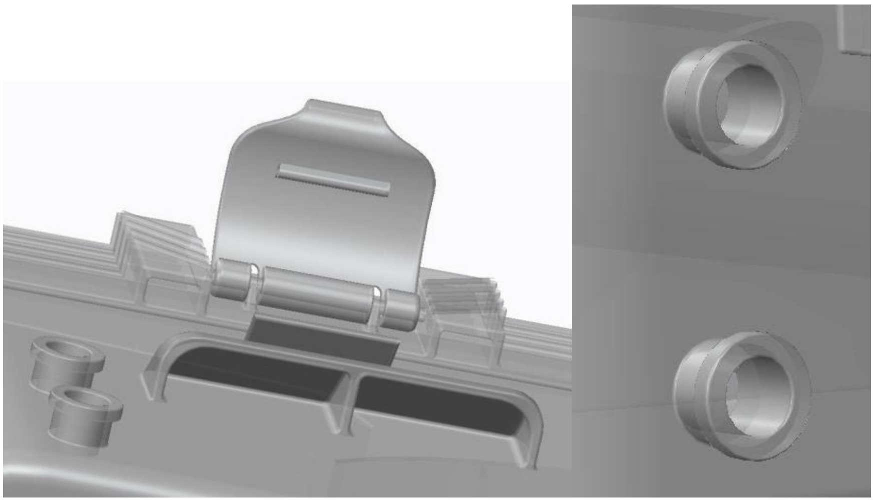


Figure 31. Another view of the open latch, liquid ports and the side handle.

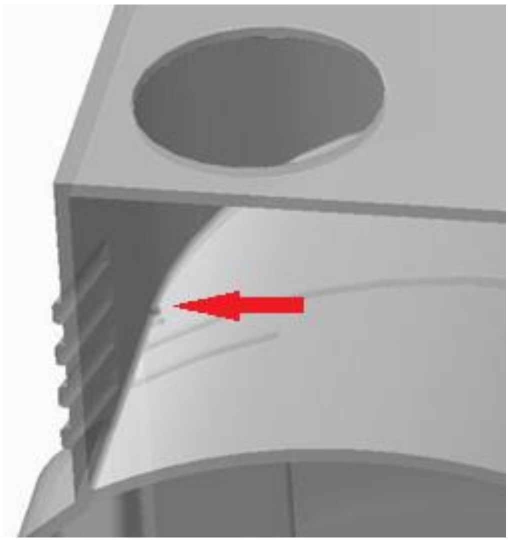


Figure 32. In the front part of the mixing chamber there are two small holes, one on each side of the center line, to facilitate liquid droplets to flow back into the sampling liquid.

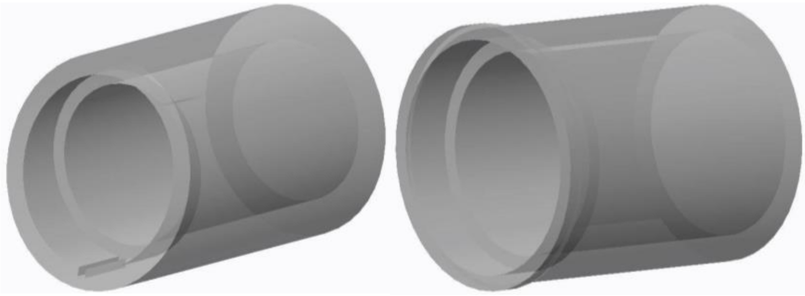


Figure 33. Cylinders for inlet on the left and outlet on the right. These cylinders allow for piping from the specified aircraft measurement system to be attached to the impinger. The inlet cylinder has a groove on the bottom, to make assembly simpler. These cylinders are made as separate parts, preferably 3D printed inside the impinger to save cost.

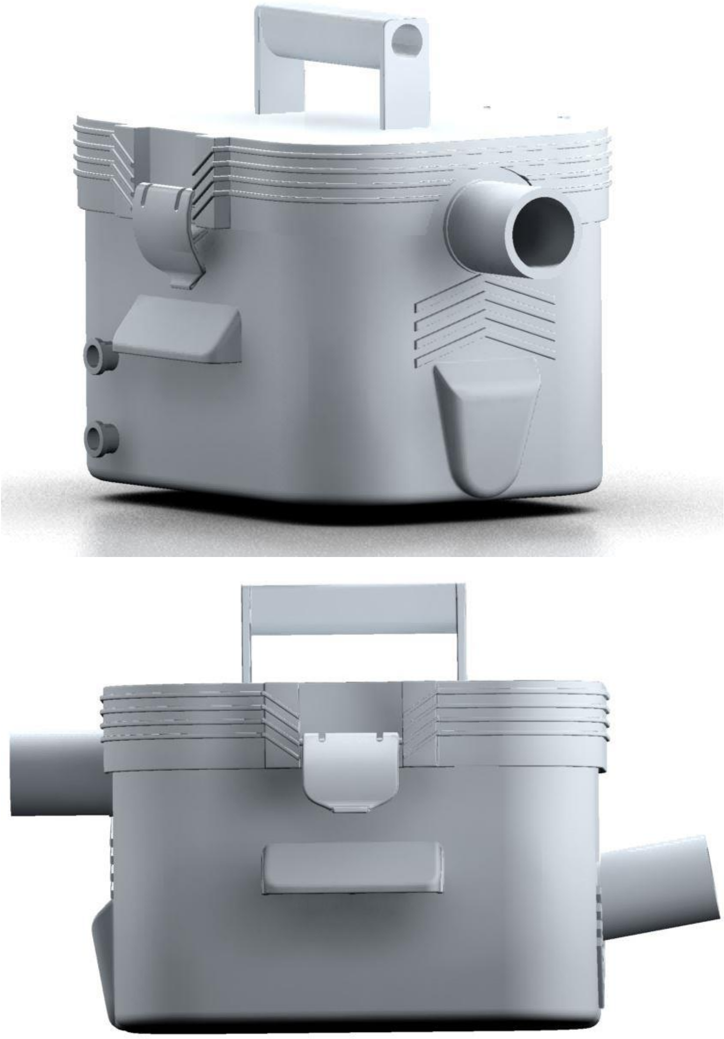


Figure 34. The final design seen from the front and side.

5.2 Final result, physical prototype

The purpose of this prototype was to test the working principles and how well the chosen design would meet the requirements. When 3D printing, the outer volume of the product decides the cost, therefore efforts were undertaken to reduce the overall size as much as possible. This was done in 3 steps. Firstly, some parts were omitted from production such as the entire lid (with latches) and the inlet cylinders. The parts omitted were deemed not be critical for the testing of the prototype. The lid was simplified into a flat shape. The ribs on the inlet side were also cut away. The protruding part of the inlet pipe was cut down and the outlet was moved to the top

Secondly, the size of the impinger had to be reduced. The way this was done was by reducing the height, as the height wouldn’t interfere with the amount of water the impinger holds. After the air passes through the mixing chamber, there are no critical operations left and it can be let out using the shortest possible path. It was assumed that the reduction in height wouldn’t impact on the mixing or water retention capabilities. The third step was to redesign components so that they were detachable and could be 3D printed inside the impinger. The components in question were the exhaust pipe, one side handle and three ports for liquid insertion/removal. These parts were later glued into position by two component epoxy glue. The CAD model of the redesign can be seen in Figure 35.

