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HYDRO CYCLONIC SEPARATION OF POLYESTER MICROFIBERS FROM WASHING MACHINE WASTEWATER

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Abstract

Clothing made from synthetic materials shed fibers in washing machines, and these fibers find their way into the effluent water. These fibers can absorb toxic materials in the wastewater treatment plants and can then carry these toxins into other aquatic environments.

It's believed that a hydro cyclone could be scaled down enough to fit into a washing machine and could be used to filter out up to 80% of the microparticles from the effluent water. It's proposed to investigate if a hydro cyclone can be used for this application. The overall goal was for the hydro cyclone to concentrate the micro plastics into a semi solid sludge. A hydro cyclone design and reservoir were designed and tested to show a system efficiency of up to 90%, and the reservoir was able to collect the particles in such a way that they could be disposed of in the trash.

1. Introduction and Problem Description

Plastics are some of the most common materials in our modern world. From automotive parts to food containers, to even the clothing that we wear, plastic and polymer material are found in all of them. The current annual global plastic production rate is estimated to be about 280 million tons (Teresa Rocha-Santos, 2015). Plastic material is cheap and easy to manufacture on a large scale and will not break down quickly. It is this aspect of plastic that is concerning from a sustainability standpoint. When plastics work their way into the environment, they do not decompose quickly, and can become pollutants. The amount of plastic pollution in the environment, and especially in waterways, has become a growing concern in the past decade, especially microplastics which are defined as plastics particles that are smaller than 5 mm (Bellaguzi, 2020). Due to their small size, these microplastics are difficult to sequester, and they have worked their way into environments from fresh water to saltwater, as well as terrestrial environments. One significant source of these microplastics is clothing.

Currently many clothing items are made either partially or completely from synthetic materials such as polyester or nylon. The production of polyester as a clothing fiber has increased from 5.3 million tons in 1980 to 70 million tons in 2018 (Mishra, 2019). As these clothes are worn and washed, the fabric wears and breaks down shedding microfibers that are then carried out in the effluent water. One concern is that these fibers can work their way into the food chain by being ingested by aquatic organisms. Microplastics have already been found to be ingested by marine life at several levels of the marine food chain (Fossi, 2014). Another major concern is that these particles are difficult for wastewater treatment plants to remove with conventional methods, because of the volume of water and the size of the particles. These fibers can absorb toxic materials while in the wastewater treatment plants and can then carry these toxins into other aquatic environments (DeFalco, 2019). Since these microplastics have already been finding their way into organisms, it is likely that the toxins these fibers that have absorbed can also find their way into marine life. While changing the material that clothes are made of natural fibers like cotton, this will not fully solve the problem of microfibers from clothing finding their way into our waterways.

Finding a way to remove these fibers from the water flow while in the washing machine would prevent them from making their way into aquatic environments. Currently, there is no industry standard in washing machines for dealing with these small plastic fibers, although certain models of washing machines have components that aid in the sequestration of pet hairs, which are usually much longer than microfibers, being on the scale of longer than 1 cm. (Vaishnav, 2021). There are several current and past options for dealing with this problem. Conventional and membrane filtration, froth flotation, and density separation techniques have all been or are currently being studied, with varying levels of success. One promising technology is hydro cyclones.

Hydro Cyclones are an existing technology that have been used in the mining and pulp and paper industry for many years to separate solid particles entrained in fluid flows. They are used to separate solid particles from water streams using centrifugal force. Hydro cyclones allow for a high volume of water to be processed, and do not restrict the flow of water through the device, as a filter would.

It is believed that a hydro cyclone can be used successfully to filter microplastics in wash water. A hydro cyclone in this application would not drastically restrict the flow rate of the water, and unlike a filter, would not clog. A hydro cyclone malfunction would not affect the washing machine performance. With the advent of 3 d printing, a standard hydro cyclone can be printed from plastic materials cheaply and quickly. It was investigated if a hydro cyclone could be used for this application.

1.1 Fibers Produced by Washing Clothes

Microplastics as an environmental hazard have only recently been studied. As plastic production has increased over the last decade, dealing with the waste has become a large problem. Most conventional plastics do not break down quickly, so when they are released into the environment, they can persist for decades or hundreds of years. It is estimated that between 5 and 15 million pounds of plastic end up in the ocean annually (Katnelson, 2015) Due to their size and low concentration, microplastics are difficult to detect and accurately quantify, so estimates as to how many tons of microplastics are released, and their chemical makeup are difficult to come by. Textile fibers have been identified as one of the major sources of microplastics in waterways and are estimated to account for 35% of primary microplastics in waterways (Jagadeesh, 2021). Only in recent years have there been truly thorough studies into the ways in which textile fibers enter water ways. The most likely source is from washing machines. Currently there are no official standards as to how to measure and quantify microfibers suspended in water.

In 2019 Francesca DeFalco conducted wash trials with real clothes in a commercial washing machine to try and quantify and characterize the fibers released. Several different types of garments were washed and filtered through different pore size filters. (DeFalco, 2019) Some garments were washed multiple times to assess the effects of multiple washes. The weight of microfibers released ranged from 0.124mg to 0.308mg of fibers per kg of washed garment. This translated to a range of 640,000 microfibers to 1,500,000 microfibers released for each load (De Falco, 2019). The size range of these fibers was 12-16 micrometers in diameter and 360 to 660 micrometers long (De Falco, 2019). This leads to an average fiber weight of 0.000064 mg to 0.000738mg. Note that synthetic and blended fabrics were used in this test, and cellulose fibers were also released during washing. DeFalco conducted trials to understand how multiple washes of the same garment affected the fiber release. These trials showed that as the garment goes through multiples washes, the fibers weight released per wash decreases. However, it is important to note that the garment was not worn or used in between subsequent washes. It is possible that use of a garment in between subsequent washes could change this result.

In 2020 Sarva Praveena also studied the release of microfibers from laundry wastewater. In this study, rather than purchasing clothes and a washing machine and performing washing loads, the researchers went to 99 different households and collected samples of laundry effluent water from their washing machines and studied the results. Results showed that plastic fibers present were polyester, nylon, and acrylic (Praveena 2020). Also, the concentration of microfibers in water ranged from 0.0069g/m^3 to 0.183 g/m^3 with an average concentration of 0.083 g/m^3. The average fiber length measured was 2258.56 micrometer (Praveena, 2020). Just comparing these two studies alone shows that the fiber content and size can vary greatly from place to place. Also, as stated before, much of this variation could stem from the lack of scientific standards for measuring and quantifying microfiber content in water.

In 2020, Ana Galvao conducted a similar study. Clothing, bedding, and towels from 4 domestic households were collected and washed in a commercial washing machine. (Galvao 2020). A total of 205 pieces of textile were washed in 10 separate washing occurrences. The textiles were made of a variety of materials including cotton, polyester, viscose, elastane, and acrylic (Galvao 2020). Some of the articles of clothing were made up of more than one material. The most common fiber released was cotton, which is cellulose based, and not plastic. The most common synthetic fiber released was polyester (Galvao 2020). 79% of microfibers collected in the study were between 50 and 100 micrometers in length, 17% were in the range of 100 to 500 micrometers, and only 4% were larger than 500 micrometers. On average, the concentration of fibers by count, not by weight, was 297,400 fibers/L of washing water, with roughly 56,000 of those fibers being synthetic in nature (Galvao et al). It was estimated that for a washing load of roughly 6 kg, 180,000 synthetic fibers were released into the washing water effluent (Galvao 2020).

Polyester is the most used synthetic fiber in the textile market (Almroth, 2018), and was the most released synthetic fiber found in Galvao's work. Multiple studies have focused on how polyester sheds from textiles during washing. As stated, each study has a slightly different method for characterizing and quantifying the microplastics that are generated during washing. The results have also been reported in different ways, and there is no standard way of conveying how many microfibers are in water. Some studies have reported it as a weight of fibers per liter of wash water. Others have reported it as a count per liter of water. Yet others have reported it as a count per weight of clothing washed. Due to all these different measurements, it is difficult to compare one study to another.

When studying the three most common types of synthetic fiber clothing materials, polyester, acrylic and nylon, (Almroth 2017), Almroth discovered that not just the type of material is important, but also the construction of the garment. Polyester fleece garments released significantly more fibers than knit polyester garments. Fleece polyester garments released 7360 fibers per m^2 of garment area per liter, compared to 87 fibers per m^2 per liter for knit polyester fabrics. Almroth, used a metric of fibers per area of garment washed, per liter of water, to account for the fact that the area of textile washed was recorded, as well as the volume of the wash water. These units are, however, quite confusing, and their calculations show that a fleece garment would release roughly 110,000 fibers per wash as opposed to 900 fibers per wash for a non fleece garment. Almroth also studied how detergents affected the shedding of fibers in the washing process and demonstrated that adding detergent increases the amount of fibers released during the washing process, in some trials close to doubling the amount of fibers released (Almroth 2017). The effects of wear and tear through use of the garments was investigated as part of this study and found that wear and tear increase the amount of fibers released from garments.

A summarized breakdown of the work conducted by Defalco, Praveena, Galvao, and Almroth can be found in table 1.1. The main takeaway is that the units used to record the amount of fiber for all studies is different, and the size findings for fiber length do not compare favorably to each other.

Table 1.1 Previous Fiber Analysis Summary

Researcher	Fiber Materials	Amounts	Size
De Falco, 2019	Polyester, Cotton	0.124 mg to 0.308 mg of fibers per kg of washed garment or 640,000 to 1,500,000 microfibers released for each load	12 microns in diameter by 330 to 660 microns in length
Praveena, 2020	cotton, polyester, nylon, and acrylic	0.183 and 0.007 g/m^3 of wash water	2258.56 microns in length
Galvao, 2020	cotton, polyester, viscose, polyamide, elastane, and acrylic	washing load of 6 kg, 180,000 synthetic fibers are released	79% of microfibers collected between 50 and 100 micrometers in length, 17% in the range of 100 to 500 micrometers, and 4% were larger than 500 micrometers
Almroth, 2020	Polyester fleece and knit	Fleece polyester garments released 7360 fibers per m^2 of garment area per liter, compared to 87 fibers per m^2 per liter for knit polyester fabrics.	Not Clear

1.2 Physical properties of Fibers

Galvao and Almroth both found the synthetic material most released from the washing of garments is polyester. The physical properties of these polyester particles determines how they will behave in a hydro cyclone. For particles to be separated by a hydro cyclone, the particles need to be of a higher density than water. The density of polyester in ordinary drawn yarn material is 1.39g/cm^3 (Kiron, 2013). This compares favorably to the density of water at standard conditions, which is 0.998 g/cm^3. Some wash cycles are run with hot water, which is less dense, but this change in temperature would have minimal effect on the water in the cyclone, and would likely not affect the separation. Table 1.2 shows the densities of polyester and other materials that may find their way into washing machine wastewater.

Table 1.2 Fibers and Densities Found in Washing Machine Water

Fiber	Density g/cm^3	Source
Polyester	1.39	Kiron, 2013
Polyamide	1.13	Palabiyk, 2000
Cotton	1.52	Delham, 2018
Viscose	1.52	Slapnik, 2022
Nylon	1.14	Yarns and Fibers 2023
Acrylic	1.17	Textile Handbook, 1995

1.3 Current sequestration methods in Literature

There are a number of technologies that could potentially remove microplastics: filtration, froth flotation, continuous centrifugation, and hydro cyclones. Trying to remove these fibers once they have entered a waterway is difficult, so targeting the removal inside the washing machine itself is the most likely method to succeed. Most household washing machines do not have filters at all, and none that target microplastics specifically. Due to the size of the particles, and the relatively low concentration of microfibers, which is on the level of mg of microfibers per liter of wash water, traditional filter set ups are difficult to implement inside of washing machines themselves. Due to the size and shape of the fibers that would be encountered, the pore size of any filter would have to be extremely small to retain most of the microfibers that would need to be collected. Disc filters with an opening size of 18 microns were tested by Simon et al in 2019 and found to retain large fractions of microfibers. (Simon et al, 2019) However using disc filters or other membrane-based filters will inevitably clog which will shut down the entire washing machine. Also, a high-pressure gradient would be needed to quickly filter the effluent water. The main hindrances to using membrane type filters such as disc filters would be the potential of filter fouling and clogging, and the time and pressure requirements to force up to 40 Liters of water, which is an average water volume for laundry loads, through a filter with extremely small pore sizes. Granular filtration reduces these issues by using granules to capture particles based on transport and attachment steps (Zhang 2021). This method would be difficult to fit inside a washing machine due to the large granule volume needed, and would have similar difficulties with time that membrane filtration would. These problems of high volumes and long filtration times would be present in all filtration methods.

Froth Flotation is one form of particle separation that is commonly used in the minerals processing industry. When particles are suspended in water, gas bubbles are blown upwards through the water. The hydrophobic particles stick to the surface of the bubbles, and float until they are all concentrated in the froth at the surface of the fluid (Zhang 2021). The froth can then be removed from the rest of the fluid, leaving behind only the non-hydrophobic particles. The problem with using froth flotation in a washing machine environment would be removing froth layer from the fluid layer. Again, it would take time and space for froth flotation to effectively happen. Also, polyester is not naturally very hydrophobic, meaning that the microplastics would not readily stick to the surface of the air bubbles and so collector chemicals would need to be added (Kim, 2009).

Centrifugal separation methods use centrifugal force to separate particles from fluids. For these technologies to work, the particles must be denser than water. The most common methods are continuous centrifuges and hydro cyclones. Continuous centrifuges use centrifugal force to separate particulates from fluid. In a simple explanation, fluid enters a carrier, that spins very fast. The solids collect on the outside edge of the carrier while the fluid leaves the carrier. For continuous centrifuges, water enters and leaves the carrier device in a continuous fashion. In 2019 Hildebrantd et al conducted a study to evaluate how well continuous centrifuges can separate microplastics from river water. Six different microplastic types of polymers; Polyester, PET, Polystyrene, PVDC, EPS and Polypropylene were tested with size ranges from 1 micron to 1 mm. (Hildebrant, 2019) The efficiency of separation was 96%, based on gravimetric and microscopic analysis. This is a promising efficiency number and won't have the running difficulties that filters have. However, the centrifuge used in the experiment would be difficult to implement in a washing machine environment. The centrifuge used in Hildebrandt's experiment is large (9.5"X11.2"X14.8") and would be very difficult to install inside the chassis of a washing machine. While an external attachment would theoretically be possible, such an external modification would be clunky and inconvenient to deal with for a consumer. Another problem with using a centrifuge in commercial washing machines would be the prohibitively large cost. The centrifuge used in Hildebrat's experiments costs over $1400 (Thermo Fisher Scientific). Even if it is assumed that mass production of centrifuges could drop the price down to roughly $1000, that would still be a significant cost increase for the washing machine, which on average costs around $700 to $1500. This increase in investment would nearly double the cost of washing machines.

1.4 Hydro Cyclone Theory and Design

Hydro cyclones on the other hand have a much smaller footprint than centrifuges, and since there are no moving parts inside of the hydro cyclone, they are much cheaper to manufacture. Hydro cyclones have been widely used in the mining and paper industry to remove pulp fibers or mine tailings from water streams for decades, with successful installations in the coal and paper industry as early as the 1930s (Bradley, 1964). There are several different design equations, but the most used design equations are the Ateburn equations and the Bradley relations. The Bradley relations equate the other important dimensions such as the spigot, feed inlet and vortex diameter to the diameter of the cyclone body.

One of the main benefits of using a hydro cyclone to remove solids from water is that unlike traditional filters, hydro cyclones do not restrict the flow rate of the water as they filter. In fact, increasing the flow of liquid into a hydro cyclone can increase the efficiency of, depending on the Reynolds number (Hildebrandt 2019). Hydro cyclones use centrifugal force and density difference to separate particles from water flows. Water flows into the inlet of the cyclone and then flows in a circular pattern down the body of the cone. As the water is spinning around the outside of the conical section, centrifugal force pushes water and some of the particles outwards towards the edge of the cyclone. Particles of certain size or weight and some of the water will flow down and out of the apex. The rest of the water and remaining particles will flow up and out of the hydro cyclone via the vortex. Figure 1 below shows well the flow pattern of a generalized hydro cyclone, as well as the main dimensions that are important in the design of the hydro cyclone.

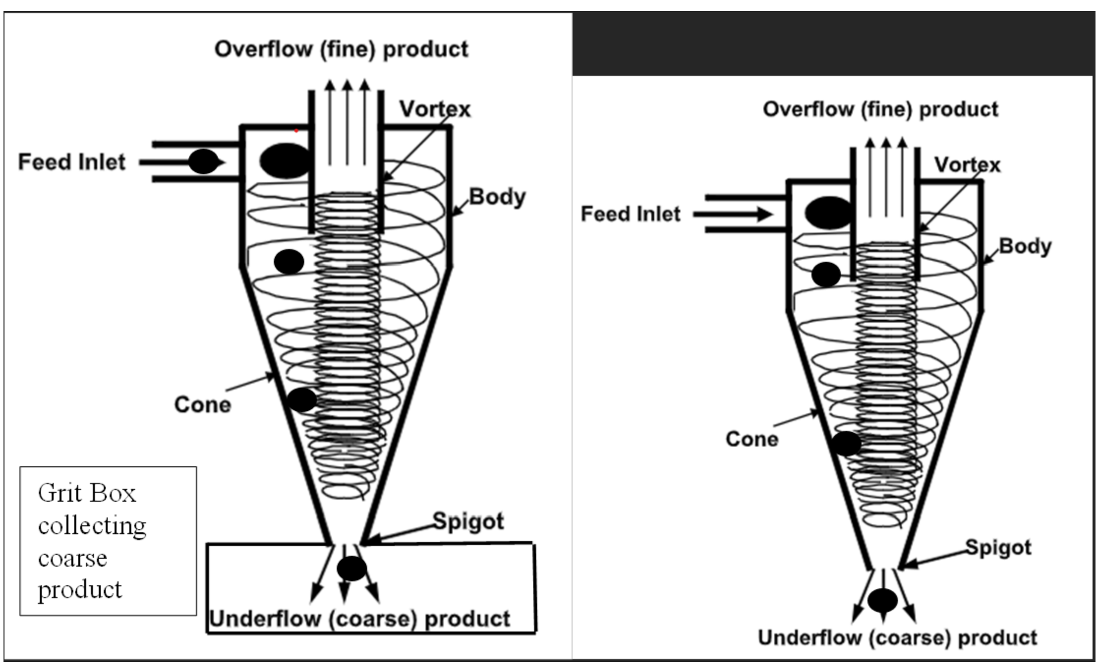

Figure 1.1 Hydro Cyclone Flow Pattern (Bradley) Right and With Grit Box Left with Particles

The characteristics of both the particles and fluids determine the design of the hydro cyclone; the size distribution and shape of the particles, the concentration of the particles in the water, and the relationship between the solid's density and the liquid medium density, which in this case would be water. The size of the particles and size ranges present as well as the size range that is targeted for removal are important in the design of the hydro cyclone, as an important design factor is d_{50}. The d_{50} number is the particle size at which 50% of the particles that go into the cyclone will end up in the underflow. D_{95} is the particle size at which 95% of particles that enter the cyclone will end up in the underflow. This is usually the size or tight size range that is targeted for removal. The d_{50} size is the particle size that is more often used in design equations as it is easier to correlate (Bradley, 1964). This d_{50} size range for this application could be either the fiber diameter, or fiber length. It is assumed that fiber diameter is the more important metric. The distribution of particle sizes in the feed material is also important as a large size range can make separation difficult, and in certain situations cause the spigot to clog, or wear. If there is a very large size range, it is not uncommon to have a pre filter or pre cyclone to eliminate large particles. The concentration of particles in the water is also important in the performance of our cyclone as a material that is too concentrated can negatively affect cyclone performance. In general, if the concentration is below an 8:1 ratio of fluid to solid volume ratio, there will be no measurable effect on the cyclone (Bradley, 1964), and laundry washing water is usually much more dilute than this threshold, on the scale of 200mg per 40 liters. The relationship between the sloid particle density and the water density governs the separation. The equation 1 below relates the d_{50} particle size to the difference in water density (ρ) and solids densities (σ) for small cyclones.

$$d_{50} \propto (\sigma - \rho)^{-0.62} \qquad \text{Equation 1.1}$$

Bradley design equations use several ratios to size the dimensions of the cyclone based upon the d_{50} particle size. It is important to note that the equations in this section assume roughly spherical particles. There is not much empirical information on non-spherical particles in the literature other than they behave unpredictably. These equations can be a good starting point for fiber tests, but actual experimental results will be needed to verify them. The cyclone diameter (Dc) is sized based on the d_{50} particle size shown in equation 1.2, and the feed inlet diameter (Di) and the underflow diameter (Do) are based on the diameter of the cyclone. The most common ratio used to size the inlet diameter is given in equation 1.3 and the most common ratio to size the under-flow diameter is given in equation 1.4. The length of the vortex finder (L) is dependent on the cyclone diameter as well, and the common equation for sizing the vortex finder length is given in equation 1.5 (Bradley, 1964)

$$d_{50} \propto (Dc)^{x} \qquad \text{Equation 1.2}$$

Where x is between 0.41 and 0.5

$$Di = \frac{Dc}{6.7} \qquad \text{Equation 1.3}$$

$$Do = \frac{Dc}{5} \qquad \text{Equation 1.4}$$

$$L = \frac{Dc}{2.5} \qquad \text{Equation 1.5}$$

Hydro cyclones are designed to operate at a certain pressure drop, and the range of pressure drops at which a hydro cyclone will operate as intended is narrow. If the pressure drop is not adequate, the forces acting on the particles in the flow regime will not be strong enough to push them to the outside of the circular flow and down into the underflow. Most hydro cyclones, especially in the diameter ranges that we operate in, discharge their underflow into an open container (Bradley, 1964). There have been applications where a closed vessel was used called a "grit box", but empirical data showed that having a grit box reduced the efficiency of separation (Bradley, 1964). A diagram of a hydro cyclone with a grit box can be seen in Figure 1. Design of A collection vessel is investigated in Chapter 4.

The idea of using a small hydro cyclone for microplastics filtration is a novel idea that has only been studied in the past three to five years. Hydro cyclones as a technology have existed for decades and have seen most of their use in the mining industry. They are used to separate solid particles from liquids. Their applications are mostly used on spherical particles, and not much data exists on how fibrous particles behave in hydro cyclones. There is some general information on particle shape to be found, but the transport phenomena that govern their interactions is not well understood. The only inferences of how long thin particles behave in a hydro cyclone that can be drawn from the literature is that they do not behave as theoretically expected.

1.5 Previous Work with Hydro Cyclones

In 2021, Fabio Borgia conducted a study to see how hydro cyclones would handle microplastics. CFD (computational fluid dynamics) was used to develop a theoretical model of whether several hydro cyclones would be able to separate different kinds of microplastics. Using design equations from Ateburn (Borgia) a theoretical hydro cyclone was designed. The chosen hydro cyclone was designed to remove particles as small as 5 micrometers, and with a density of 1.5g/ml. The results of the CFD modeling showed that the cyclone was able to achieve 98% efficiency. This model was based on existing design equations, which assume roughly spherical particles. This is not a fully representative model of what would be happening in the water of a washing machine. Any computational simulation needs to be verified experimentally.

In 2021, Ana Lorentzon performed experiments using hydro cyclones to separate microplastics from washing machine water. Based on previous studies, it was decided to use polyester particles for this test, as polyester is denser than water and the most common synthetic fiber in washing machine water. (Galvao 2020). Polyester blankets were washed in a Compass Pro washing machine. One blanket was washed for each test, and the water was collected in a tank. A sample was collected from this tank, and then the water from the tank was pumped through the hydro cyclone. The tops, or clean water out of the top of the cyclone, and bottoms, or dirty water out of the bottom of the cyclone, water were collected and samples were taken from each stream. To take samples from each tank, the water was agitated by stirring, and then a sample was taken. These samples were filtered, and the filters were weighed. The weight of the fibers in the bottoms was compared to the weight of fibers in the water coming out of the washing machine. (Lorentzon 2021). Four different hydro cyclones of different dimensions were tested. Detailed information on the design of the cyclones was unavailable. Ateburn and Bradley relations were used to design the hydro cyclone, both of which are based on the assumption of spherical particles. The highest efficiency achieved was 17.5 % with an average of 11% separation efficiency.

In 2022, Lequin He conducted experiments on hydro cyclones to remove microplastics from water in a small-scale lab set up. The particles that were intended to be separated are smaller than those that have been studied in other papers. The material of the microplastics were PMMA which has a density of 1.19 g/cm^3, and the particle size was an average of 10 micrometers with a size range of 5 to 15 micrometers. Three hydro cyclone designs were tested, all with a body diameter of 10 mm, and varying other dimensions. The particles that were tested in this experiment were small spherical particles of PMMA, not fiber strands. The set up for the experiment was similar. A suspension was made of water and fiber particles that was roughly 4% by volume. A peristaltic pump was used to pump the suspension through the hydro cyclone. The tops and bottoms from the mini hydro cyclone were collected. Three hydro cyclone designs were tested experimentally, and 9 designs were simulated with fluid modeling software. For the experimental tests, the recovery ranged from just over 50% to just under 90%. These results were generally close to the results from the fluid modeling results. These results are promising, but due to the spherical nature of the particles tested, and the small size range, they may not be reflective of how a mini hydro cyclone would work in the applied environment of a washing machine.

In 2020, Sandro Holzer conducted another test of using a hydro cyclone to separate microplastics from washing machine water. Experiments used synthetic water, which contained only polyester fiber, and washing water, which contained polyester fibers, cotton fibers, hair, and other contaminants. The two different kinds of water were pumped through a hydro cyclone, and samples were taken from both the overflow line and the underflow line. These samples were dried, and the solid content of these samples was calculated in mg/ml. The washing water performed much better than the synthetic water. The mean underflow dry material concentration was 1.97 mg/ml. The mean dry material concentration in the overflow was 1.047 mg/ml. The concentration of dry material in the underflow is nearly double that of the concentration in the overs. The results for synthetic water, however, are not as promising. The mean value of the dry concentration in the underflow was 0.291 mg/ml and the concentration of the overs dry material was 0.289 mg/ml. With these concentrations being nearly the same, it shows that the hydro cyclone made very little difference in separating microplastics from synthetic water. The choice to report cyclone performance as a concentration, rather than an efficiency based upon dry weight makes the results of this study difficult to compare to others. Table 2 is a summary of all the previous hydro cyclone work done in the past. The results vary greatly, and the results from simulations are much more promising than experimental results.

Table 1.3 Previous Hydro Cyclone Testing Summary

Fiber Type	Concentration and size	Cyclone Design Info	Separation Efficiency	Comments	Reference
Modeled plastic pellets, Density of 1.5g/cm^3	1% solids by volume concentration, minimum size 5 microns	Designed for pressure drop of 50 kPa	up to 98%	Only simulation, no experimental data, and assumed roughly spherical particles	Borgia 2021
Polyester blanket fibers	Whatever was produced by washing	design for 1.04 L/min and 60 psi pressure drop	average of only 11%	Experimental results, could include sampling error	Lorentzon, 2021
PMMA spherical particles	5 to 15 microns, 4% by volume solids	Flow rate of 1.13 L/min	Range of results from 50% to 90%	spherical particles used	He, 2022
Polyester Fibers	Whatever was produced by washing	Flo rate of 1m^3/h	50% for wash water, very low for synthetic water	did not separate polyester from other fibers in washing tests	Holzer, 2020

1.6 Quantification of Fibers

There are currently no official or industry standards for measuring and reporting the number of microfibers in water, and the number of microfibers that can be found in washing machine effluent water is as varied as the clothes that go into the washing machine. Several studies have been conducted to investigate what kinds of fibrous materials come from washing machines, and how many. These results vary and are also reported in different ways.

According to De Falco, between 0.124 and 0.308 mg of fibers are released per kg of garment washed per load, which translates to a grand total of between 640,000 and 1,500,000 microfibers being released each load, with a fiber diameter of between 12 to 16 micrometers and a length of between 360 to 660 micrometers. Fibers released were calculated based on a 2 to 2.5 kg wash load and the density and average size of the fibers.

When Praveena studied the same phenomena, her conclusions were different, and were also reported in different units, making it difficult to compare the two studies. Praveena reported fiber release as a concentration in water, rather than as a total fiber count estimation or a fiber weight per garment. Her results were fiber content varied between 0.0069 and 0.183 g/m^3 with an average fiber length of over 2 mm.

According to Galvaos work, who studied both synthetic and non-synthetic garments, the most released synthetic fiber from household clothes washing was polyester. Galvaos work shows that the synthetic fiber lengths agree better with De Falco's work than with Praveena's. 79% of microfibers collected in the study were between 50 and 100 micrometers in length, 17% were in the range of 100 to 500 micrometers, and only 4% were larger than 500 micrometers. These results show that most synthetic fibers released by washing machines are smaller than 100 micrometers. This contrasts with previous studies conducted. Almroth studied the release of microfibers from washing machines, but due to polyester being the most released fiber, focused only on polyester garments, and reported his results in terms of fibers per square meter of fabric per Liter of water. This way of reporting fiber counts makes his work difficult to compare fiber counts to other studies.

The design equations used currently in industry are assuming that the particles being separated from the water flow are roughly spherical. Looking at photos in the studies of fiber released from washing machines, as well as preliminary data collected here, the particles that are released from clothing are not spherical at all. They are more shaped like very small hairs. There is little data on how these thin fibrous materials will behave in a hydro cyclone. Figure 1.3 shows an optical microscope picture of polyester fibers that were collected by washing a polyester blanket.

There have been some studies of hydro cyclones that attempt to separate fibrous materials from water streams. In 2021 Fabio Borgia conducted a study where simulations were used to see if hydro cyclones based on the Aterburn and Bradley equations could separate microplastics as small as 5 micrometers. While the results were promising, the CFD software used did not consider the non-sphericity of the particles.

Lorentzon washed polyester blankets, collected the wash water, took a 1 L sample of the wash water, and then ran the remaining wash water through her various hydro cyclone set ups, collecting a 1 L sample of both the tops and bottoms of streams of the cyclone. These samples were then filtered, and the weight change in the filters was used to calculate the mass of fibers generated. The efficiency was calculated by comparing the mass of fibers in the bottoms sample to the mass of fibers in the wash water sample. The results of this experiment were not promising.

Holzer tested wash water with polyester fibers and other materials and filtered both the overs and underflow in much the same way that Lorentzon did. However, when the weights were compared, polyester and non-polyester fibers were not distinguishable from each other on the final filters. It is important to know the amount of specific polyester fibers captured by the hydro cyclone, as well as the amount of other materials separately.

1.7 Proposed Work

All the previous studies used various forms of sampling methods to collect the data on materials released. Clothes were washed, and then samples of varying sized were collected and filtered and weighed. The size of the samples collected varied from study to study but was very small compared to the total water generated. This coupled with the fact that washing machine water does not produce a homogeneously mixed effluent likely introduced sampling error into any results collected, which is why much of the data does not agree with other studies. To correct this, it is proposed to filter and analyze all the water generated during the washing process, this will eliminate the sampling error found in other studies. A standard wash cycle can produce up to 40 liters of water and filtering all this water could prove difficult and time consuming. To avoid having to spend hours filtering, and introducing sampling error, a pressure filter system can be used to filter large volumes of water. A 11-inch diameter Whatman number 1 equivalent filter can be used in the pressure filter system to speed up the filtering process and allow all the generated wash water to be filtered. An example of a pressure filter system is in Figure 2. This pressure filter system will allow analysis of all wash water generated to be analyzed for particles. This will help in the investigation of the effectiveness of the ability of a hydro cyclone to separate microfibers from washing machine water. The Galvao and Almroth Studies stated that the most common synthetic material found in washing machine water is polyester. For our proposed studies we build upon these studies by investigating whether polyester fibers can be removed by a hydro cyclone, since polyester is denser than water.

Figure 1.2 Pressure Filter System

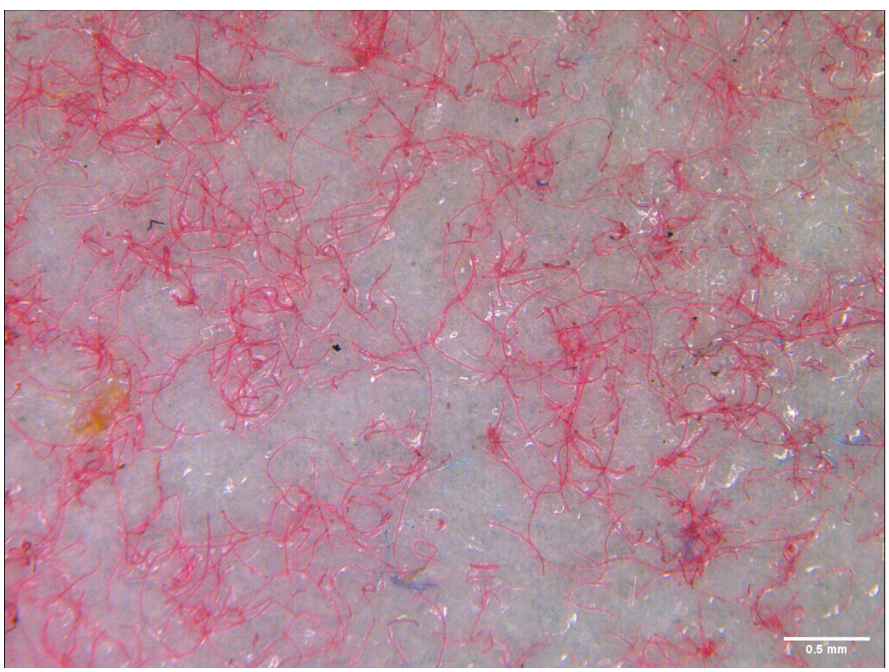

Figure 1.3 Optical Microscope Picture of Polyester Fibers Produced at Michigan Tech

The experiments performed by Lorentzon and Holzer are most applicable in this area. The following work is like the work of Lorentzon, but with a few additional test factors that will improve accuracy, and better simulate how a hydro cyclone would work in a washing machine environment. The previously stated sampling would be eliminated with the proposed work, and when polyester fibers are released in washing machine water, other fibrous materials are released as well. These non-synthetic materials could affect the efficiency of the hydro cyclone. In order to be able to distinguish the polyester fibers from cotton fibers, sand, and pet hair, a Thermo-gravimetric analysis was used. The details of this procedure are found in Chapters 2 and 3.

1.8 Problem Statement

The overall goal of this project was to have a device that could remove microplastics from washing machine wastewater, leaving behind a semi solid sludge that could be emptied into the trash much like a dryer's lint screen. A separation efficiency of 80% was set as a performance goal. When hydro cyclones are used, they do not remove particles from the water stream in a dry state. They concentrate the removed particles into a water stream that is usually collected in an open-air tank. Some hydro cyclones operate with a "grit box" or reservoir, which is a closed tank that attaches to the bottom of the hydro cyclone. The reservoir needed to be able to collect the hydro cyclone underflow, and then be able to remove the collected water, leaving behind a fiber sludge that could then be disposed of in the trash. This reservoir needed to be easily removable in a way that did not cause connections to leak. The procedure for removing, emptying, and re-installing the reservoir needs to be simple enough for the average consumer to be able to complete with basic instructions. The design process and testing of the reservoir became its own set of investigations that can be found in Chapter 4.

The hydro cyclone and reservoir needed to be able to fit inside the chassis of the washing machine. According to the project sponsor, this meant that the maximum height of both the hydro cyclone and the reservoir could be no higher than 228 mm, and the maximum diameter of both the hydro cyclone and the reservoir was 50mm. These size constraints were put in place by the funding agency to ensure that the hydro cyclone and reservoir would be able to fit within the chassis of all models of their washing machines.

Efficiency was an important factor in judging the hydro cyclone performance. There are two definitions of efficiency used in this paper: apex-based efficiency, and system efficiency. Apex based efficiency is calculated by measuring the weight of polyester recovered in the apex of the cyclone and dividing it by the weight of polyester added to the system. In the example system in Figure 4, the apex-based efficiency would be the weight of polyester recovered in the reservoir divided by the weight of polyester added to the washing tank. System-based efficiency is the weight of polyester that left the system altogether, divided by the weight of polyester that went through the cyclone. In this case, it would be the weight of polyester recovered in the clean water collection tank divided by the weight of polyester recovered in the clean water collection tank and the apex.