Initially, the idea was to print the prototype in a transparent plastic material but the cost would then increase by a factor 3. The cost was calculated by uploading the CAD-file to Shapeways and comparing different printing materials. It was decided to instead of printing the whole prototype, only one half would be printed with a piece of a transparent plastic stuck to the open halve. Since the entire impinger is symmetrical, the cut would be made in the middle, parallel to the inlet pipe. It was assumed that the flow would be made visible and undisturbed by this arrangement and would correspond to the CFD analysis in Figure 36. The transparent plastic used in this prototype was made from Plexiglas and it was initially attached with a transparent silicone gel. However, this could not withstand the forces used in the experiment without leakage. Instead a woodworking water resistant polyurethane glue was used. This glue is strong enough to keep the Plexiglas plate in place but the bonding is weak enough so that the plate could be detached without destroying the entire impinger, should the need arise.

As Nylon 12 can absorb small amounts of water, a spray of varnish was applied over the entire to protect the chamber. The outer shell was painted in a bright green colour to look more appealing (Figure 37).

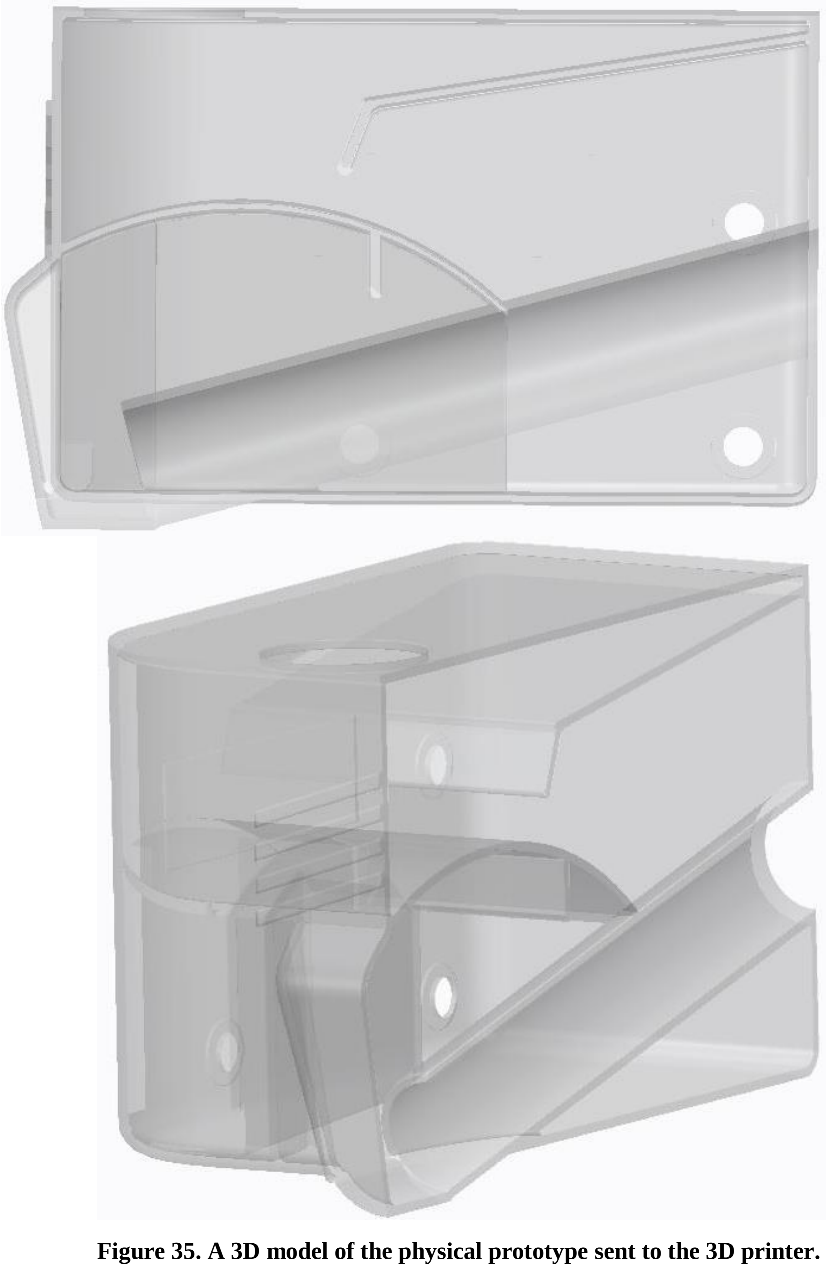


Figure 35. A 3D model of the physical prototype sent to the 3D printer.

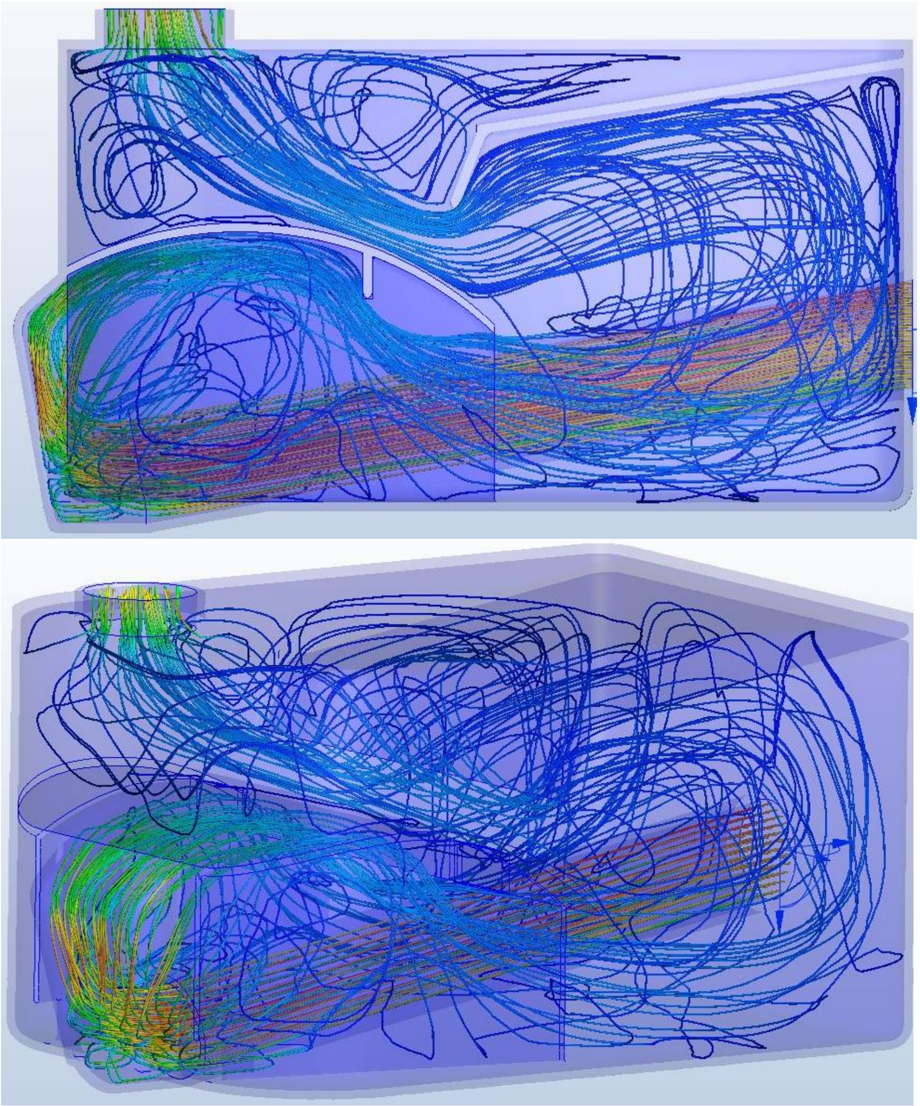


Figure 36. CFD simulation of the flow in the physical prototype.