Apex based efficiency is easier to measure and is a worst-case efficiency. Because of how the system operates, the system efficiency will always be higher than the apex-based efficiency, because fibers are retained in other parts of the system. However, the sponsor of this study is most concerned with system-based efficiency.

Apex based efficiency is represented by equation 1.6 and system based efficiency is represented by equation 1.7 below.

$$\frac{Weight\ of\ fiber\ in\ resevoir}{Weight\ of\ fiber\ added\ to\ tank} * 100 \quad \text{Equation 1.6}$$

$$\frac{Weight\ of\ fibers\ recovered\ in\ clean\ water - Total\ Weight\ of\ fibers\ recovered}{Total\ Weight\ of\ fibers\ recovered} * 100$$

Equation 1.7

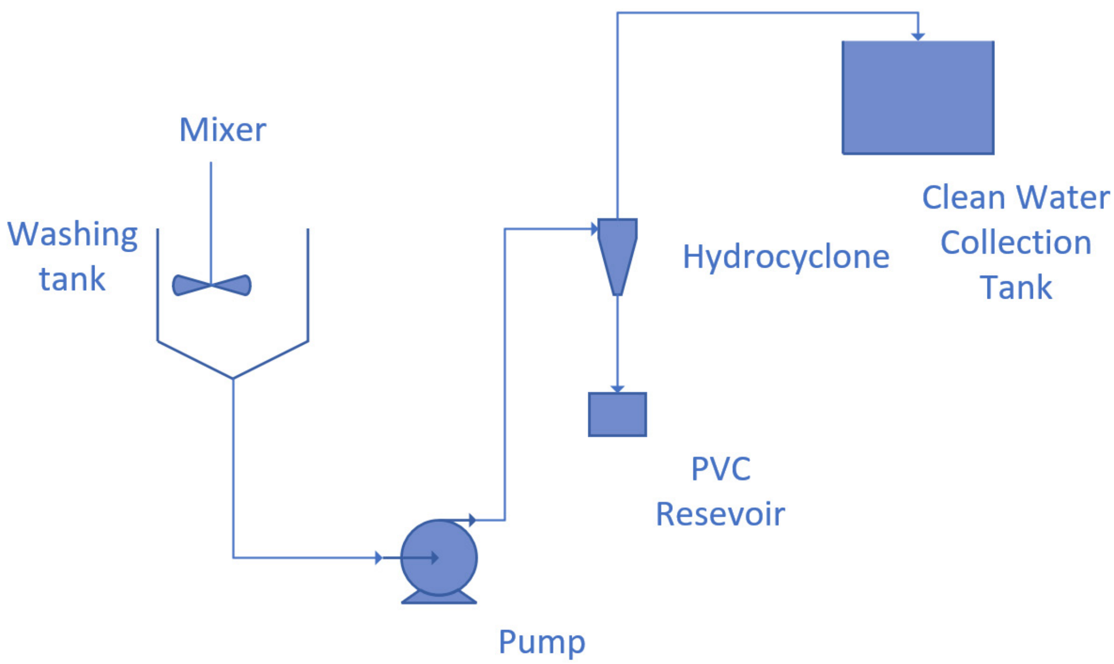

Figure 1.4 Example PFD of System

2. Analysis of Fibers Created, and Fiber Generation Procedure.

To properly size a hydro cyclone to separate the fibers created by washing garments in a washing machine, the size of the particles produced needs to be known. Previous work in this area has been done, but the results are difficult to compare to each other as fiber size and fiber count vary. De Falco found that the average fiber size was 12 to 16 micrometers in diameter and between 330 and 660 micrometers in length (Defalco, 2019). Praveena, who also studied fibers released from washing machines, found the average fiber length to be over 2 mm (Praveena 2020). Galvao's investigations found the bulk of the fibers recovered to be between 50 and 100 micrometers in length (2020). The size differences between these findings are quite large. Due to the variation in reported fiber lengths, it was decided that our own fiber analysis needed to be conducted. All studies agreed that polyester was the most encountered synthetic material in laundry water. For this reason, polyester material is what our analysis focused on.

In order to test a hydro cyclone's ability to separate fibers from washing machine effluent, fibers were added to water in a tank and pumped through the hydro cyclone. Previous studies have created test water by washing garments, and then taking a sample of the wash water, then pumping the remaining wash water through the hydro cyclone, and collecting samples from the overflow, and underflow. All three samples were filtered, and then the weight of fibers found in the overflow was compared to the weight of fibers found in the wash water and was used to calculate efficiency. The sponsor intended for efficiency to be calculated differently. A known initial charge of microfibers was added to a tank with a known amount of water. The water was pumped through the hydro cyclone, and the tops and bottoms were filtered and weighed separately. Efficiency was calculated by comparing the weight of microfibers captured in the underflow to the weight of microfibers added to the system in the initial known charge. For this to work, a procedure had to be developed to generate standardized test microfibers that imitated those fibers created by washing garments in a washing machine. In addition to being able to create fibers with a similar morphology, the procedure needed to produce a significantly large amount of fibers at one time. The weight of fibers created would need to be controlled, so the initial charge of fiber added to the tank could be accurately recorded. In order to generate test fibers, we once again turned to minerals processing equipment.

The goal of the investigations carried out in this chapter were to understand the amount of fiber produced in a washing machine, and the size distribution of those fibers. Milling equipment was then investigated to understand whether the fibers produced were of a similar morphology to those produced in the washing machine. Then a procedure needed to be developed to create said fibers in a way that could be used for microfiber testing.

2.1 Wash Tests Materials and Methods

The following equipment and materials found in Table 2.1 were used to perform washing machine tests to determine what kinds of fibers were produced in a washing machine, and in what amounts.

Table 2.1 Washing Test Materials

Front loading washing machine provided by sponsor
Top loading washing machine provided by sponsor
New Unwashed 1.5-yard Mainstays 100% polyester antipill fleece precut fabric blanket
Denver Labs 11" pressure filter set up 2.7-gallon volume, 11.875" by 8.25"
Fortiflex 66 L MPB plastic tubs
Curtis Matheson 11-inch laboratory filter paper with 11 micron pore size
XS1025 Dual range analytical balance with wind block and resolution of 0.001g
Mechanical analog floor balance with resolution of 0.5lbs
Isotemp forced air drying oven
Optical microscope
Avery ½" by 2" self-adhesive white labels
Slip Glass
Tide liquid detergent

There were 8 trials of these washing test to perform, 4 in a front load washing machine, and 4 in a top load washing machine, to determine if the washing machine type would affect the weight of fibers produced during the washing cycle, and to understand what the fiber morphology was of fibers created in a washing machine. Table 2.2 describes the procedure used to carry out these tests.

Table 2.2 Washing Test Procedures

Step #	Step
1	Washed 1 anti-pill fleece blanket on quick wash cycle with cold water, heavy dirt setting and single rinse with detergent
2	Collected washing machine water in 66L plastic tubs wash water in one tub and rinse water in another

3	Took filter out of 100° C oven (filter should have been in oven for 1 hour)
4	Placed filter paper in filter press
5	Filled the cylinder with water to be filtered and closed the cylinder
6	Applied air pressure until all water was our of the cylinder
7	Removed the cover of the cylinder. repeat steps 4-7 until all water has been filtered.
8	Once all the water had been filtered, removed the cover and cylinder, and transferred filter paper to the oven for drying.
10	Left filter out to "temper" in room temperature roughly 70 F for 1 hour
11	Weighed filter paper
12	Pressed slide label onto paper filter sticky side down. When removed fibers stuck to label
13	Slip glass was then pressed onto slide label with washing trial and date
14	Optical microscope was used to take image at 25X magnification refer to figure 1.3
14	Image J was used to manually trace fibers, and calculate length breakdown

Figure 2.1 is an example of the post processed image once fiber analysis had been completed.

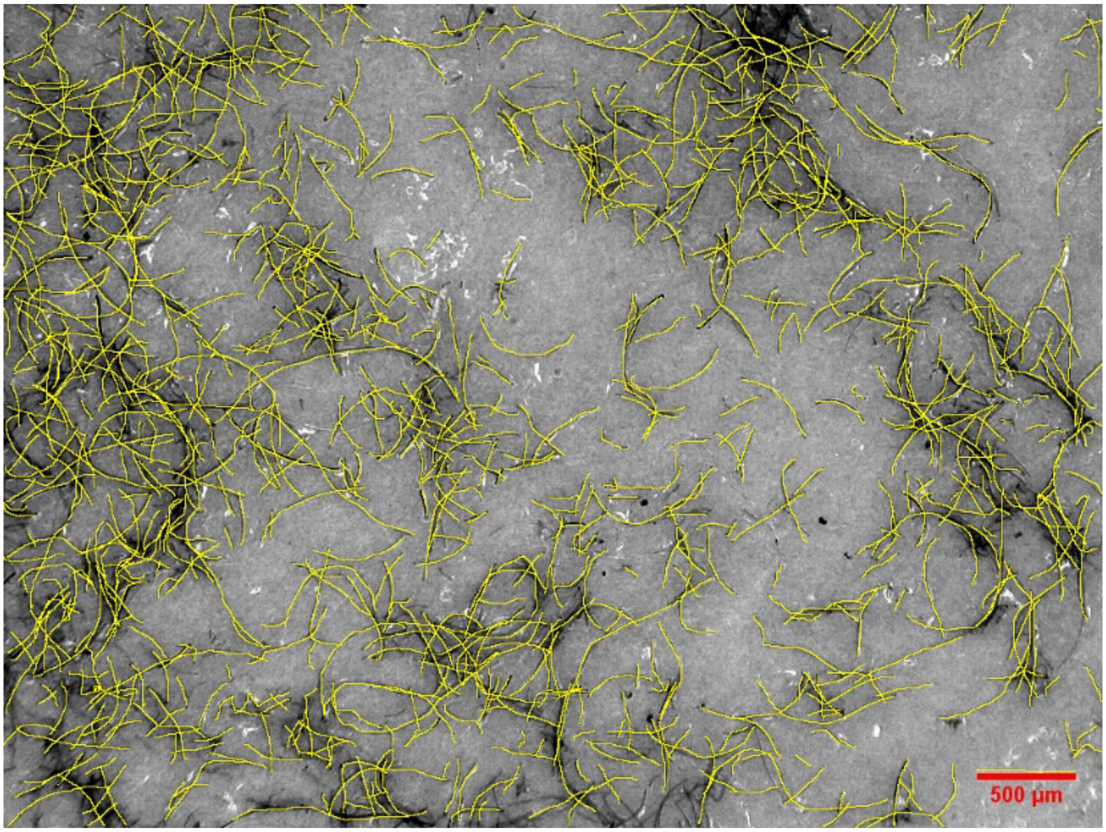

Figure 2.1 Post Processed Image of Fiber Analysis

2.2 Wash Test results

A single polyester fleece blanket was washed once for each test in either a top loading washing machine, or a front-loading washing machine. A new blanket was washed for each trial. All the water created during each washing test was filtered, and the mass of fibers created during the washing cycle was calculated by subtracting the final dry filter weight from the initial dry filter weight. An empty cycle was run to clean the system after each trial. Table 2.3 shows the weight data from the washing tests. Tests 1 through 4 were performed in a top loading washing machine, and tests 5 through 8 were performed in a front-loading washing machine.

Table 2.3 Washing Test Weight Data

Top Loading Machine	Test #	Fiber Weight Produced	Average	Standard Deviation	Relative standard deviation
	1	0.16			
	2	0.12			
	3	0.07			
	4	0.06	0.1025	0.0465	0.45
Front Loading Machine	5	0.04			
	6	0.07			
	7	0.14			
	8	0.05	0.075	0.0451	0.60

There are two aspects of this data to note. The large standard deviation compared to the measurements shows that the weight of fibers created varies much from wash to wash. There is a lot going on in the washing machine during a wash cycle, and it is difficult to predict any stable behaviors. The second is that each trial only creates a very small weight of fibers. When an average confidence interval was calculated for each different washing machine design, it showed no statistically significant difference in average weight produced.

Along with gathering data on the weight of fibers produced, the morphology of the fibers was important as well. Using the procedure described in the methods section, pictures were taken of the filters used to filter the wash water. Using image J, each individual fiber was traced, and the length of each fiber was calculated. These fiber lengths are broken down in figure 2.2. Figure 2.2 is a histogram that shows the fiber length bins on the X axis, and percentage of total fibers in each bin on the Y axis. The majority of the fibers, 86% are 500 microns in length or below, with 71% of the fibers being between 100 and 400 microns in length. Diameter measurements were not taken at this stage of the analysis. This size breakdown is different than some of the size information that was found in our literature research. The target size range for the hydro cyclone from these findings was designed for fibers that were 100 to 500 microns in length. This size range was slightly larger than initial hypotheses.

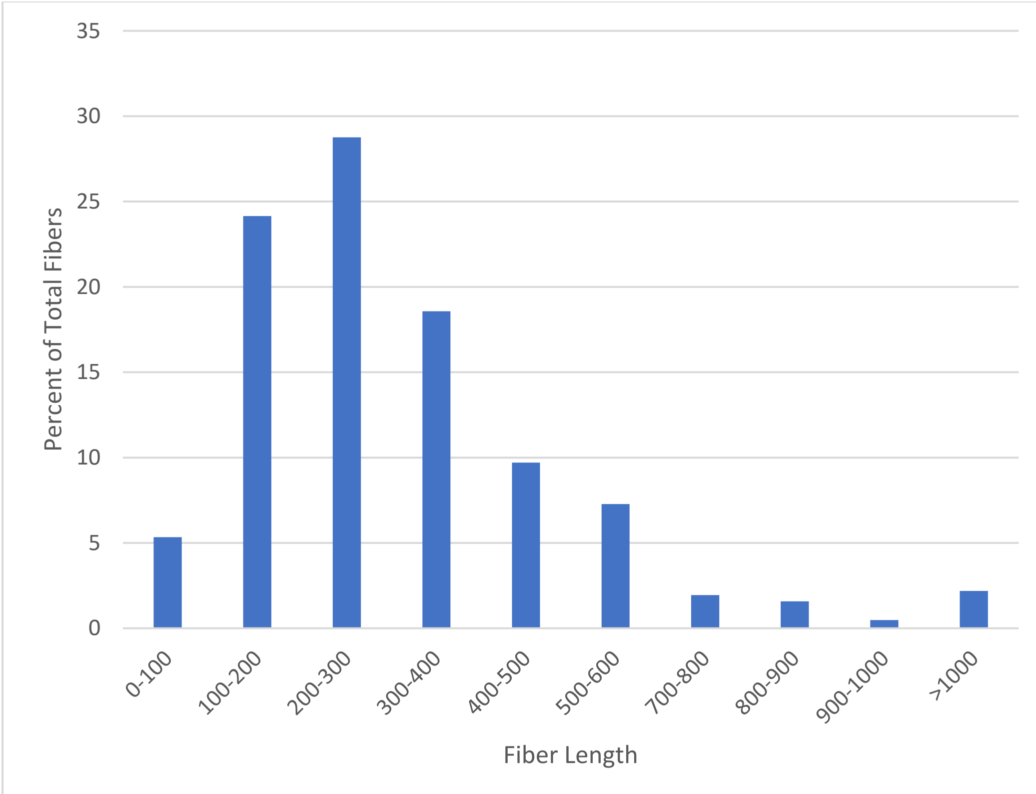

Figure 2.2 Wash Test Fiber Length Break Down

2.3 Alternate Generation Methods

Due to the small amount of fiber generated during each wash, and the variation of fiber weight produced from wash to wash, the washing machines were unsuitable for making the standard reproducible consistent batches of fibers needed to perform hydro cyclone test. A different more reproducible method would need to produce fibers with a similar morphology to those produced in the washing machine and would produce them in greater amounts. Fibers shed by garments in a washing machine are worn and broken off, they are not cut or sheared off, so milling polyester material would be a good way of imitating that wearing action.

There were two available pieces of equipment that had the potential to produce fibers. A rod mill, and a puck mill. A rod mill is a cylindrical hollow carrier usually made of stainless steel that is filled with the material to be milled, and several stainless-steel rods. Once the carrier is loaded, the carrier is placed in the mill, and the carrier is spun. As the carrier rotates, the rods inside crush up the material inside. In this case the rods interacting with the polyester fabric would imitate wear. A rod mill is shown in Figure 2.3.

Puck mills are usually used to crush mineral samples down to a small enough particle size for element analysis. A puck mill has a carrier made of tungsten carbide, inside of which there is a tungsten carbide ring and tungsten carbide puck. The mineral sample is put inside the carrier, between the ring and the puck. The carrier is closed, and then loaded into the mill. The mill shakes the carrier violently, and inside the carrier, the puck and ring smash into each other, crushing the sample. A picture of the inside of the carrier can be seen in Figure 2.4.

Figure 2.3 Picture of Carrier and Rods of a Rod Mill

Figure 2.4 Inside the Carrier of a Puck Mill

Table 2.4 shows the dimensions of the puck mill and rod mill components.

Table 2.4 Puck and Rod Mill Dimensions

Rod Mill Carrier ID	8"
Rod Mill Carrier OD	10.31"
Rod Mill Carrier Height	10.75"
Rod Diameter	0.75"
Rod Height	9.63"
Puck Mill Carrier ID	5"
Puck Mill Carrier Depth	2"
Puck Diameter	2"
Puck Height	1.63"
Ring OD	3.88"
Ring ID	3"
Ring Height	1.63"

Initial trials of each piece of equipment showed that the puck mill would be the better option for creating milled test fibers. Small pieces of blanket were put into both pieces of equipment and processed. The puck mill succeeded in breaking down the fabric to produce fibers, whereas in the rod mill, all the pieces of blanket wrapped around a single rod and due to this did not get milled very much. A series of tests were run to establish the morphology and number of fibers generated by the puck mill. Table 2.5 shows the materials used in the puck mill tests.

2.4 Puck Mill Test Materials and Methods

Table 2.5 Puck Mill Test Materials

Siebtechnik 22V puck mill
1.5-yard Mainstays 100% polyester antipill fleece precut fabric blanket
Denver Labs pressure filter set up
Curtis Matheson 11-inch laboratory filter paper
XS1025 Dual range analytical balance with wind block
Empty clean polyethylene Ovaltine jar, 8.25” ID by 8.63” H
1150 standard mesh stainless steel screen
Isotemp forced air drying oven
Optical microscope
Slide labels

Slide cover

Table 2.6 shows the methods used to conduct the puck mill tests.

It was determined through initial pre trials that there is a relationship between the amount of material inside the puck mill, and the time the puck mill runs. The fuller the puck mill is, the more time it needs to be run to degrade the fibers properly. 10 g and 1 minute were found to be a good balance of both factors. Also, the addition of water is very important. When this experiment was conducted without water being added to the fibers, the action inside the puck mill would cause the fibers to heat up and start to melt. However, adding too much water would cause the fabric to wrap around the puck, and the fibers would not be damaged enough. 25 g of water allowed nearly all of the water to be absorbed by the fibers and did not make a mess when the fibers were milled.

Table 2.6 Puck Mill Test Procedure

Step #	Step
1	Weighed out 10 g of fabric, cut into 2” by 2” squares. Put in a plastic jar. Create 8 bottles of blue blanket squares and 8 bottles of pink blanket squares
2	Added 25g of water into the bottle with fabric. Stir until water is fully absorbed by fabric.
3	Placed fabric squares in the puck mill. Distributed fabric so that 2/3 are in the outer ring and 1/3 are in the inner ring.
4	Run puck mill for 1 minute
5	Removed fibers and fabric from the puck mill and returned to plastic jar. Used spray bottle to wash any remnants out of puck mill carrier and into plastic bottle.
6	Repeated steps for each of the 16 samples
7	Dried filters at 100 C for at least 1 hour in drying oven.
8	Took filters out of drying oven and let equilibrate at room temperature for at least 1 hour in tempering box.
9	Weighed empty filters with analytical balance inside wind shield.
10	Put filter in pressure filter rig.

11	Placed 1168 micrometer screen on top of pressure cylinder.
12	Shook for 20 seconds sample with 300 ml of water, poured onto screen. Repeated for 7 rinses.
13	Collected screened fabric to dry and weigh.
14	Filtered slurry water that was generated by rinsing fabric.
15	Removed filter from pressure filter rig and dried in oven at 100 C for 1 hour.
16	Placed puck mill remnants on paper towel and dried in oven for 1 hour.
17	Let filter equilibrate in tempering box at room temperature for 1 hour.
18	Let puck mill remnants equilibrate at room temperature for 1 hour
19	Weighed filter with analytical balance in windshield.
20	Weighed puck mill remnants with analytical balance in windshield
21	Repeated for each of the 16 milled samples

The image analysis had been conducted using the same procedure described at the end of table 4 for the washing machine tests.
The breakdown of the fiber length was used to compare the blue blanket tests to the pink blanket puck mill tests, and to the tests generated by washing the blankets. The results can be seen in the results section.

2.5 Puck Mill Test Results

Table 2.7 shows the weight of fiber created by each sample. Sixteen 10 g samples were milled in the puck mill. Eight samples were made with pink blanket, and eight samples were made with blue blanket.

Table 2.7 Puck Mill Fiber Weight Data

Pink Blanket								
Test	1	2	3	4	9	10	11	12
Fiber weight	0.0176	0.0438	0.0308	0.0106	0.0349	0.1018	0.0748	0.087
Average Weight	0.0502							
Standard deviation	0.0336							
Blue Blanket								
Test	5	6	7	8	13	14	15	16
Fiber weight	0.1265	0.1442	0.194	0.1203	0.0648	0.1273	0.1175	0.134
Average Weight	0.1286							
Standard Deviation	0.0355							

The blue blanket created more fiber by mass than the pink blanket, and both the pink and blue blanket have significant variation in fiber weight created from trial to trial. New blankets were used for all trials, and the hemmed edges of the blanket were not used for tests. Also, the weight of fiber created by each individual test is not hugely different from the weight created by running each individual washing test when comparing this data to table 5. The big differences between the two processes is the time taken to perform the tests, and the amount of material needed to make the fibers. A washing test can take between 1 and 2 hours to generate fibers, and requires and entire blanket, where the puck mill only uses roughly 10 g of fiber. This puck mill procedure is much faster. In a single day maybe 3 to 4 wash tests can be performed, where all 8 puck mill tests were performed in a single workday. As with the wash tests, the fiber length breakdown was calculated in the same way. Figure 2.5 is the fiber breakdown of the pink blanket fibers, and Figure 2.6 is the breakdown of blue blanket fibers.

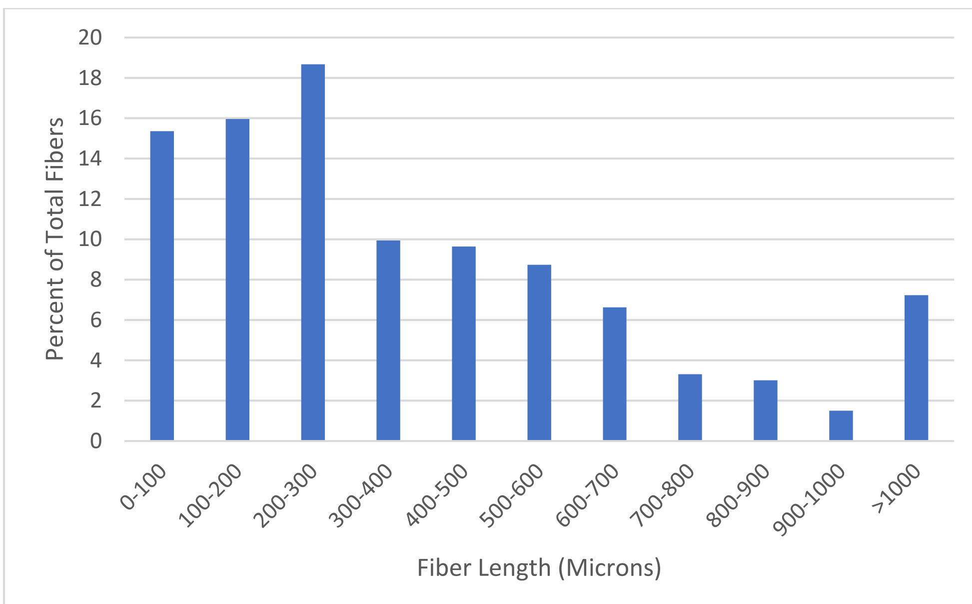

Figure 2.5 Pink Blanket Puck Mill Fiber Length Breakdown

The milled pink blanket size breakdown is like the wash test breakdown, but not quite identical. Like the wash test breakdown, most of the fibers are shorter than 500 microns in length, but there are a greater percentage of longer fibers in the milled fibers. 70% of the fibers are shorter than 500 microns in length, as compared to 86% with the wash test. The wash test had 70% of its fibers in the range of 100 microns to 500 microns. This is different for the milled fiber from the pink blanket. Only 46 % of the fibers are between 100 to 400 microns. This is mostly because there are a significant number of fibers that are less than 100 microns in length.

The fiber breakdown for the blue blanket can be found in figure 2.6

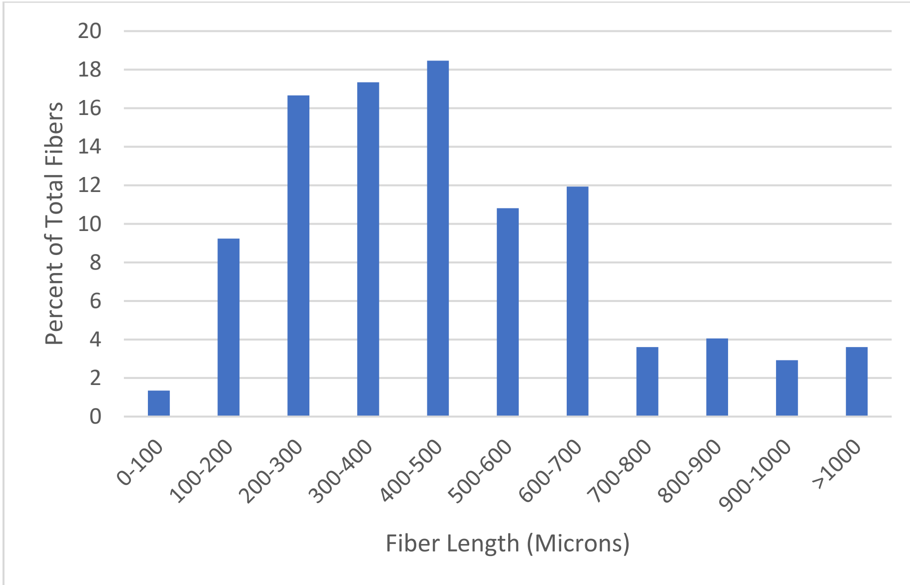

Figure 2.6 Blue Blanket Puck Mill Fiber Length Breakdown

The milled blue blanket has a slightly different fiber breakdown than the wash fiber breakdown but is more similar to the pink blanket breakdown. Most of the fibers are still shorter than 500 microns at 63%. The percentage of fibers that are between 100 microns and 500 microns is only 43 percent, which is like the breakdown of the pink blanket. There is not as large of fines tail in the blue blanket, and there are slightly more coarse particles in the blue blanket than the pink blanket. In general, the milled fibers create a larger spread in particle size created than the wash water but are not excessively different. The majority of the particles are below 500 microns, so they should behave fairly similarly in a separation environment, and it is more difficult to separate particles with a wide range than a small range, so our test particles should give an accurate imitation of what would happen with the wash fibers. Figure 2.7 shows the wash fibers imposed on the same graph with the averages of the puck mill fibers. The wash fibers have a tighter size spread and are less coarse although they are close to the range of variation by fibers.

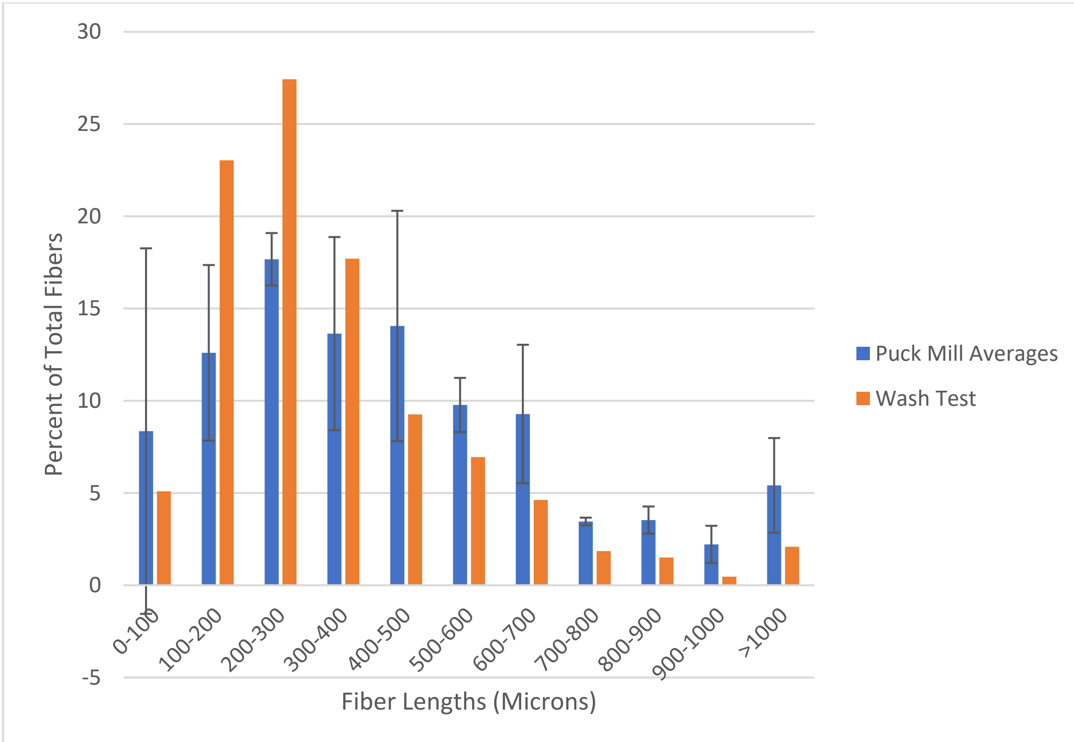

Figure 2.7 Wash vs Puck Mill Fiber Lengths

2.6 Development of Fiber Generation Procedure to Produce Reproducible Samples for Hydro Cyclone Tests

In the previous puck mill tests, each set of 10 g of fabric was puck milled, and then filtered on to a separate filter. Sixteen trials of this procedure were carried out to determine how many fibers are produced, and what their morphology is, resulting in sixteen filters. To create test fibers for efficiency tests, a large among of fiber would need to be made at one time, and then would need to be able to be split into smaller containers each holding roughly 0.2g each, as requested by the project sponsor. It was attempted to change the above procedure slightly to develop test fibers. The milling procedure would stay the same, but the filtering procedure would change. Instead of rinsing and filtering each trial onto a separate filter, all puck mill trials would be rinsed and filtered onto a single filter. Then many fibers would be gathered into one place. This would concentrate anywhere between 3 to 4 grams onto a single filter. The next challenge that needed to be solved was how to remove the fibers from the filter.

The initial attempt was to rinse the fibers off the filter using water into a beaker. Then this water fiber mixture would be split using a sample splitter into 5 equal samples. The idea was that a roughly equal amount of fibers by weight would be in each sample of solution, and that this solution could be added to a tank full of water and used for an efficiency test. Solution and samples were spit in a way to have roughly 0.2g of fiber in each vial of solution. The funding agency was working under the assumption that each regular washing load of clothed produced 0.2 g of synthetic fibers. The solution method was abandoned due to poor weight results that can be seen in the results section.

Alternatively, the fibers would be left in a dry state, and scraped off the filter using a spatula. The dry fibers could then be mechanically divided into representative samples. The procedure for creating fibers in this way is listed in table 2.8.

Table 2.8 Fiber Generation Procedure

Step #	Step
1	Weighed out 10 g of fabric, cut into 2” by 2” squares. Put in a plastic bottle. Made 16 10 g samples. 8 of each color.
2	Dried a single filter at 100 C for at least 1 hour in drying oven. Started steps 3 -7 while filter was drying
3	Created solution of detergent and water with 500g of water and 2g of detergent.
4	Added 25 g of solution to each plastic bottle.
5	Placed fabric squares in the puck mill. Distributed fabric so that 2/3 is in the outer ring and 1/3 are in the inner ring.
6	Ran the puck mill for 1 minute.
7	Removed fibers and fabric from the puck mill into plastic bottle. Used spray bottle to wash any remnants out of puck mill carrier and into plastic bottle. Wiped down puck mill in between each sample.
8	Repeated steps for each sample.
9	Took filter out of the drying oven and let equilibrate at room temperature for at least 1 hour in tempering box. Finished steps 3-7 while filter is tempering.
10	Put filter in pressure filter rig.
11	Placed 1168 micrometer screen on top of pressure cylinder.
12	Shook each sample 20 times with 300 ml of water, pour onto screen. Repeat for 7 rinses.
13	Collected screened fabric to dry.
14	Repeated for each sample.
15	Filtered slurry water that was generated by rinsing fabric. Filtered all 16 samples onto a single filter paper. Rinsed sides of cylinder to wash down any fibers that were trapped on the side, and filtered rinse water.
16	Removed filter from pressure filter rig, and dried in oven at 100 C for 1 hour.

17	Placed collected fabric on paper towel and dried in oven for 1 hour.
18	Removed single filter from drying oven and let equilibrate in tempering box for one hour.
19	Removed collected fabric samples from drying oven and let equilibrate for 1 hour.
20	Weighed filter with analytical balance in windshield.
21	Once filter weight has been recorded, used steel spatula to scrape fibers off filter and onto plastic sheet.
22	Took one corner of plastic sheet, and folded over to opposite corner, and returned to normal. Repeated with all corners
23	Repeated with all corners 15 times.
24	Got tare weights on vials. (Number of vials depends on the weight of fibers generated)
25	Used steel spatula to evenly distribute fibers into each vial.
26	Rubbed filter onto plastic to get any last fines out of the filter.
27	Mixed fines and evenly distribute among vials.
28	Weighed each vial.

Figure 2.8 is a picture of the fibers on the filter. Figure 2.9 is a picture of the fibers in the vial. Note that the fibers are very fluffy and so even small masses of fibers take up a considerable volume.

Figure 2.8 Fibers on the Filter

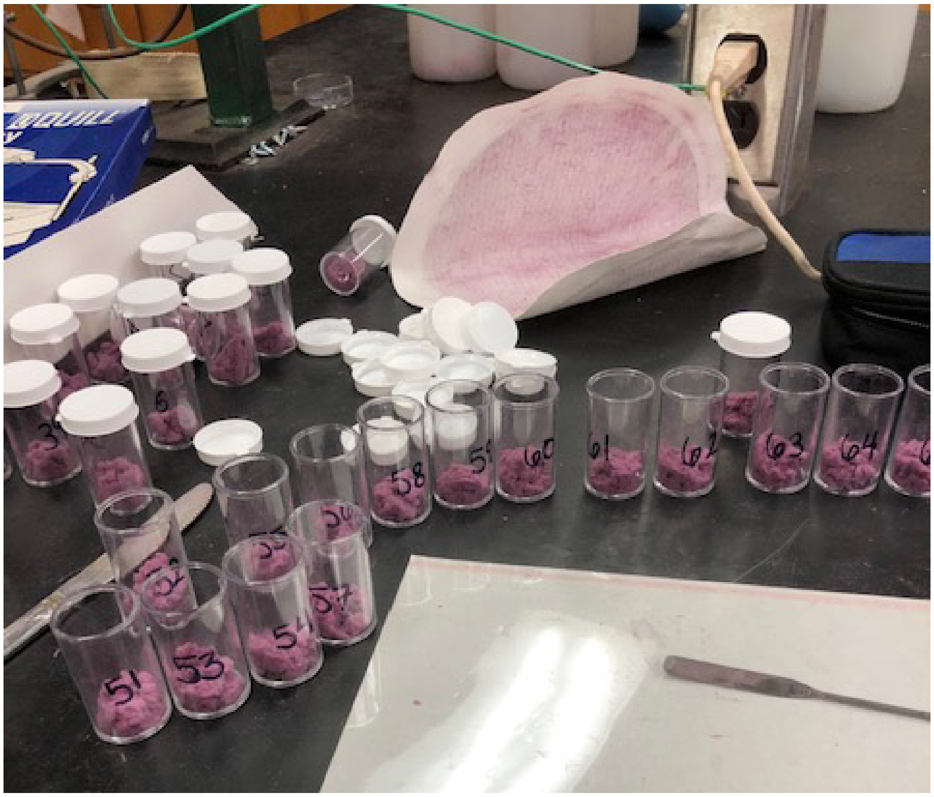

Figure 2.9 Fibers in Vials

This procedure has several positives. Since the tare weight of each vial, and the gross weight of each vial is known, the exact weight of fibers within each vial is known. The mixing procedure of the dry material on the plastic sheet helps to eliminate sampling error, and the last steps for the fines makes sure that each sample has a random distribution of all sizes present in the fiber generation. Knowing the mass of fibers in each vial is very important for the hydro cyclone testing process, as separation efficiency will be calculated as weight of fibers collected in underflow divided by weight of fibers added. The goal of the generation process was to have vials containing between 0.18g and 0.22 g.