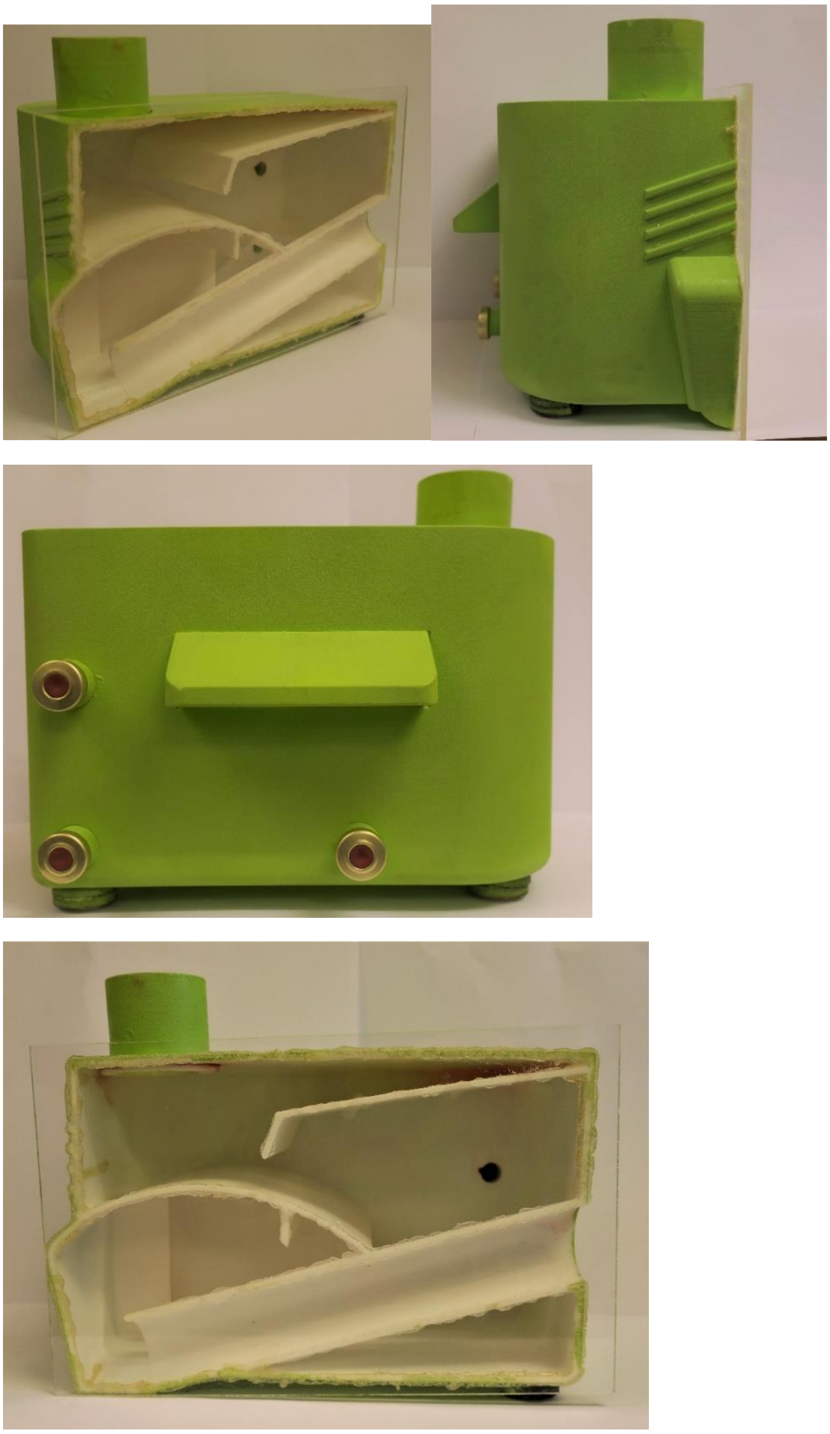


Figure 37. The physical prototype built in this project.

5.3 Results from prototyping tests

During the prototype testing it was found that the water and air flow mixing seemed to match the CFD simulations (Figure 38). The water is pressed back in the tank and then circulates forward through the sidewalls, returning to the mixing chamber as desired. More importantly, the expected vortex appeared inside the mixing chamber.

There was a string of water on the drainage hole located where the mixing chamber connects to the front wall, during operation (seen in Figure 38). The reason for this might be that the air suction through the hole prevents drainage or that the new liquid is brought there in higher rates than it disappears. A possibility is that distance between the baffle plate and the mixing chamber was deemed too short. This might have had the unintended consequence of accelerating air passing through it, increasing the chance for water droplets exiting the impinger by being dragged along. This could at times be observed from water droplets moving on the Plexiglas. The water losses during the test without tilting, can be seen in Figure 39.

By tilting the impinger 30 degrees (the left variant in Figure 38), the total amount of initial water loss decreased (Figure 40). Probably because of gravitation, more water was forced back into the mixing chamber. Tilting also led to a more noticeable vortex being formed in the mixing chamber. The amount of bubbles in the water mixture also increased during tilting. It was also observed that less water droplets were formed in the baffling plate. The string of water above the mixing chamber increased in size and formed a small pool.