2.7 Fiber Generation Results

When testing the solution method, when each of the 5 samples of solutions were filtered to check the actual weight of fibers in solution, the weights varied a lot. It was decided that making a solution was a bad idea that was difficult to control as can be seen in table 2.9 Weights are in grams.

Table 2.9 Fiber Samples and Weight Using Solution Method

Split Sample	1	2	3	4	5	Standard deviation
Fiber Weight in Sample (g)	0.2325	0.112	0.1615	0.2725	0.23	0.0641

The goal was to have samples with weights between 0.18 and 0.22 g of polyester in each sample. When the samples of solution were filtered under vacuum filtration, the above weights were found for each sample. Not a single sample was within our goal weights, so it was decided to amend the fiber generation process.

Table 2.10 shows the fiber samples and weights using the dry fiber splitting method detailed in the list earlier.

Table 2.10 Fiber Samples and Weight Using Dry Split Method

vial number	16	17	18	19	20	21	22
vial tare weight (g)	6.6272	6.5241	6.8434	6.5959	6.5265	6.6266	6.5279
vial gross weight (g)	6.8235	6.7208	7.0419	6.7871	6.7092	6.8262	6.6929
sample weight (g)	0.1963	0.1967	0.1985	0.1912	0.1827	0.1996	0.165
standard deviation	0.0112						

As can be seen by the above data, there is an exact known fiber weight for each vial, and the range of weights is much smaller than with the solution splitting method. Only one of the vials in table 2.10 is outside of the acceptable weight range. In a single fiber generation, roughly 12-15 vials of fiber samples can be generated, usually only 2-4 of which are outside of the acceptable range. Those samples that are outside of the acceptable range can be identified and not used in testing.

2.8 Fiber Analysis and Generation Conclusions

Polyester fleece blankets were washed in a washing machine to understand what kind of fibers, and how many were created per wash. The weight of fibers created per wash was all over the place with a standard deviation of 45% or 60% of the total weight as can be seen from table 1, and the difference between washing machine types compared to the random variation.

When the morphology of the fibers was analyzed, it was found that most fibers created were smaller than 500 microns, with a significant portion of those fibers being between

100 and 400 microns in size. The use of the puck mill to create fibers like those created by the washing machine was investigated. The weight of fibers created with the puck mill depends on the time the puck mill is run, and how much material is loaded into the carrier. Like the washing machine, the weight created by each puck mill run also varies. The morphology of the fibers created is similar to those created with the washing machine, with the majority being smaller than 500 microns, although the fraction of fibers between 100 and 400 microns, while still significant, is not as large as with the washing machine fibers. In general, the spread of fiber lengths is longer than those created by the washing machine, but they will still accurately simulate the washing fibers.

A method was developed to use the puck mill to create fiber samples of known weight that can be used for testing. Table 2.10 shows that the weight variation from sample to sample is not excessive, and mostly falls within our weight range. Those samples that are outside of our defined weight range can be easily identified and removed.

3. Hydro Cyclone Testing

With an understanding of the kinds of fibers produced during the washing process in both front load and top load washing machines, and a method for generating larger amounts of similar fibers, the investigation into the hydro cyclones ability to separate these fibers began. As stated at the end of chapter 1, there was a size constraint placed upon the hydro cyclone so the overall length could not exceed 228 mm, and the diameter could not exceed 50 mm. Bradley Design equations (Bradley, 1964) were used as a design basis for the design, and the particle size that the initial cyclone was designed for was 15 micrometers in diameter and 250 microns in length. Several simulated versions of a basic design were tested by the sponsor in Ansys Workbench, which is a CFD program, with the most promising design selected and 3d printed for testing.

Initial testing of the cyclone was to understand how the orientation of the cyclone, and the flow rate through the cyclone would affect the separation efficiency. Running at below the designed flow rate would decrease the efficiency of the cyclone (Bradley, 1964). As an initial starting point to investigate efficiency and the factors that govern it, a two factor, 3 level factorial test plan was developed to understand how flow rate and orientation affected hydro cyclone efficiency. The test plan would also show what pump power would be needed in the final design to effectively make the cyclone work.

The goal of the testing of the hydro cyclone was to establish an understanding of how the cyclone would behave in the washing machine environment. The initial hydro cyclone testing sought to understand the relationship between pressure drop, flow rate, and efficiency, and also if hydro cyclone orientation would affect the efficiency.

The effect on efficiency of recirculating the overflow water through the system multiple times was also investigated, as well as the possibility of other non-plastic solid particles in the wash water affecting the separation efficiency of the hydro cyclone.

3.1 Materials and Methods for Initial Testing

Table 3.1 Materials Used for All Hydro Cyclone Tests from This Point Forward

Curtis Matheson 11-inch laboratory filter paper
XS1025 Dual range analytical balance with wind block
County Line ½ HP 8.5 gpm 65 psi Cast Iron Shallow Well Jet Pump
Cone bottom tank
Water Source 100 PSI pressure gauge
Fortiflex 66 Liter plastic tub
5-inch Whatman number 1 paper filter
500 ml Erlenmeyer flask

Buchner funnel
Denver Labs pressure filter rig
Fiber reinforced plastic tubing 1/4”, 7/16”, and 3/8”
Stainless steel plumbing
3d printed hydro cyclone 1 ½” diameter 0.15” underflow diameter
Isotemp forced air drying oven
Tractor supply 5-gallon bucket
Analog floor balance max capacity 1000 lbs. to the closest half pound
IKA RW 20 Propellor mixer with digital display
Generated microfibers
Tide Liquid Detergent

The 2 factor 3 level factorial testing plan was developed to test the effect of flowrate, and cyclone orientation on separation efficiency. The factors and levels were flow rate at 6 L/min, 14 L/min, and 22 L/min and orientation at regular vertical, sideways, and upside down.

A test stand was constructed to allow testing of hydro cyclone efficiency. A tank was connected to pump, which was connected to the hydro cyclone. The bottoms of the hydro cyclone were collected in an Erlenmeyer flask that was closed, and the tops of the hydro cyclone went back into the tank. Figure 14 shows a PFD of the test stand.
There are pressure gauges at the cyclone inlet, and the cyclone apex, and the cyclone overs discharge. The pressure gauge at the cyclone inlet was used to calibrate the flow rate via pale and scale. The pressure gauge at the inlet and the apex were used to calculate the pump power required to supply the necessary flow rate and pressure drop. The first iteration of the hydro cyclone was designed for 22 L/min of water flow rate. It was noted during testing that the maximum flow rate our pump was able to supply was 20 L/min at the design pressure.

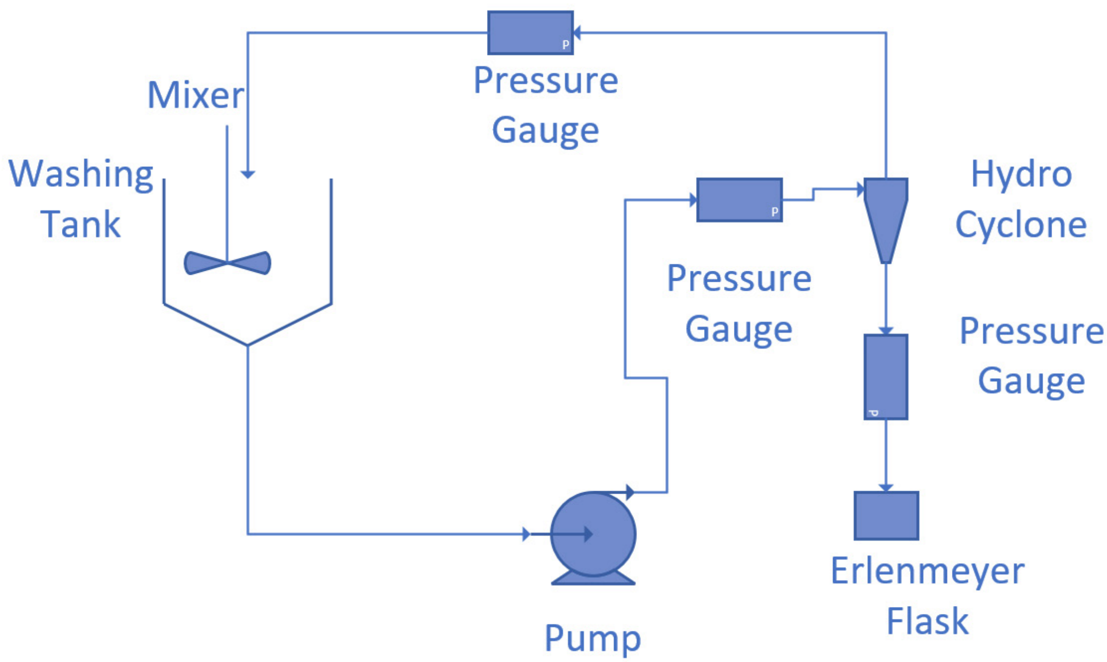

Figure 3.1 PFD of Hydro Cyclone Test Stand

Initial hydro cyclone tests were conducted according to the procedure outlined in table 3.2.

Table 3.2 Initial Hydro Cyclone Testing Procedures

Step #	Step
1	Between 38.5 and 41 kg of water was weighed out. Water weight was dependent on weight of fiber sample. Concentration of 0.2g of fiber to 40 kg of water was maintained
2	Water was poured into test tank
3	Hydro cyclone and reservoir were attached to test set up
4	Pump was turned on to establish flow rate and then turned off
5	0.2g of fiber and 5g of detergent were added to tank
6	Stand mixer was turned on
7	Pump was turned on and timer was started. Timer was set for long enough for all water to pass through system 3 times (based off flow rate calculation)

8	When timer went off, pump and mixer were turned off
9	Contents of wash tank were drained into 66 L plastic tub
10	Additional 80 L of water were ran through system and collected in plastic tubs
11	Hydro cyclone was disconnected, and contents of reservoir were emptied into beaker
12	Contents of reservoir were filtered onto 5-inch filter paper via vacuum filtration
13	Contents of plastic tubs was filtered onto 11-inch filter paper via pressure filter
14	Filters were dried and weighed

The initial and final weight of the filters were used to calculate the weight of fibers that were collected by the cyclone, and the weight of fibers that left the system. The separation efficiency of the cyclone was calculated by dividing the weight of fiber added to the wash tank by the weight of fiber in the cyclone apex container according to equation 1.6 in Chapter 1.

The hydro cyclone broke before the full testing run was completed, but some useful data was still gathered. The vortex finder and overflow connection warped during testing causing a dramatic drop in efficiency before the vortex finder broke off all together and fell into the cyclone body. Changes were made to the design of the cyclone by reenforcing the inlet and overflow sections and adding connection ports. The data gathered can be seen in the results section.

3.2 Initial Test Results

Table 3.3 shows the pressure results from the factorial design tests. These results were needed to calculate what the pump power requirements needed to provide the necessary pressure drop and flow rate for this hydro cyclone design. It was found that the pump power requirements for this hydro cycle design were in excess of 100 Watts. The hope was for a 30-to-50-watt pump.

Table 3.3 Initial Hydro Cyclone Testing Results

Run Order	Orientation	Water Flow L/min	Inlet Pressure PSI	Apex Pressure	Discharge Pressure
6	Horizontal	6.5	9	8	1
5	Horizontal	14	30	12	4
1	Horizontal	20	50	17	3
3	Vertical	6.5	8	8	1
11	vertical	6.5	9	9	1
4	vertical	14	30	13	2
13	vertical	14	27	14	3
9	vertical	20	48	16	4
10	Upside down	6.5	9	8	1
2	Upside down	6.5	7	10	1
12	Upside down	14	31	12	3
7	Upside down	20	48	13	3
8	Upside down	20	49	16	3

Table 3.4 shows the efficiency of the tests performed in the horizontal orientation, at the three different flow rates. The highest efficiency is the 1st test, which was performed at the highest flow rate. The separation efficiency drops as the flow rate drops. This aligns well with what we already know in that hydro cyclones do not perform well when they are not running with their designed flow rate or pressure drop.

Table 3.4 Efficiency for Horizontal Orientation

Run Order	Orientation	Water Flow L/min	Apex Efficiency
1	Horizontal	20	64.9
5	Horizontal	14	3.2
6	Horizontal	6.5	0

Literature and known empirical knowledge show that the orientation of the hydro cyclone should not affect the performance (Bradley 1965). When breaking the data from the 1st round of efficiency tests, the orientation has a large effect on performance. Table 3.5 Compares the efficiencies of trials run at the design flow rate. The horizontal orientation performed the best, while the vertical orientation showed the lowest separation efficiency. This is likely due to the cyclone malfunction. The design was modified, and reinforcement was added to the vortex finder and inlet and outlet ports, to prevent further warping and damage. Several other design changes were made to make the cyclones more durable, and practical for use.

Table 3.5 Hydro Cyclone Efficiency Results at Design Flow Rate and Different Orientations

Run Order	Orientation	Water Flow L/min	Apex Efficiency %
1	Horizontal	20	64.9
7	Upside down	20	50
8	Upside down	20	35
9	vertical	20	12

While the above data is not conclusive that the horizontal orientation is the best for efficiency, it does show that the horizontal orientation will not harm the cyclone efficiency. Orienting the cyclone horizontally helps with space constraint problems, so it was decided to continue testing in the horizontal configuration.

It was noticed, especially when running at higher flow rates, that water flows into the reservoir, and then back out again. It is believed that when water flows in this circuit, fibers that have made their way past the apex and into the reservoir may remain entrained in the water flow, and flow right back out of the reservoir and into the tops with the rest of the water. In order to counter this idea, a new reservoir was constructed from PVC, and a small back flow block was constructed at the top of the reservoir to help prevent particles from making their way back into cyclone from the reservoir. This handmade PVC reservoir was used in the next investigation. The next learning goal was to investigate the effect of recirculation of water on the hydro cyclone efficiency.

3.3 Recirculation vs Single Pass Tests Materials and Methods

The materials for the recirculation vs single pass test are the same as the initial hydro cyclone tests from table 8 except for a PVC constructed reservoir instead of an Erlenmeyer flask. Figure 3.2 shows a PFD of the test set up.

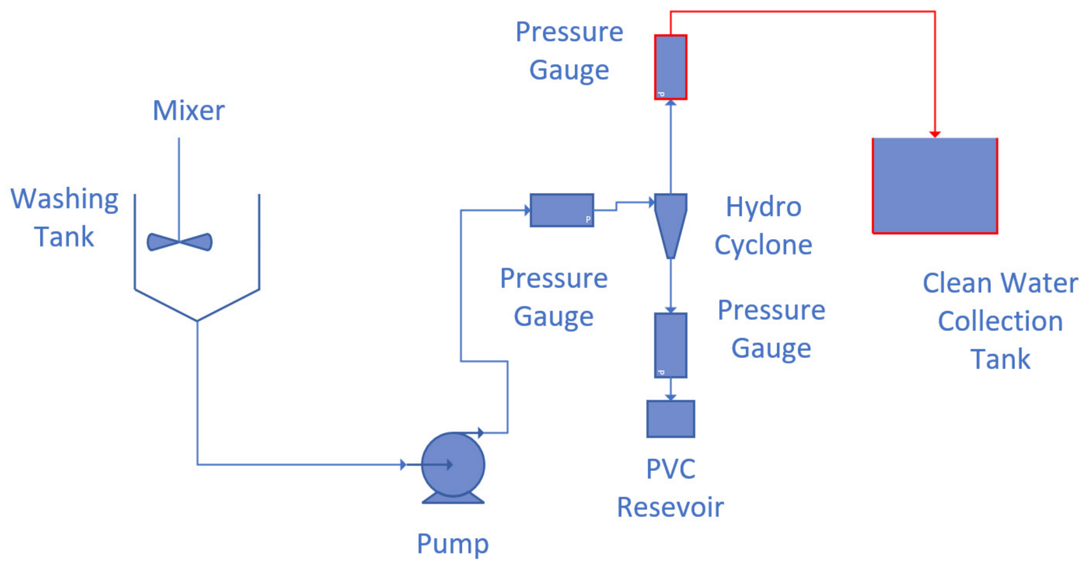

Figure 3.2 PFD of Single Pass Set Up

For the recirculation tests, the methods for running the tests were the same those used in the previous factorial experiments with the following exceptions. All trials were conducted using the new cyclone with a reenforced vortex finder, and new reservoir with flow back stopper. All trials were run at 20 L/min in the sideways orientation.
For the single pass trials, the procedure can be seen in table 3.6

Table 3.6 Single Pass Test Procedure

Step #	Step
1	Between 38.5 and 41 kg of water was weighed out. Water weight was dependent on the weight of fiber sample. Concentration of 0.2g of fiber to 40 kg of water was maintained
2	Hydro cyclone and reservoir were attached to test set up
3	Water was poured into test tank
4	Pump was turned on to establish flow rate of 20 L/min and then turned off
5	0.2g of fiber and 5g of detergent were added to tank
6	Stand mixer was turned on
7	Pump was turned on and ran until tank was empty
8	3 gallons of extra water was poured into tank as pump was running to make sure all water passed through cyclone
9	When tank was empty, pump was turned off

10	Additional 80 L of water were run through system and collected in plastic tubs
11	Hydro cyclone was disconnected, and contents of reservoir were emptied into beaker
12	Contents of reservoir were filtered onto 5-inch filter paper via vacuum filtration
13	Contents of plastic tubs was filtered onto 11-inch filter paper via pressure filter
14	Filters were dried and weighed

3.4 Recirculation vs single pass Results

Efficiency as with the previous tests was calculated by taking the mass of fibers recovered in the apex reservoir and dividing that by the mass of fibers input into the system. Table 3.7 below shows the efficiency numbers for the recirculation trials and table 3.8 shows the results of the single pass results.