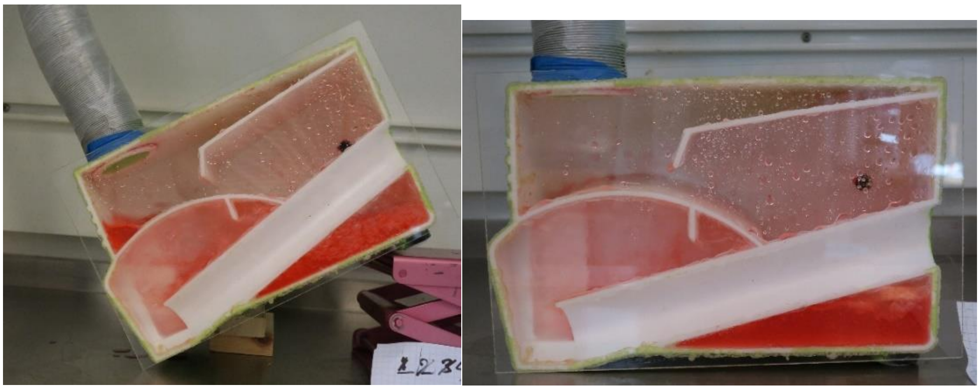
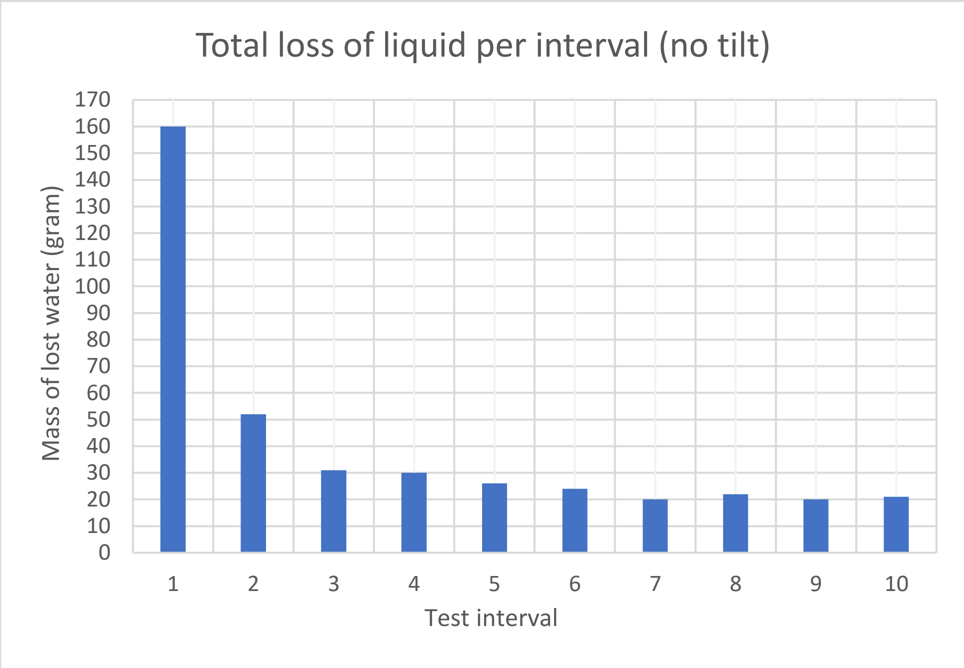


Figure 38. Impinger prototype, loaded with dyed water during testing. The impinger is tilted 30 degrees on the left. The vortex is more visible during tilting.



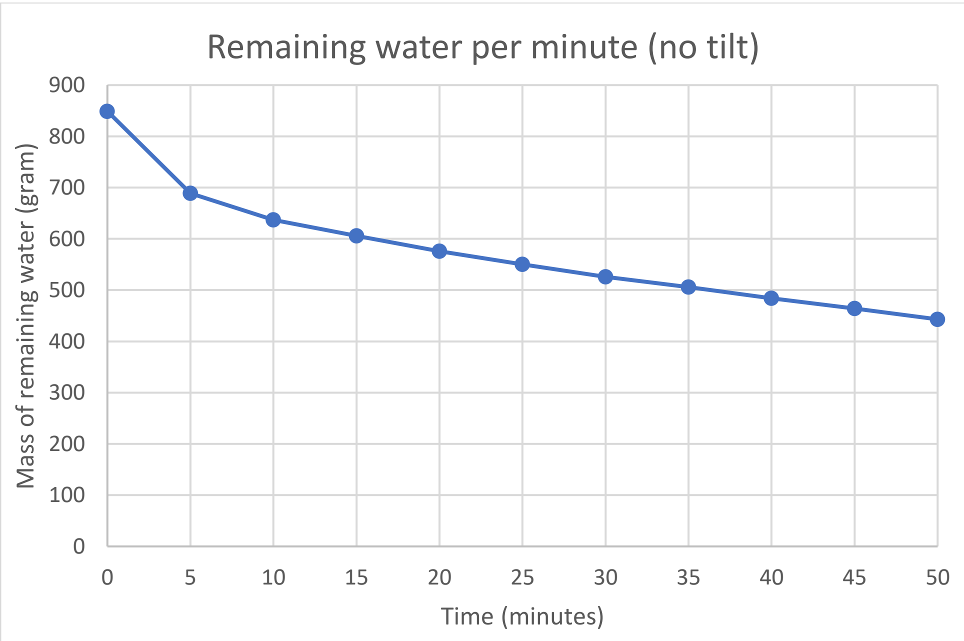
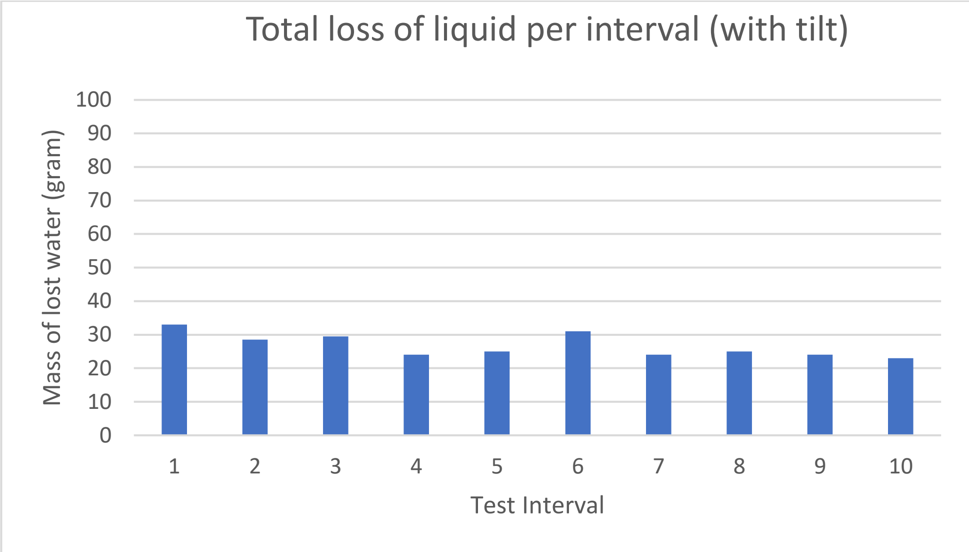


Figure 39. Graphs illustrating water losses when the impinger operates without tilt. There is a notable initial loss of water.



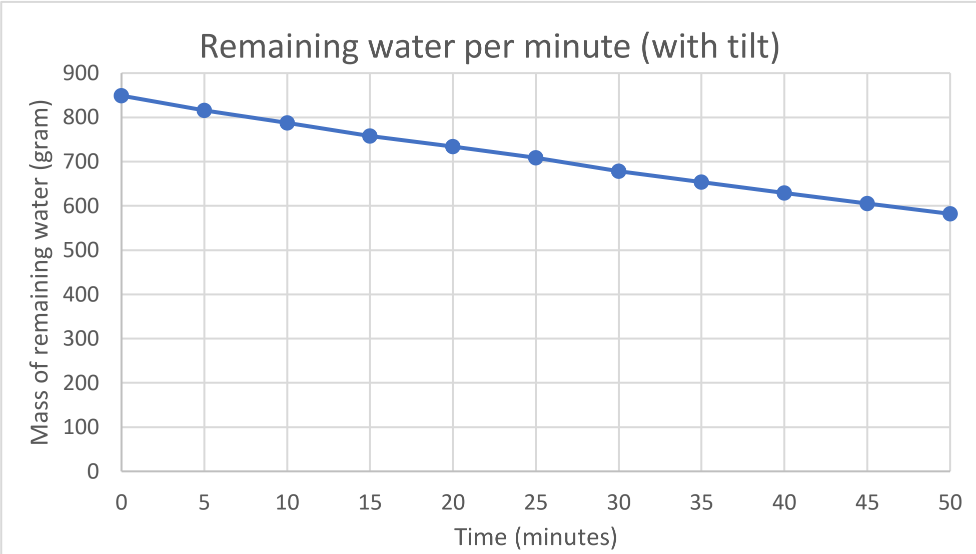


Figure 40. Graphs illustrating liquid losses when the impingers operates with 30-degree tilt. When the impinger is tilted, the water losses are linear.

Another purpose of the prototype test was to examine the capabilities of the liquid insertion ports. The testing was done in three steps. In the first step, the crimping tool for vials was tested on the ports (Figure 41). One of three ports were detached during the test, probably the glue bonding is too weak to tension. When the impinger was operated, no leakage from the ports was noticed. In the second step, the ports were examined by adding liquid into the impinger with a needle, when there was already liquid inside. This worked without any leakage occurring. In the third step, the dye was added during operation. The aim was to examine how the dye would be mixed in the chamber. Unfortunately, the dye spread around too quickly so this could not be examined.

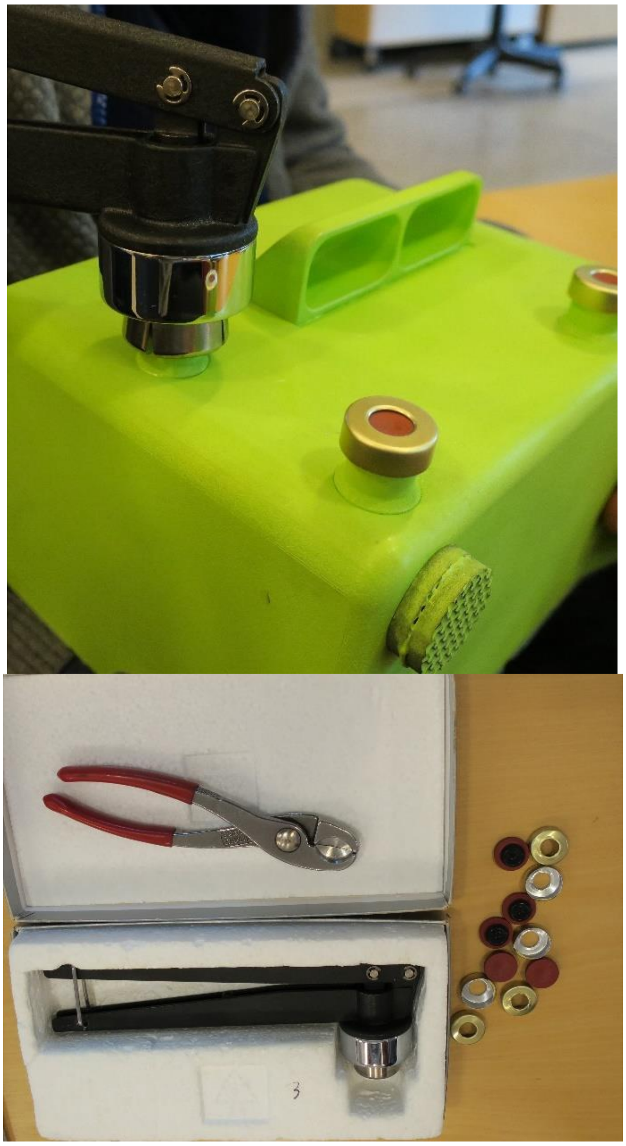


Figure 41. Crimping tool used for testing the ports.

The handle was also tested by pulling and dragging it. The tests were performed with dry and wet hands. The handle was working well but triangular shape makes the grip somewhat flimsy and weak. The triangular shape prevents the fingers from getting a good, solid grip. Bungee cords were fastened on the handles and the grip was good.

5.4 Prototype and final result discussion

Fortunately, the results from the prototyping matched the simulations concerning the airflow and the vortex appeared in the mixing chamber. There were however significant water losses during the testing. These could probably be reduced by moving the outlet towards the middle, which would increase the travel distance for the air stream. Another suggestion is to increase the distance between the baffle plate and the mixing chamber. This can be accomplished by making the entire impinger 1 or 2 cm higher. The shape of the baffle plate above the inlet pipe could be redesigned, it could be simply reduced in length.

Tilting the prototype 30 degrees increased the water retaining ability of the impinger. However, some care should be exercised, as increasing the tilt means also increasing the inlet angle. There is a possibility that the inlet efficiency then decreases, and this must be examined in further work.

When working with the prototype it would have been easier to manage with a lid installed. This need arose when filling up and draining the prototype, which was somewhat awkward with the current setup. During the experiments, a piece of hair fell inside and was very difficult to remove. This further argues for having a lid on the final design. However, certain areas near the pipe impaction point would be hard to access even with a lid.

The side handles met the functionality demands but the ergonomics could be improved. During testing, the handle did not slip easily, felt stiff and firm but the grip was somewhat thin and delicate. This is suitable for precision work, but the 1,5-kg prototype is too heavy to only rest on the knuckles. A stronger side handle grip would be required, preferably one that allows fingers to pass through, in this way the handle would lay in the palm. The grip on the side handles could have slightly more mass in the middle or at the ends, to accommodate rotation. This can also be considered for the top lid handle. The side handles were possible to latch onto with bungee cords without having them breaking. The tests of the handles lead to the conclusion that larger handles could be designed as separate parts and later be attached by gluing.

The insertion holes, did also meet their functionality in terms of shape and form. Syringe insertion and removal of liquid worked without leaks. One of the inlet holes detached from the impinger body during tests with the crimping tool. The reason for this is that glue bonding is too weak, the holes should be integrated into the main body and printed in one piece. The syringe used in the test could only insert 3 mL of liquid, therefore practicalities of drawing out or inserting larger amounts of liquid this way is not known.

In conclusion, the impinger prototype worked. It has higher inlet efficiency than the KPI because the inlet pipe doesn't bend. And just like the KPI, it allows for higher flows than the other impingers found. The prototype is also far more ergonomic than the KPI and sterilization won’t be such an issue because of the autoclavable plastic material used.

One of the drawbacks is that the water losses from the prototype seem higher than the KPI. According to our interviews with field users, the KPI could run for 5 h but it was not clear how many times they had to refill it. It can be seen in Figure 39 and Figure 40 that the prototype at least loses 20 g of water per 5 min. Under a 5 h sampling session, 1.2 L would be lost. It is unclear of this is because of humidity losses or because of the design, it could be that the HEPA filter in the vacuum cleaner prevents water from leaving.