Table 3.7 Efficiency Data for Recirculation Set Up

Test #	1	2	3	4	5
Fiber Addition G	0.1947	0.2079	0.202	0.1974	0.1996
Water Addition L	38.94	41.58	40.4	39.48	39.92
Tops Fiber Wt. G	0.0591	0	0.0585	0.0899	0.1541
Bottoms Fiber Wt. G	0.1921	0.1603	0.1545	0.1527	0.1603
Apex Based Efficiency	99%	77%	76%	77%	80%
Average Efficiency	0.82				

Table 3.8 Efficiency Data for Single Pass Set Up

Test #	1	2	3	4	5
Fiber Addition G	0.2153	0.1834	0.1988	0.2002	0.1851
Water Addition L	43.06	36.68	39.76	40.04	37.02
Tops Fiber Wt. G	NA	0.067	0.0454	0.0908	0.1162
Bottoms Fiber Wt. G	0.1784	0.1324	0.1675	0.2345	0.1763
Apex Based Efficiency	83%	72%	84%	117%	95%
Average Efficiency	0.8364				

The average efficiencies of the single pass and recirculation trials are very similar to each other, and when performing a confidence interval test on the averages, the confidence intervals overlapped, showing that there is no statistically significant difference in the averages. This means that the filtering device can be placed in the drain line of the washing machine without losing effectiveness. The high efficiency result in run 4 was due to material carryover during the tests and was not used in calculations of the average. Also, having parts of the cyclone reinforced against warping made it perform as intended, and on average the cyclone was able to hit the 80% efficiency average that the sponsor was hoping to achieve.

The design of the hydro cyclone was changed slightly to reduce the pump requirements, so a 55 Watt pump would be sufficient to provide the necessary pressure drop. This meant that the design flow rate of the new hydro cyclone would be 15 L/min rather than 20 L/min. The next step in the investigation was to understand how the introduction of other contaminants would affect the performance of the hydro cyclone. When clothes are washed, polyester fibers are not the only solid particles that become entrained in the water. Dirt, cotton, pet, and human hair can be released from clothes in much larger amounts than the specific polyester microfibers that we are currently studying. One challenge that has been seen with traditional filters is that all these other materials clog filters and affect performance. While clogging the hydro cyclone is not anticipated to be a great danger, there is still concern over how the introduction of these other particles could affect the performance of the hydro cyclone. The concern is that shorter smaller polyester fibers can tangle with the cotton and longer hairs. For the most part, hair and cotton fibers are not well separated by this hydro cyclone. The dog hair tested in our lab floated in water, which meant it was less dense than water and would not be separated by the hydro cyclone. The cotton, which is made of cellulose and has a density of 1.52g/cm^3 still ends up mostly in the tops. While the density of cellulose is denser than water, these cotton fibers are likely hollow (Hsieh, 2007), and the fiber length may also make them harder to separate. The concern is that the polyester particles that tangle with hair or cotton will be carried out of the tops of the hydro cyclone. Tests were designed to understand how the addition of other solid materials affected the performance of the hydro cyclone.

3.5 Other Materials in water Methods and Materials

Same materials initial hydro cyclone testing in table 3.1 in addition to the materials seen in table 3.9

Table 3.9 Additional Materials used in Other Materials Tests

PVC constructed reservoir
Sand
Cotton
Dog hair
Thermo Gravimetric Analysis machine

The methods for these tests follow the instructions given in table 3.10.

Table 3.10 Other Materials Tests Method

Step #	Step
1	Washed 4kg of blue Walmart cotton towels in front loading washing machines to produce cotton fibers
2	Filtered washing water and removed cotton fibers from filters
3	Weighted out 1 g of polyester, 9.2 g of sand, 0.8 g of dog hair, between 0.2 and 0.3 g of cotton and 5 g of detergent
4	Weighed out roughly 40 kg of water using floor scale
5	Cyclone and reservoir were attached to the test rig
6	Water was poured into the tank
7	Pump was briefly turned on to establish flow rate
8	Pump was turned off, stand mixer was turned on
9	Hair, polyester, cotton, sand, and detergent were added to the water
10	Timer was set for roughly 9 minutes which is enough time for all water to pass through system 3 times
11	When all particles were suspended, timer and pump were started
12	When timer went off, pump was turned off
13	Tank water was drained into plastic tub,
14	Cyclone and reservoir were disconnected from system, water and solids in reservoir was transferred into beaker
15	80 additional L of water were run through system and collected in plastic tubs
16	Water in plastic tubs were filtered via pressure filter, water in beaker filtered via vacuum filtration
17	Filters were dried and weighed, and solid material was scraped off and put into TGA for analysis

A PFD for the experimental set up for this test can be found in figure 3.3.

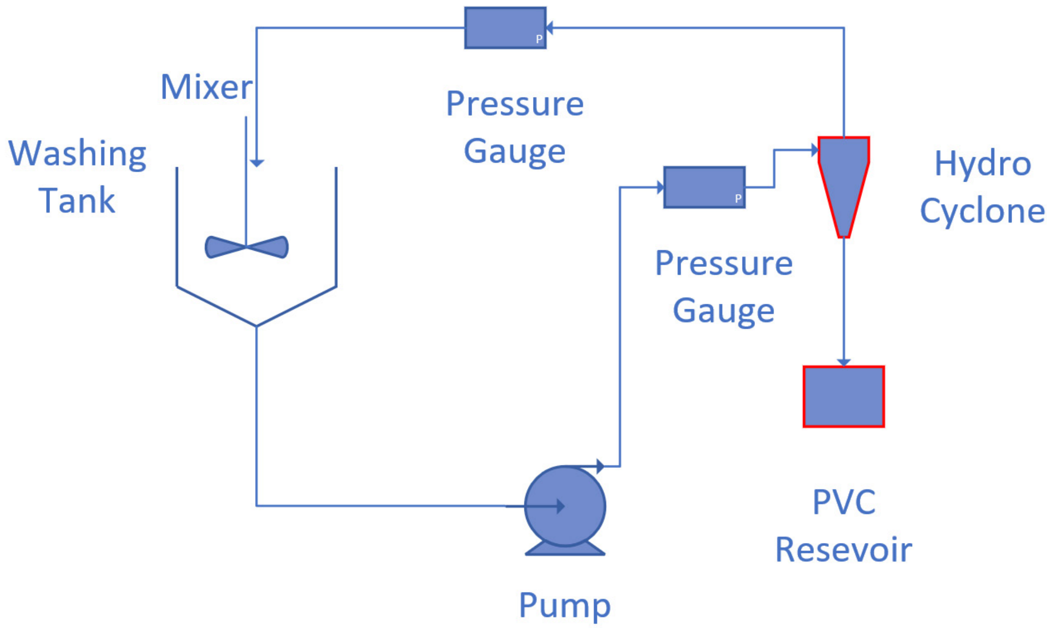

Figure 3.3 Experimental Set up PFD for Other Materials

Thermo Gravimetric Analysis Calculation

To determine how much of the material captured by the cyclone was polyester, and how much material was something else, a Thermo Gravimetric analysis was used hereby referred to as TGA. Standard samples of pure polyester, pure cotton, pure hair, and pure sand were put into the TGA machine to determine the temperatures at which each pure material degrades. Weight loss curves were found for cotton and polyester. Hair did not have a clear temperature at which it degraded, and sand in general did not degrade with temperature. Figure 3.4 shows a graph of the raw material weight loss Trends. Material from the reservoir filter was scraped off the filter and put into the TGA machine. The peaks for cotton and polyester were used to distinguish what percentage of the total weight of material collected was polyester. This polyester weight percentage was used to calculate the polyester weight captured in the reservoir.

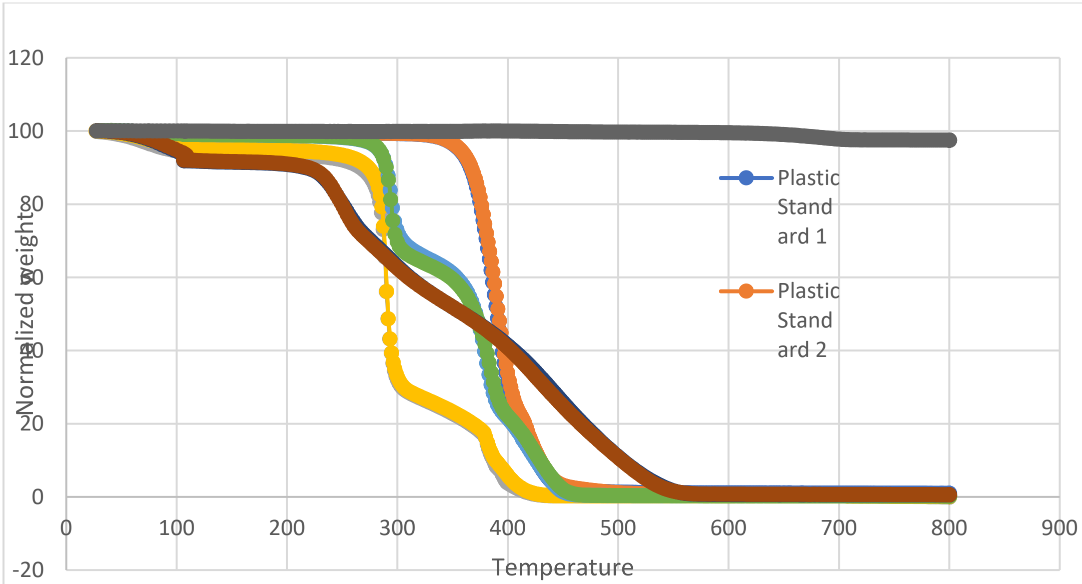

Figure 3.4 Raw Material Weight Loss Trends

Example calculations:

Figure 3.4 shows that plastic loses 96% of its weight between the temperatures of 330 degrees to 460 degrees. Cotton loses 60% of its weight between 265 and 305 degrees and 25% of its weight between the temperatures of 330 and 460 degrees. The data collected on 10-21-2022 showed that the sample lost 3.21% of its initial weight between the temperatures of 265 to 305 degrees. This temperature loss was 60% of the total cotton weight loss. So, dividing this percentage by 0.6 results in 5.35% of the total weight being cotton. 38.85% of the sample weight was lost between the temperature of 330 to 460 degrees. The total percentage of cotton weight in the sample was 5.35%. 25% of that weight would have been lost between 330 and 460 degrees. So, 1.33% of the 38.85% loss in that range would have been cotton loss. The rest of that weight percentage would have been polyester losing weight. Subtracting 1.33% from 38.85% results in 37.51%. From our standards graph, we know that polyester loses 96% of its weight between 330 460 degrees. Dividing 37.15 by 0.96 gives 39.07%. Of the material sample collected, 16.8% of the weight is polyester. The equations for these calculations can be seen in equations 5 and 6.

$$\%cotton = \frac{\%\,loss\ betweein\ 265\ and\ 305}{0.6} \qquad \text{Equation 5}$$

$$\%\ polyester = \frac{\%loss\ between\ 330\ and\ 460 - \%cotton\ loss * 0.25}{0.96} \qquad \text{Equation 6}$$

For all apex-based efficiency calculations, only the material collected at the apex went through TGA analysis. Due to its low density and high fiber length, the amount of pet hair in the apex material was negligible, so was not considered in the TGA analysis until the final test runs. The sand did not degrade over the temperatures tested, so was not considered in the calculation.

3.6 Other Materials in Water Results

To determine whether the addition of materials that are commonly found in a washing machine affects the efficiency of separation for polyester, 2 sets of 5 trials were performed. 5 trials where only polyester material was used, and 5 trials where other materials were added to the tank. For the trials that had other material in the tank, the TGA was used to differentiate polyester from the other materials. Tables 3.11 and 3.12 show the separation efficiencies for each set of trials.

Table 3.11 Efficiency Results for Only Polyester Fibers

Test #	1	2	3	4	5
Fiber Addition g	0.994	0.9892	0.9543	0.9752	0.9231
Bottoms Fiber Wt. g	0.7065	0.6866	0.5456	0.72	0.6241
Apex Efficiency	71%	69%	57%	74%	68%
Average	68%				

Table 3.12 Efficiency Results for Polyester and Other Materials

Test #	1	2	3	4	5
Fiber Addition g	1.0035	0.9881	1.0385	1.0092	1.0068
Bottoms Fiber Wt. g	1.5854	1.6148	1.8101	2.8821	2.7402
% Bottoms Polyester	37%	37%	39%	23%	25%
Apex Efficiency	59%	61%	67%	67%	68%
Average	64%				

The average efficiency over the five trials is 68% for only polyester fibers, and 64% for other materials added. These averages are close to each other, and when a confidence interval was performed on the averages, the intervals overlapped, showing that there is not a statistically significant difference between the two sets of data. This shows that adding other materials to the wash water does not interfere with the ability of the cyclone to separate polyester. Most of the cotton and pet hair that went through the cyclone ended up in the tops, but that is not a concern if it does not take a significant portion of the polyester with it. What ends up in the bottoms is almost exclusively polyester and sand, with a very small amount of cotton. This makes sense as sand is made up of roughly spherical particles, and although this cyclone was designed for a certain size of polyester, sand is also separated due to is high density and spherical particle shape. There is a chance that a particularly large sand particle clogs the apex. When this happens, all water and material go out the tops, and the cyclone does not separate any solids. To avoid this, the apex of the cyclone should be 5 times wider than the diameter of the sand particles, reducing the length of the apex has made this significantly less likely.

3.7 Conclusions

There were three considerations that we wanted to learn about the hydro cyclone, and its capability for this application. The first piece of information was to establish whether the cyclone could operate upside down and sideways as well as right side up. Conventional knowledge shows that this should be possible, and for space constraints inside the washing machine, sideways is the most likely orientation. The other bit of knowledge that was gained from initial testing is that running cyclones at a lower than designed flow rate will result in very bad separation.

The second piece of information that we intended to learn was how recirculating water through the cyclone multiple times would affect the separation of polyester in these cyclone designs. A set of trials was conducted in a single pass set up, and in a set up where water was recirculated through the system 3 times. The results showed that recirculation vs single pass did not significantly change the results. The other important learning from those set of tests was that the cyclone was able to reach the 80% efficiency mark. However, that design of hydro cyclone was too demanding in terms of pump power, and the design was changed to reduce the pump needs. This is the reason for different efficiency data in later investigations.

Thirdly we wanted to gain an understanding of how the cyclone would react with other materials. Sand, cotton, and dog hair were added to the water as well as polyester, and efficiency tests were run. The data for the efficiency tests showed that the cyclone was able to separate the polyester and sand selectively from the mixture. The data also showed that adding other materials into the system did not significantly reduce the separation efficiency of the cyclone, which had been a concern up to that point.

The hydro cyclone itself can separate polyester from a water mixture that contains all the materials that are commonly found in washing machine wastewater. However, the collected underflow will always have water in it. What happens with the collected underflow is another challenge. A reservoir needed to be designed to pair with the hydro cyclone, that could meet the project sponsor's needs, and be simple enough for consumers to use.

4. Reservoir Development and Design

Coming up with a hydro cyclone that was able to isolate and separate polyester from washing machine water was only one of the design considerations. As described in Chapter 1, the overall goal of this project was to come up with a device that would separate micro plastics from water, leaving a semi solid sludge that could be disposed of in solid waste. The way a hydro cyclone works is that the cyclone separates water into a clean stream and a dirty stream. So, in our system, the polyester is still entrained in a water stream when it leaves the cyclone. The reservoir needs to be able to de water the dirty stream and leave behind semi solid polyester sludge that can then be emptied into the trash. The reservoir also needs to be easily removed, cleaned out, and re attached into the washing machine without causing water to leak excessively.

The development of the reservoir involved several stages of ideation and design work. The first stage of understanding the reservoir was to observe what happened in the reservoir as it filled up with solid particles. This would show us how the reservoir would fill up with solid particles. The hope was that as the reservoir filled with fibers and sand, the solid particles would displace the water, and that the reservoir would de water itself naturally. This ended up not being the case, so more design work went into developing a way of manually dewatering the material captured in the reservoir.

To this end, two variations of what were called the “French press” designs were prototyped, the “push french press” and the “pull french press”. The designs are similar to a french press coffee maker, that uses a plunger to separate coffee grounds from water. Both the push and pull configurations had a similar design but operated differently to examine the best way to make the unit more user friendly.

One other design feature of the reservoir that may become an important innovation is the reservoir recirculation line. Leaving this line open would increase the efficiency of the hydro cyclone compared to a closed grit box. This is because water must flow in and out of the grit box via the hydro cyclone apex. Having this line open would introduce some bias flow through the apex and would increase the efficiency of the separation. This was tested several times in the investigation of the reservoir and more detail can be found in the results section.

4.1 Reservoir Filling Test Methods and Materials

Reservoir filling tests materials can be found in Table 4.1

Table 4.1 Filling Test Materials

XS1025 Dual range analytical balance with wind block
Maytag model MVW8230HC VMAX2 pre pilot top loading washing machine
County Line ½ HP cast Iron shallow well jet Pump
Cone bottom tank
Water Source 100 PSI pressure gauge
Fortiflex 66 L MPB plastic tub
Braided plastic tubing
Stainless steel plumbing
5-inch Whatman number 1 paper filter
500 ml Erlenmeyer flask
Buchner funnel
3d printed hydro cyclone
Hand made pvc reservoir
Tractor supply 5 gallon bucket
Analog floor balance
Stand mixer
Generated micro fibers
Sand
Blue cotton towels
Mineral oil
Dog hair
Graduated cylinder

The reservoir filling tests were qualitative tests, not quantitative tests, so no numerical data was collected or recorded. The point of these tests was to observe how the solid materials behaved when they entered the reservoir, to give insights into the shape and orientation that the reservoir should be. Dryer lint was collected by emptying the lint trap of a domestic dryer and putting in a plastic bag. To carry out the filling tests, the below procedure in table 4.2 was used.