6 Conclusions and Outlook

In this work, a general layout of the impinger is established, a layout that would solve many important requirements detected in the customer needs phase. The flow was analyzed and certain trouble spots were located, that are remedied in the solution presented. The flow was examined analytically with CFD software as well as practical testing. The team did develop a physical prototype and it answered many of questions, especially unanticipated ones.

The Ulrich and Eppinger design methodology used was an immensely helpful guide when designing the prototype and collecting product requirements. It was not helpful during concept generation, evaluation of solutions and or to establish the overall layout and shape. Here it was too general and unspecific, which lead to a riskier intuitive approach being used.

Before finalizing the proposed design solution, it will be necessary to clarify, confirm and optimize many of the details. In the short term, the product has a long way to go before it can be sent to manufacturing, certainly more testing is required. Bioefficiency of the proposed solution needs to be examined, to answer whether the impact velocities would cause damages to the microorganisms. This could be examined by running the prototype in this work next to the KPI in parallel and then compare the particle concentrations collected. Also, the liquid losses on the prototype need to be examined further. The prototype water retention tests need to be run again until there is little water left. The aim would be determining the character of the water losses. Perhaps at some levels, the water losses are exponential and at another level the loss stabilize themselves.

During the prototype testing, a string of water was formed above the mixing chamber. One way to deal with this is to either make bigger drainage holes or more of them.

Some monitoring of the exhaust would also be needed, this to measure pressure drop and overall drag, the amount of bioaerosols the exhaust air is laced with and the relative humidity at the outlet. Measuring the pressure drop needs to be done on the prototype as this can verify the pressure drops from the CFD analysis. As mentioned before, the baffle plate above the inlet pipe and the ports need to be redesigned. The side handles could be more ergonomic by making them thicker, rounded and more mass in the middle.

The product developed during this work is of very complex character. The transparency of the relationship between inputs and outputs is still low. To fully illuminate the workings of the mixing chamber during different flow situations, designing a testing rig would have been preferable. In this way, direct and indirect effects of changing the layout and different design parameters of the mixing chamber would be easier to monitor. The redesign could be done by acquiring a simple plastic box with the dimensions matching the desired outer shell of the impinger. Slots or sliding grooves would then be put on the inner walls, so that the baffling plate, mixing chamber and the pipe could then be assembled in different configurations. In this way, more could be learned about the flow process without printing a large prototype each time something is changed. In terms of collection efficiency, inlet efficiency and biological collection efficiency, working with analytical tools alone is not possible and practical test have to be conducted.

Another issue worth examining a bit further is design for assembly. While some of this was used in this work, such as the handles and inlet ports being separate and then glued on, one could go on much further. The entire outer shell for example could be split into 4 separate parts that are 3D printed inside each other, reducing the total printing area and cost with 75%. Of course, this would require extensive redesign, to make sure that the product after assembly will end up being sturdy and the changes wouldn't affect the product properties in a negative way.

The airborne sampling methods examined here were done by aircraft and tethered balloons. In the future, drones would be used as they are much cheaper compared to manned aircraft. The design solution proposed we propose is small, light and requires no need for a pump if the drone picks up enough velocity. What would be needed is an automatic liquid refilling system, to compensate for losses during the sampling session. For all types of air sampling, connections with the inlet needs to be investigated. The inlet tubing length and amount of bends needs to be kept at a minium. The best way would be to omit them completely by putting the impinger outside the aircraft. Also in this case, an automatic system that manages refilling, needs to be developed. While it has not been investigated in this work, developing an inlet nozzle that draws the atmospheric air into the impinger inlet pipe, is of paramount importance to the overall efficiency of an air sampling system. That needs to be developed in further work.

Two great challenges had to be tackled during this design process. The perhaps greatest was to recognize and manage trade-offs in a way to increase the success of the product. For example, was time and energy spent on designing a lid meaningful? Wouldn't it have been better to spend this time on testing the prototype? Maybe in hindsight, after the total cost increase the lid would bring was known. But during the prototype testing, it was found that a lid would make things easier to work with. Furthermore, it was much harder to anticipate how the product would work than we imagined. So, how should things be evaluated? One would think that more scientific methods are available than visually examining the flow and mixing. And perhaps this is something as well for the future.

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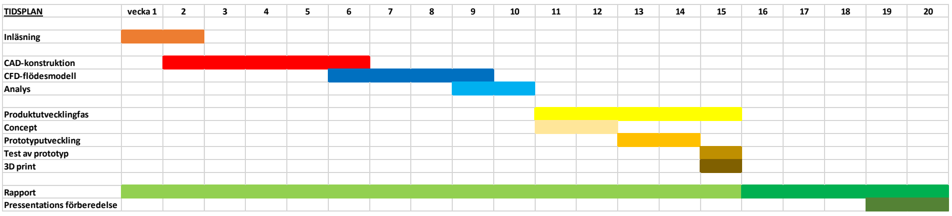
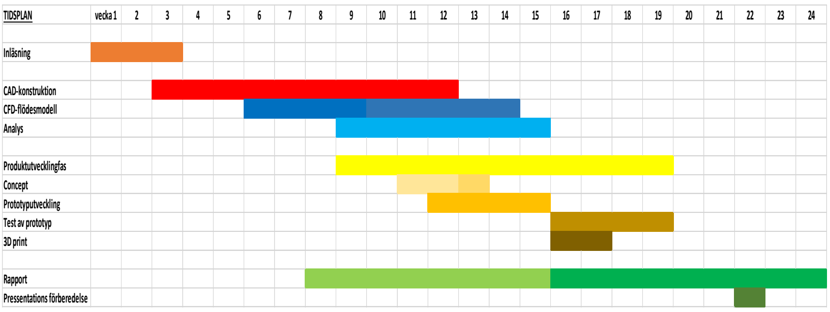
7 Appendix A1 Time schedule

7.1 A.1.1 Initial time schedule



A.1.2 Actual time schedule



Appendix A.1.3 Division of labor

The work has been carried out in collaboration between the two students throughout the entire project. Hamza took the main responsibility for writing the report while Saman took the main responsibility for CFD analysis and prototyping. CAD modelling was done together. No further division is necessary to report.

8 Appendix A2 Poster

Designing an Improved Sampling Device for Bacteria in Air

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[1] Department of Design Sciences, Lund University.
[2] Department of Environmental Science, Arhus University.

BACKGROUND

There is currently no satisfiable high-volume-flow impinger for health and environmental applications. A prototype has been developed and tested with good results[1]; It utilizes a sophisticated mixing chamber, inside which the bacterial particles are being stripped from the air, flowing at approx. 2 L/min, into 1.5 L of an aqueous liquid. In the transition from air to liquid, bacteria are concentrated by several orders of magnitude and preserved for later analysis. The efficiency of the prototype was characterized recently[2]. However, as the prototype was not originally designed for microbiology, limitations persist in terms of usability, sterility, size and weight.

AIM

The aim is to improve the prototype in order to overcome the current limitations.

The model will be produced from an autoclavable material in order to facilitate sterile sampling conditions. It will include a sealed lid and connection ports for easy cleaning and sample exchange.

Other design constraints include minimized airflow resistance, minimized loss of water and maximized retention of particles in the water.

OBJECTIVES AND RESEARCH QUESTIONS

Currently, designs concepts are being generated. Other objectives are:

- How does the air and water flow inside the mixing chamber?
- Where are trouble spots located in the flow?
- Can the inlet be redesigned to reduce bacterial losses during the flow?

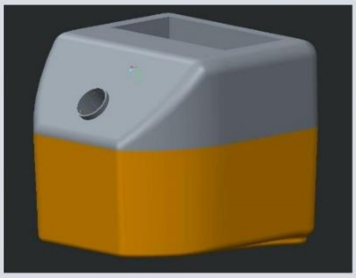

Figure 1. CAD-model of impinger.

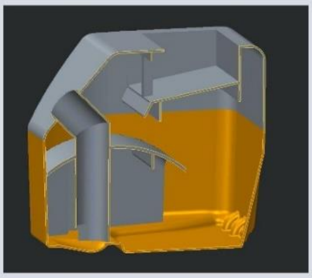

Figure 2. CAD-model of inside of impinger.

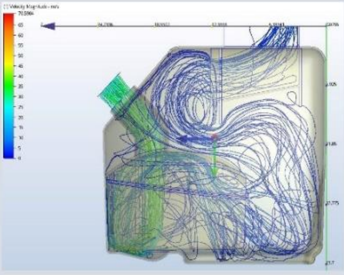

Figure 3. Airflow simulation.

METHODS

By analyzing the air flow of the prototype, areas of improvement will be identified in terms of usability and accuracy.

RESULTS

The prototype has been translated in computer-aided design (CAD) software (Creo Parametrics™ 2.0), Figs. 1 & 2. The CAD model has been exported into a flow analysis software (Autodesk Simulation 2017), so far without considering the liquid phase, Fig. 3. With the data provided from further analysis, a product development phase will be started. Once an optimized model has been achieved, it will be manufactured by 3D printing and tested under working conditions.

1. Ulla Li Zweifel, Åke Hagström, Karin Holmfeldt, Runar Thyrhaug, Camilla Geels, Lise Marie Frohn, Carsten A. Skjøth, Ulrich Gosewinkel Karlson. 2012. High bacterial 16S rRNA gene diversity above the atmospheric boundary layer. Aerobiologia 28 (4): 481 498.
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9 Appendix A3 Interviews

Interview Questions concerning the Kärcher Vaccum Cleaner

- When and why do you use this type of product?

- Walk us through a typical session of using the product?

- What do you like about the product?

- What do you dislike about the product?

- What improvements would you make to the product?

- Can you give us an example of products that work in a similar way?

Interview 1.
The interviewee is experienced with using vacuum cleaners to sample the atmosphere from ground level.

When and why do you use this type of product?
To perform air analysis, especially when large amounts of air are to be analyzed in clean environments.

Walk us through a typical session of using the product?
First step is sterilization. This is an annoying part and takes a long time. First hydrochloric acid is poured in, after which the cleaner is run for 5 minutes. Then it is poured out, carefully. After that, purified water is used to wash the inside of the chamber. In the last step uses 95% etanol is inserted and run in the vacuum cleaner. After that it is poured out. Too pour liquid in and out, is physically demanding because contamination needs to be avoided. It also takes a lot of time.

After that the sampling liquid is inserted, the impinger is put in a sealed plastic bag. The sealed plastic is torn off just before putting it inside the vacuum cleaner. Then the sampling is done for 5 hours. The sampling liquids I've used are RNA-later and PBS. Because of the high salt concentrations of RNA-later, the filters needs to be switched out after 2.5 hours.

Lastly after the sampling is done, the liquid is removed by inserting a vaccum driven hose. The hose is also connected to a filter which the sample passes, and is collected in. This collection is later used for analysis. To insert the hose, the lids need to be open, which could contaminate the sample.

What do you like about the product?
It can use the correct fluid from the start, it works with large amounts of air. And lastly it does not destroy so many bacteria. This is the most important part.

What do you dislike about the product?
It is a bit of clumsy to clean and sterilize under field conditions. It is physically demanding to move the lid and hold it into position during removal of liquids. To put liquid inside is also a bit clunky.

What improvements would you make to the product?
It would be nice to reduce the maintenance during use. Ways of doing it would be to try to remove the filter and hopefully there should be no need to insert more sampling liquid during use. It would make things easier to avoid opening the lid during sterilization and when removing the sample. One suggestion is to have a tap on the side, were liquid can be poured in and removed, without risking contamination.

Interview 2

When do you use this product?
When sampling in environments when bacterial concentration is low. We need to get satisfiable concentration of bacteria for analysis. It takes usually 3-5 hours.

What do you like about the product?
It is very cheap compared to the competitors. It works fine. It handles high flow rates, the competing products could handle 100L / min. This one can do more.

What do you dislike about the product?
Our test showed that concentration sometimes get lower. That should not be possible unless there is particle rebound. Sterilization is hard to make properly because it cannot be autoclaved or put in an oven. Instead we get by with nitric acid and bleach.

What improvements would you make to the product?
Size fractioning of particles and flow meter for concentration. I would use a

collection cube made either out of metal or glass so that sterilization can be made properly.

Do you have any concern regarding how much energy it consumes?
No, since we plugged it in the power grid. I am not sure if it could be used from a battery.

Interview with lead user (ground and air experience)

- *When and why do you use this type of product?*
I've been using samplers for about 8 years. I use them both for ground and airplane operations. I've been using it for arctic research, molecular studies, quantifying ice nuclei. I've also been using it to study efficiency on different impingers.

- *Walk us through a typical session of using the product?*
For ground sampling I prepare everything in the lab. First there is a sterilization process where hydrochloric acid is used, then sterile water and later it is washed with ethanol. I also do a quick run with the vacuum cleaner with these liquids. Afterwards a do a quick sampling, then a test for contamination. This is to see how well the sterilization was carried out. If it is acceptable, then it's ready to run. For airplane operations, it is rinsed in acid, sampling liquid is inserted and then I use duct tape to secure the lid. There is also a rubber stopper put in the inlet to prevent liquid from spraying out or something getting in, during transportation. When assembling the impinger on the airplane, the impinger itself does not take up much time. It is the other activities that take. A metal pipe is put in the inlet which increases the diameter to 5 cm. This pipe is then connected to a tube that leads to the wing.

- *What do you like about the product?*
It samples big volumes, a lot of cells get inside, a lot of difficult to get cells. Another good thing is that different kinds of liquids can be used. I've used fosfatebuffer, it keeps pH levels konstant. This cultivates cells. Other liquids used are those containing high sodium concentrations. These snap freeze molecules.