Table 4.2 Reservoir Filling Test Methods

Step #	Step
1	Wash 4kg of terry towels, 9.2 g of sand, 0.8 g of dog hair, and 32 g of mineral oil in top loading washing machine. Collect wash water in cone bottom tank of testing rig
2	While wash is running, create dry mix by mixing sand with previously collected dryer mix
3	When wash cycle is finished and water has been collected in tank, hook up hydro cyclone and reservoir to test stand
4	Set up camera to film reservoir as it fills
5	Turn on pump and start recording
6	After three minutes have passed, add two spoonsful of dry mix to tank every 90 seconds
7	Observe what happens in the reservoir
8	Continue running test until reservoir is full or apex of cyclone clogs

4.2 Reservoir Filling Test Results

The first filling test was conducted with the reservoir in the horizontal orientation as shown in Figure 4.1 The apex discharged into the middle of the reservoir. The solid material formed a large pile in the middle of the reservoir and did not migrate to the edges. Thus, there was a lot of space that was occupied by water. When the pile in the middle of the reservoir reached the point of the apex, the apex clogged, and no more material was able to enter the reservoir. Figure 4.2 shows a picture of this initial test. As shown by the image, there is a lot of unutilized space, so this configuration is undesirable.

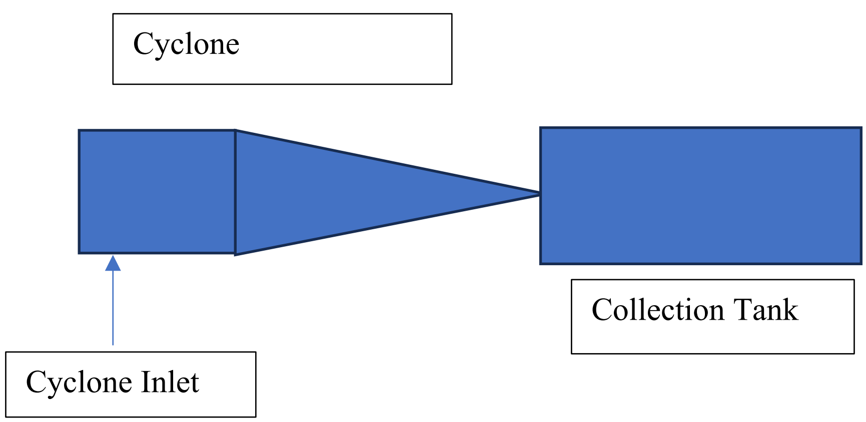

Figure 4.1 Diagram of Horizontal Filling Test

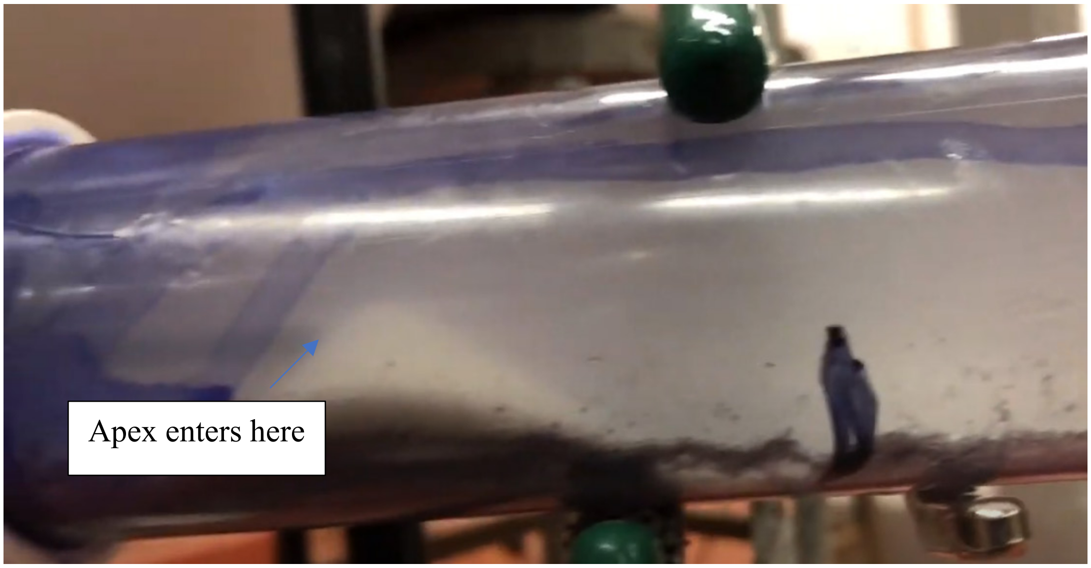

Figure 4.2 Picture of End of Filling Test with Horizontal Reservoir

The next tests were conducted with the reservoir in the vertical orientation and cyclone in the horizontal orientation. Figure 4.3 is a diagram of how the cyclone and reservoir fit together. The procedure for the test was the same as before, with dry mix being added to the system every 90 seconds. With the reservoir in the vertical orientation, when material enters the reservoir, gravity pulls it down to the bottom of the reservoir. The reservoir filled from the bottom up and did not fill in a linear fashion. Once a layer of solid particles formed at the base of the reservoir, the solids deposited more quickly, with sand being the main solid particle in the reservoir. As before, when the solid particles built up to the point where the apex entered the reservoir, the apex plugged, and no more material entered the reservoir. See Figure 21 which is a picture of the reservoir after filling test was completed. As can be seen from the pictures, having the reservoir oriented vertically allows for a greater utilization of the space. However, even though some water is displaced, there is still a lot of water in the reservoir when it can no longer be filled with solid particles.

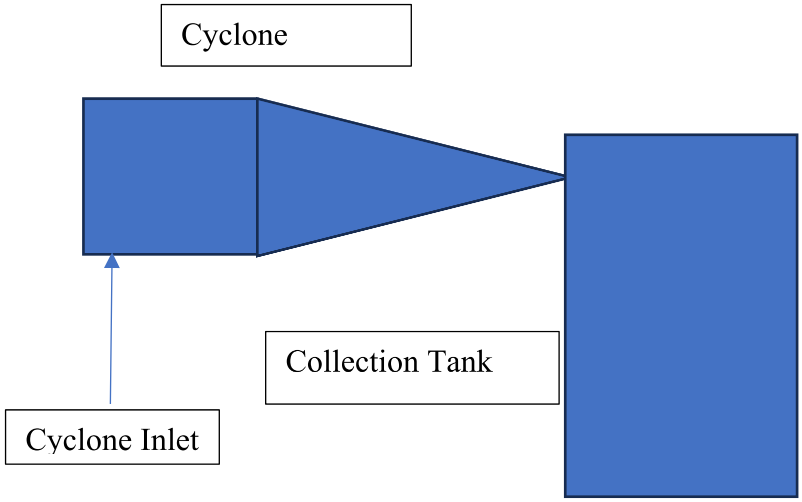

Figure 4.3 Diagram of Vertical Orientation Test


Figure 4.4 Picture of End of Horizontal Filling Test

The initial hope had been that as solids filled the reservoir, that they would displace the water, and what remained in the reservoir would be a solid sludge. When the reservoir was opened after the vertical filling test, there was a significant amount of water still in the reservoir, too much for it all to be disposed of in solid waste. This is because water was able to remain in the void spaces between particles.

4.3 Push vs Pull Test Methods and Materials

To effectively eliminate the water in these void spaces, the plunger concepts were introduced, to compress the particles and push the water out of the void spaces between the particles, and out of the reservoir. The push French press design was operated in a similar way to a French press coffee maker. A hollow cylinder was the main vessel, and at one end of the vessel, there was an attachment to attach a hose. The lid of the vessel had a hole in it, and a plunger attached to a shaft went through this hole. At the opposite end of the vessel, there would be a stainless-steel mesh screen. The idea was that when the reservoir was full, the plunger would press downwards. The plunger would compress the solids, and push the water out of the reservoir, leaving behind mostly solid particles. The water would enter a recirculation line and end up back in the system. The reservoir could then be detached from the cyclone, opened up, and emptied into the trash. Figure 4.5 is a diagram of the French press reservoir.

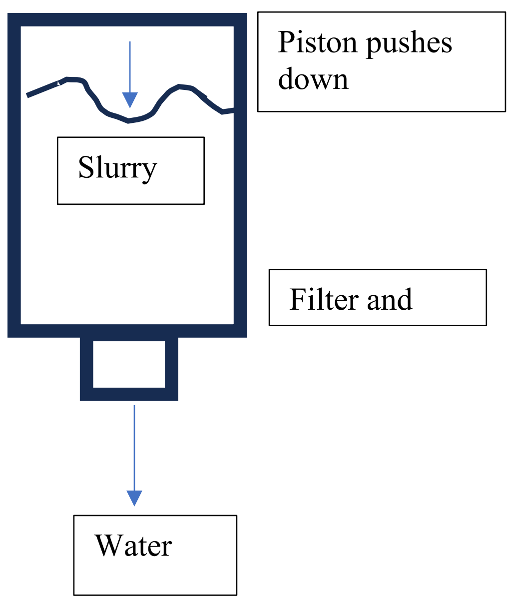

Figure 4.5 French Press Push Reservoir Diagram

The French press pull design was similar to the push design, except backwards. The pull design started with the plunger completely depressed inside of the reservoir. When the reservoir was filled, the plunger was pulled out, pushing the water and material against the lid of the reservoir. The idea was that the water would be forced back into the apex of the cyclone, and that the solids would pack against the lid of the cyclone. A valve at the apex of the cyclone could then be closed, isolating the water in the apex of the cyclone from the solid material in the reservoir. The reservoir could then be detached and emptied into the trash in a similar manner as the push prototype. A diagram can be seen in Figure 4.6.A series of efficiency tests were conducted to see if there was a measurable difference in efficiency between the two designs.

Push vs pull efficiency test materials were the same set of materials as the initial hydro cyclone test in Table 3.1 except for the addition of the materials shown in Table 4.3

Table 4.3 Additional Materials used in Push vs Pull Tests

Push style 3d printed reservoir roughly 300 ml
Pull style 3d printed reservoir roughly 300 ml
Puck mill generated microfibers
Sand
Cotton
Dog hair
TGA machine

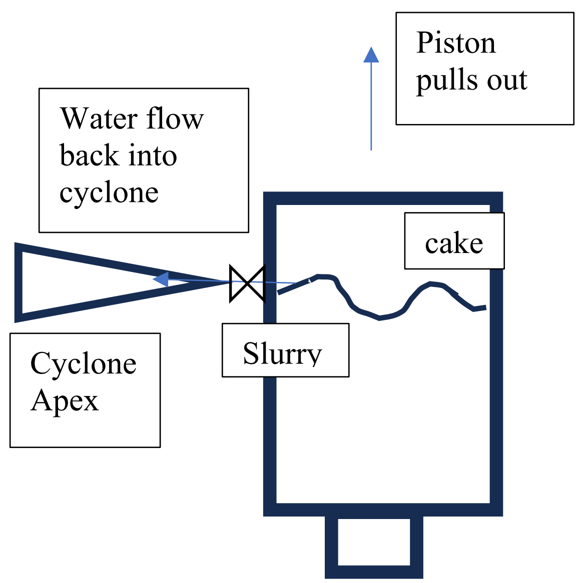

Figure 4.6 Diagram of French Press Pull Reservoir

Figure 4.7 is a PFD of the experimental set up used for the push vs pull French Press tests.

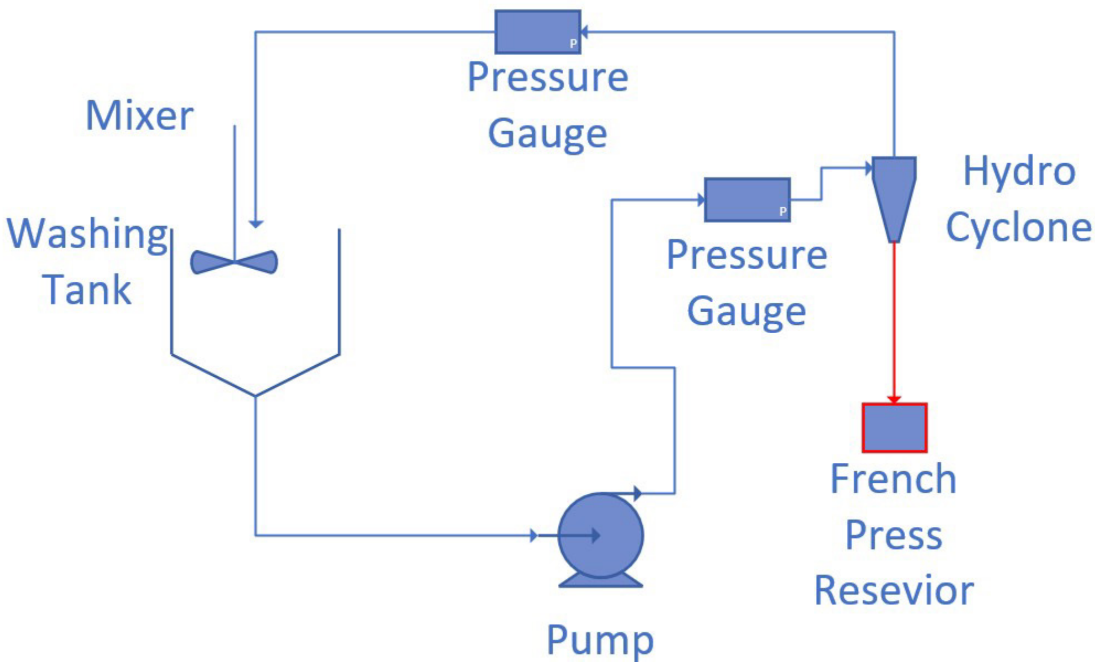

Figure 4.7 PFD of Experimental Set Up

These sets of tests were performed with a hydro cyclone design that had been altered to require a pump power of 35 watts. The separation efficiencies as an absolute number are quite low but are useful for the purposes of comparison. Two sets of tests were carried out, one in the push configuration, and one in the push configuration. The tests were carried out according to the procedure outlined in Table 4.4.

Table 4.4 Push vs Pull Efficiency Test Methods

Step #	Step
1	Weight out 1 g of polyester, 9.2 g of sand, 0.8 g of dog hair, between 0.2 and 0.3 g of cotton and 5 g of detergent
2	Weigh out roughly 40 kg of water using floor scale
3	Cyclone and reservoir were attached to the test rig
4	Water was poured into the tank
5	Pump was briefly turned on to establish flow rate
6	Pump was turned off, stand mixer was turned on

7	Hair, polyester, cotton, sand and detergent were added to the water
8	Timer was set for roughly 9 minutes which is enough time for all water to pass through system 3 times
9	When all particles were suspended, timer and pump were started
10	When timer went off, pump was turned off
11	Plunger was either pressed in or pulled out depending on test
12	Tank water was drained into plastic tub,
13	Cyclone and reservoir were disconnected from system, water and solids in reservoir was transferred into beaker
14	80 additional L of water were run through system and collected in plastic tubs
15	Water in plastic tubs were filtered via pressure filter, water in beaker filtered via vacuum filtration
16	Filters were dried and weighed, and solid material was scraped off and put into TGA for analysis

A picture was taken of the material inside the reservoir once the plunger had been pressed in. The plunger was able to force most of the water out of the reservoir and create the solid mash that could be disposed of in the solid waste. This picture can be seen in figure 4.8.

Figure 4.8 Picture of De-Watered Material Inside Reservoir

4.4 Push vs Pull French Press Test Results

Table 4.5 shows the efficiency results for the push configuration, and Table 4.6 shows the efficiency results for the pull configuration.

Table 4.5 Push Configuration Efficiency Results

Test	Polyester Weight in Bottoms g	Efficiency
1	0.1296	13%
4	0.1546	15%
5	0.1444	15%
Average	0.14287	14%

Table 4.6 Pull Configuration Efficiency Results

Test	Polyester Weight in Bottoms g	Efficiency
1	0.0778	8%
3	0.2125	21%
6	0.1233	12%
Average	0.1379	14%

The average efficiency of both configurations is similar. A confidence interval test was performed for both sets of results and the test showed that there was no statistically significant difference in separation efficiency between the two reservoir set ups. The push or pull configuration does not affect the separation efficiency of the cyclone. However, while running the test, it was found that the push configuration performed better from an ease-of-use standpoint. It had a much lower risk of leaking, and made a nicer puck of solid material, which was easier to dispose of. Due to this fact, the push configuration was used in further steps of the testing process, and the pull configuration was abandoned.

4.5 Bleed Line Test Methods and Materials

The final question to answer about the reservoir was the idea of a recirculation line. Conventional knowledge of hydro cyclones states that a closed collection container at the apex of the cyclone will result in a lower separation efficiency. Part of the reason for this is that water that flows into the closed container must flow out as well through the apex. Having a way for water to leave the reservoir not through the apex is thought to solve this problem. In our reservoir, a mesh screen was added at the bottom of the reservoir. This screen can be seen in Figure 4.8 A tube with a valve was attached to the bottom of the reservoir. The theory was that this tube would attach somewhere upstream of the system. While the system ran, the valve would be partially open. Water would flow into the reservoir via the cyclone apex, and water would flow out of the reservoir and back into the system via the tube. The mesh screen would prevent most solids from leaving the reservoir. A set of six tests were run with the reservoir in the push orientation to test whether this theory held merit.

Bleed line test materials are the same materials used in initial hydro cyclone testing in table 3.1 with the following exceptions outlined in table 4.7

Table 4.7 Changed to Materials for Bleed Line Testing

Push style 3d printed reservoir roughly 300 ml
Puck mill generated microfibers
Sand
Cotton
Dog hair
TGA machine

Six tests were conducted in this investigation to determine whether having an open bleed line from the reservoir would affect the separation efficiency. Three tests were conducted with the bleed line open, allowing water to flow out of the reservoir, and three tests were conducted with the bleed line closed. Figure 4.9 shows a diagram of how the bleed line and reservoir were set up.

To carry out these tests the procedure outlined in table 4.8 was used was used.