- *What do you dislike about the product?*
The lid is hard to keep secured. I would like to avoid using duct tape to keep it close. Filters are annoying to use as they are difficult to sterilize. It also clogs and makes running the vacuum cleaner difficult. There is also some evaporation of liquid, which means this has to be checked and liquid must then be inserted. It uses a lot of sampling liquid (around 100-200 L). As you understand sending this half over the world is not cheap. Injection and removal of liquid is impractical. I want to manipulate the sample during field operations, the lid has to be removed and placed somewhere. It should be kept in one place. During sterilization, it is difficult to use it. It is big and not ergonomical. For example it takes up a lot of space and the sterilization process is messy, a lot of acids dripping around. If hydrochloric acid gets into the vacuum cleaner, there are of course problems. The older model was in some was more practical, it was easier to access things inside. It consumes a lot of energy, 1400 watts. I usually run 2-3 samplers simultaneously and honda generators

are needed for each.

- *What improvements would you make to the product?*
I would like to be able to autoclave it. It should also be airtight, right now it can easily fall apart when opened. There should also be inlets and outlets to put in and remove liquid. The inlet of the impinger could be extended so that attaching tubes would be easier. I would remove the filter too. It shouldn't there, it is very hard to sterilize. Some automatization would help a lot. Some of these environments are quite dangerous and running it for five hours without supervision would be great. I have two ideas. Firstly, automatic control of the liquid temperature. Ideally it should be around 5-7 degrees but in arctic conditions the surrounding temperature can be -20. This means slush ice can be formed in the impinger. Also in some environments, it can be hot so the sample needs to be cooled. So it would good to have some kind of heater or cooling system. What about aquarium heaters? Another problem is the evaporation, here too some kind of automatic system could be used. A tank nearby is filled up with sampling liquid and if the sampling liquid gets under a certain weight, it adds more automatically. Currently, the evaporation must be under constant vigil. But in aircraft usage, there is very little evaporation. Maybe it has something to do with the relative humidity as it is higher there about 80-100 %. I don't think re aerosolization is that common of a problem.

As for you suggestion of removing the lid completely, don't think this is a good idea. Sometimes very large particles or something like flies can get inside and need to be taken out. But I would like not having to use the lid often.

Have you used any similar products?
We had the older molder, which was more of a boxy type of thing. They layout on this one had some advantages when trying to access the different parts inside.

10 Appendix A.4 Customer Needs

Customer Statement	Customer Needs
Air flow measurement for the inlet flow.	The impinger is able to measure aerosol concentration.
Particles should not get stuck or destroyed in the bent inlet.	Particles should not get stuck or destroyed in the bent inlet.
Low air flow resistance.	Shorter air flow path.
Should run for at least 5 hours (on a plane).	Particles are retained in the sampling liquid for 5 hours.
Water should not leave the impinger during use.	The airborne particles should not leave the impinger during use
The sampler should be easy to transport.	The sampler is small and lightweight.
Good particle collectability.	It retains sufficient particles from the air stream, in the sampling liquid.
Easy to sterilize in lab.	It can be sterilized under a fume hood.
The sample is protected from contamination.	The impinger is sealed well after sterilization.
I want to add liquid during aerial use.	During aerial use, water can be added to the impinger without compromising the sample.
The sample should be easy to remove from the impinger.	After use, sampling liquid can easily be removed from the impinger without compromising the sample.
Easy to assemble for aerial use.	Short assembly time for aerial use.
Easy to sterilize in the field.	Short amount of operations from the user when sterilizing in field conditions.
Easy to fill up in the field without contamination.	It has an specialised port for inserting liquid.
It should work with large amounts of air.	The impinger works with high volume flows.
It shouldn’t be so clumsy to use.	Weight and size is reduced.

It is hard to handle the lid and prevent contamination when inserting the liquid.	The lid holds itself in place whenever handled.
Maintenance during use should be reduced.	Maintenance time during use should be reduced.
I would like to avoid inserting sampling liquid during use.	The sampler has low losses of liquid.
I would like to have a tap on the side to make removing liquid easier.	Liquid is tappable with simple operations.
I use the sampler with other liquids than water.	The sampler works with other liquids than water (ge exempel).
The sampling liquid is removed by inserting a hose with a filter and then pumping it through. The sample then sticks into the filter.	The liquid sample can be removed with a small hose.
The sampler should work in the field where on generator should be able to run 5-6 simultaneous units.	The electrical energy consumed by the sampler is low.
It is very cheap compared to competitors.	Costs are low.
Sometimes, there is rebound of particles. Concentrations drop when they shouldn't.	Bioaerosols must be retained in the impinger.
Sterilization is done by lowering it in a tank filled with acid and later bleach. However, sterilization cannot be done fully.	The impinger can be fully sterilized
It would be nice if it had a collection cube made of glass or metal so it can be autoclaved or put in an oven.	The impinger is easy to sterilize.

I would like to have a flow meter.	The impinger can measure flow
I would like to have size fractionation of particles.	The impinger can separate particles after size.
I would like to be able to remove the sampling liquid easily without compromising it.	Sampling liquid can be removed without contamination.
I would like the lid to be secured in place.	The lid holds itself firmly in position.
I want the entire container to be airtight for transport.	Inlet and outlet can be sealed.
The filter is annoying to use and hard to sterilize. Hopefully, this can be removed.	The filter doesn't clog up because and is easy to sterilize.
Sometimes during ground level use, large amounts of water evaporate.	Sampling liquid can be added during use.
It requires large amounts of sampling liquid (100-200 L) to do the desired tests.	Volume of sampling liquid can be reduced to save costs.

The lid has to be removed and placed somewhere during certain operations. This can lead to contamination.	The lid can be opened and hold itself in open position.
It consumes about 1400 watts of power.	Reduce the amount power required.
I would like to have some automatic system that could regulate the temperature of the sample.	Automatic control over temperature.
I would like to have an system that can add sampling liquid automatically.	Automatic regulation of sampling liquid content.
I need to use it in extreme environments such as the arctic or pig pens.	The impinger samples in low temperature environments (-20 degrees) or high temperature (37 degrees).

Appendix A.5 Results from water retention test

		Mass without water		782	gram	No tilt	
Test	Time (min)	weight total 1	weight total 2	mean value	water left (gram)	Water loss (gram)	
	0	1630	1632	1631	849		
1	5	1470	1472	1471	689	160	
2	10	1418	1420	1419	637	52	
3	15	1380	1396	1388	606	31	
4	20	1350	1366	1358	576	30	
5	25	1320	1344	1332	550	26	
6	30	1302	1314	1308	526	24	
7	35	1282	1294	1288	506	20	
8	40	1260	1272	1266	484	22	
9	45	1240	1252	1246	464	20	
10	50	1220	1230	1225	443	21	

Test with tilt

Test	Time (min)	weight total 1	weight total 2	mean value	water left (gram)	Water loss (gram)	
	0	1632	1630	1631	849		
1	5	1596	1600	1598	816	33	
2	10	1568	1571	1569,5	787,5	28,5	
3	15	1536	1544	1540	758	29,5	
4	20	1514	1518	1516	734	24	
5	25	1490	1492	1491	709	25	
6	30	1454	1466	1460	678	31	
7	35	1430	1442	1436	654	24	
8	40	1404	1418	1411	629	25	
9	45	1380	1394	1387	605	24	
10	50	1358	1370	1364	582	23	