Table 4.8 Bleed Line Test Methods

Step #	Step
1	Weight out 1 g of polyester, 9.2 g of sand, 0.8 g of dog hair, between 0.2 and 0.3 g of cotton and 5 g of detergent
2	Weighed out roughly 40 kg of water using floor scale
3	Cyclone and reservoir were attached to the test rig
4	Water was poured into the tank
5	Pump was briefly turned on to establish flow rate, bleed line was opened
6	Pump was turned off, stand mixer was turned on
7	Hair, polyester, cotton, sand, and detergent were added to the water

8	Timer was set for roughly 9 minutes which is enough time for all water to pass through system 3 times
9	When all particles were suspended, timer and pump were started
10	When timer went off, pump was turned off
11	Bleed Line bucket was poured back into wash tank
12	Plunger was pressed in
13	Once water was forced out of reservoir, bleed line was closed
14	Tank water was drained into plastic tub,
15	Cyclone and reservoir were disconnected from system, water and solids in reservoir was transferred into beaker
16	80 additional L of water were run through system and collected in plastic tubs
17	Water in plastic tubs were filtered via pressure filter, water in beaker filtered via vacuum filtration
18	Filters were dried and weighed, and solid material was scraped off and put into TGA for analysis

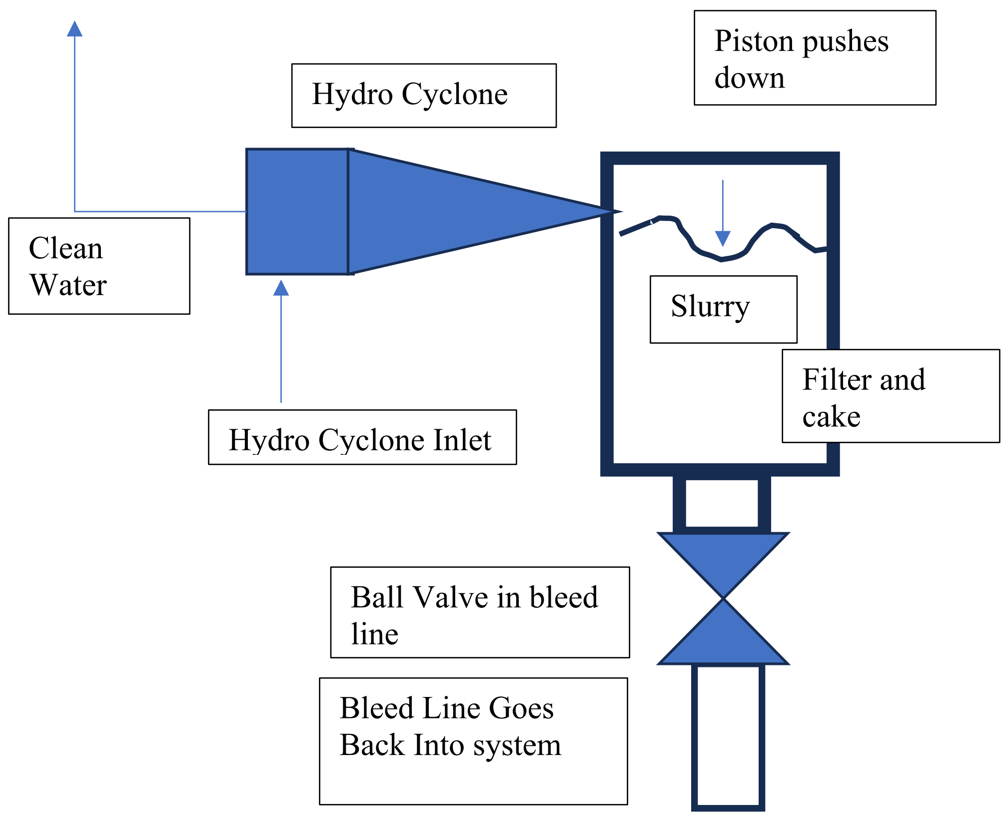

Figure 4.9 Diagram of Bleed Line Test Set Up

Figure 4.10 is a PDF of the experimental set up used to conduct these tests.

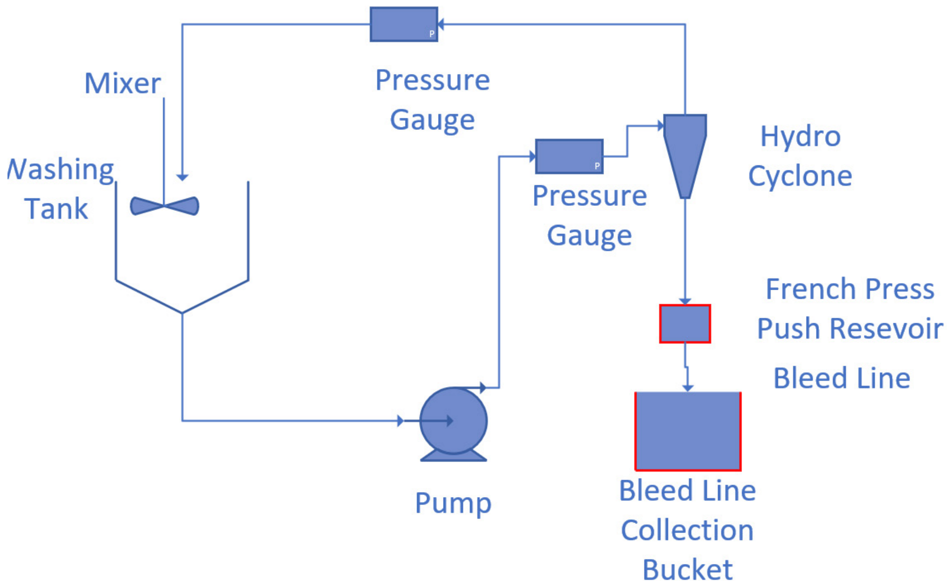

Figure 4.10 Experimental Set up for Bleed Line Tests

4.6 Bleed Line Test Results

Table 4.9 shows the efficiency of the push reservoir with the bleed line closed, and table 4.10 shows the efficiency of the push reservoir with the bleed line open.

Table 4. 9 Bleed Line Closed Efficiency Results

Test	Polyester Weight in Bottoms	Efficiency
1	0.1296	13%
4	0.1546	15%
5	0.1444	15%
Average	0.14287	14%

Table 4. 10 Bleed Line Open Efficiency Results

Test	Polyester Weight in Bottoms	Efficiency
2	0.3042	28%
3	0.2908	29%
6	0.2965	30%
Average	0.2972	29%

The average separation efficiency for the tests run with the bleed line closed was 14%, while the average efficiency for the tests with the bleed line open was 29%. A confidence interval test was performed on the average separation efficiencies. The confidence interval for the bleed line closed test was 11% to 17%. The confidence interval for the bleed line open was 27% to 31%. Since these intervals do not overlap, it can be concluded that adding a bleed line to the reservoir significantly increases the separation efficiency of the cyclone and reservoir.

To further underline this idea that a bleed line could increase efficiency, this testing was repeated with a cyclone that was designed for a higher pump power but would offer a higher overall separation efficiency. The previous tests were performed with a cyclone that was designed for a lower pump power. These power calculations were made based on pressure drop and flow rate calculations. Also, only polyester fibers were added to the tank for the subsequent testing, not hair and other materials. This meant that the TGA was not required.

4.7 Subsequent Bleed Line Test with high power Cyclone Methods Materials

The same materials were used for this test as the initial hydro cyclone testing shown in table 3.1.

The subsequent tests were run according to the procedure for initial hydro cyclone tests outlined in table 3.2 with the following changes.

- While establishing flow rate before test was run, bleed line was opened
- After pump was turned off, bleed line collection bucket was emptied into wash tank

4.7 Subsequent Bleed Line Tests with High Power Cyclone Results

Eight trials were conducted in total. Four with the bleed line open, and four with the bleed line closed. Table 4.11 shows the efficiency results for the bleed line closed tests, and table 4.12 shows the results for the bleed line open tests.

Table 4.11 High Power Cyclone Bleed Line Closed Efficiency Results

Test	PES Weight Collected	Efficiency
1	0.1113	56%
4	0.088	43%
5	0.1085	54%
6	0.0822	41%
9	0.1116	56%
Average	0.1003	50%

Table 4.12 High Power Cyclone Bleed Line Open Efficiency Result

Test	PES Weight Collected	Efficiency
2	0.1374	71%
3	0.1694	84%
7	0.1965	98%
8	0.1756	86%
10	0.1835	90%
Average	0.1725	86%

A confidence interval test was performed on the average separation efficiency for each set of tests. The confidence interval for the average separation efficiency for the tests performed with a closed bleed line was 41% to 59%. The confidence interval for the average separation efficiency for the tests performed with an open bleed line was 74% to 98%. This data reenforces the positive effect that a bleed line has on the separation efficiency, and that this cyclone and reservoir design has the potential to meet separation efficiency needs.

To this end, one more set of tests was conducted. With the data showing that a bleed line increases separation efficiency, and when used with a high power hydro cyclone the separation efficiency is close to what the sponsor deems an acceptable separation efficiency, a final set of testing was performed to get an idea of what the capability of the system could possibly be. For this set of testing some changes were made to the lab set up. The bleed line, which had previously been run to a collection bucket, was integrated into the system fully. The bleed line ran from the end of the reservoir to the inlet of the pump, so any material that got through the mesh screen in the reservoir would be recycled into the system, and not go out the drain. Also, for these tests not only apex-based efficiency was taken into account. For the regulation, the weight of micro plastics that leave the system are what is measured, not what is captured in the collection vessel. On this hand, the system-based efficiency will be calculated as well as the apex-based efficiency. The location of the cyclone inside the washing machine had not yet been fully determined so it is likely that water will only pass through the cyclone one time, rather than be recirculated through the cyclone. These tests were therefore conducted in a single pass orientation.

4.8 Final Efficiency Testing Methods and Materials

The same materials were used for this test as outlined in table 4.7 for bleed line testing:

Tests were performed according to the procedure outlined in table 3.6 for single pass tests with the following exceptions.

- 1 g of polyester, 9.2 g of sand, 0.8 g of dog hair, between 0.2 and 0.3 g of cotton and 5 g of detergent were used
- When flow rate was being established before test, bleed line was opened
- Plunger was pushed in when test was over

Figure 4.11 is a PFD of the final testing experimental set up.

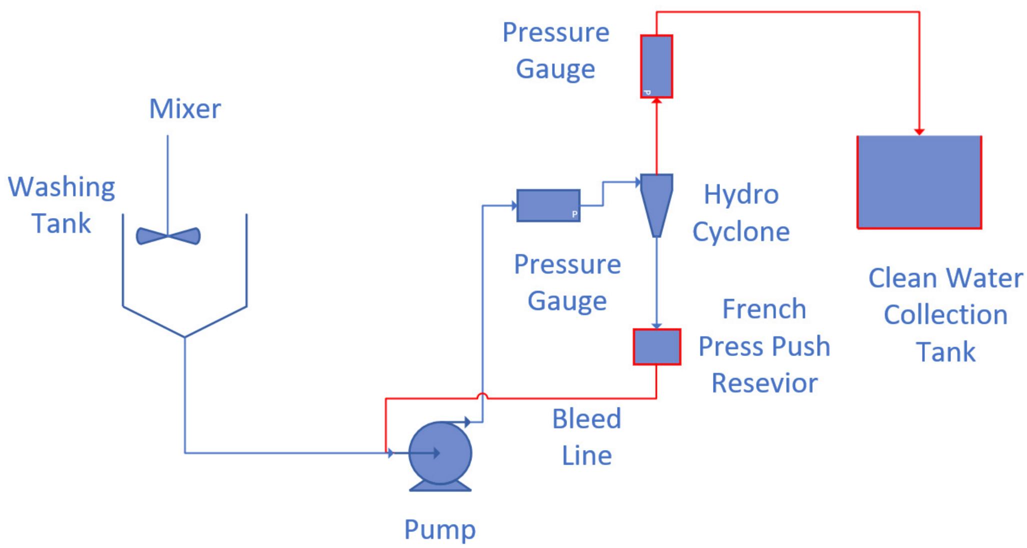

Figure 4.11 Final Testing Experimental Set Up PFD

The percentage weight of polyester in each filter collected was calculated as it was in Chapter 3. The weight of polyester in the tops is what would exit the system as a whole and would be released to the environment. To calculate the system base efficiency, the weight of polyester released to the environment is subtracted from the polyester recovered in both the tops and the bottoms. This number is then divided by the weight of polyester that went through the cyclone. refer back to chapter 1 for an in-depth description of system efficiency.

4.9 Final Efficiency Test Results

A set of five efficiency tests was conducted to see what the separation efficiency of the 50-watt cyclone attached to the push style French press reservoir with an integrated bleed line that recirculates water through the pump. Table 4.13 shows the weight of polyester captured in the reservoir, and the weight of polyester released to the environment, as well as the apex and system-based efficiency of the system.

Table 4.13 Final Efficiency Test Results

Test	1	2	3	4	5	Average
Polyester Weight in Bottoms	0.6160	0.4789	0.7796	0.7517	0.7906	0.6834
Apex Based Efficiency	62%	48%	78%	75%	79%	68%
Polyester Weight in Tops	0.0654	0.0208	0.0420	0.0525	0.0286	0.0419
System Based Efficiency	90%	96%	95%	93%	97%	94%

Table 4.13 shows that there is a large amount of variation in the weight of fibers collected in the reservoir, and this translates to a large amount of variation in the apex-based efficiency. Also, the average apex-based efficiency at 68% is lower than what was hoped for. However, the system efficiency with an average of 94% is great. This shows that while around 60 to 70% of the polyester put into the system ends up in the reservoir, only about 5% of the polyester added to the system ends up in the clean water. The rest is retained somewhere in the system. With these particles being so small and sometimes hydrophobic, the particles could be getting hung up in the pump or in any of the plumbing in the system. With these good system efficiency results, this set up is the most promising solution.

4.10 Reservoir Conclusions

Developing a hydro cyclone that could separate polyester from washing machine water was only half of the solution. The other half was to develop a reservoir that could collect the microfibers as a dry sludge, and that could be removed and emptied into a trash can without needing to be rinsed. The first step was to run filling tests on a handmade reservoir to see how particles acted inside of the reservoir. These tests showed that having the reservoir in the vertical orientation would be best for utilizing the space in the reservoir. Also, a de watering mechanism needed to be developed. This led to the development of two possibilities. The push and the pull French Press designs. Efficiency testing showed that the differences in design did not change the efficiency, but the push design was better from a maintenance perspective. The volume of the reservoir was roughly 300 ml, which would be roughly large enough to collect the solid material from 30 cycles.

The original idea for the reservoir was for it to be a fully closed reservoir, that would act sort of like a grit box. This would cause a lower separation efficiency for the hydro cyclone. One suggested design change was to add a recirculation line to the reservoir. The bottom of the reservoir had a fine mesh screen. A line would recirculate water from the reservoir to the inlet of the pump. A series of tests confirmed that having this bleed line significantly increased the separation efficiency of the hydro cyclone, as well as making the de watering process easier.

A final set of tests was conducted to understand the ability of the design as it stands to separate polyester fibers from washing machine water. System level efficiency was used, and the system level separation efficiency met the goals of the project. It is recommended to move forward with a high power cyclone and a French press push style reservoir with an integrated bleed line that connects back to the pump inlet.

5 Additional Investigations

While the hydro cyclone and reservoir concepts were being developed and tested, there were some additional investigations that were carried out, that did not end up being part of the final design. During the initial development of the reservoir, there were some questions as to how big the reservoir needed to be. The initial hope was that the reservoir would be large enough to hold the solids collected over 30 cycles. To this end a set of investigations was conducted to determine the volume of solids deposited in the reservoir during each washing cycle. This data would then be used to calculate the volume of solids that the reservoir would need to hold for 30 cycles. The tests to understand the volume of solids deposited in the reservoir were classified as autonomy tests.

During the initial hydro cyclone trials, the pump power required to achieve separation for the first iteration of the hydro cyclone design was quite large. The design of the hydro cyclone was later changed to reduce the pump power requirements to 50 watts. One of the earlier ideas to reduce the pump power required was to couple the hydro cyclone with an air sparger. Air sparged hydro cyclones have been investigated in the past (Puprasert 2012). The idea is that when the particles are hydrophobic, the air sparger introduces air bubbles into the cyclone. The hydrophobic particles are collected on these bubbles and flow out the top of the cyclone. Since the polyester particles were found to be partly hydrophobic during our testing, this phenomenon was investigated for our application.

5.1 Autonomy Test Methods and Materials

Materials used in the autonomy tests can be found in Table 5.1

Table 5.1 Autonomy Test Materials

XS1025 Dual range analytical balance with wind block
loading washing machine
County Line ½ HP cast Iron shallow well jet Pump
Cone bottom tank
Water Source 100 PSI pressure gauge
Fortiflex 66 L MPB plastic tub
Braided plastic tubing
Stainless steel plumbing
5-inch Whatman number 1 paper filter
500 ml Erlenmeyer flask
Buchner funnel
3d printed hydro cyclone
Handmade pvc reservoir

Tractor supply 5-gallon bucket
Analog floor balance
Stand mixer
Generated microfibers
Sand
Blue cotton towels
Mineral oil
Dog hair
Graduated cylinder

Autonomy tests were run according to the procedure outlined in Table 5.2

Table 5.2 Autonomy Test Procedures

Step #	Step
1	Weighed out sand, polyester, dog hair, and mineral oil
2	4 kg of blue terry towels were washed in washing machine along with above materials
3	Wash water was collected in washing tank
4	Initial weight of reservoir was recorded
5	Cyclone and reservoir were attached to test stand
6	Mixer was turned on
7	Pump was ran for roughly 9 minutes
8	Pump and mixer were turned off, and reservoir was disconnected from test stand
9	Water was drained out of reservoir
10	Final mass of reservoir and material was recorded, and weight of material was calculated
11	Graduated cylinder was used to calculate density of material in reservoir

5.2 Autonomy Test Results

Five tests were run to determine how many solids by weight are deposited in the reservoir for each wash cycle. Then a graduated cylinder was used to calculate the density of the deposited solids, so the volume of solids deposited per wash cycle was calculated. Table 5.3 shows the weight of material deposited in the reservoir.

Table 5.3 Weight of Solids Deposited in Reservoir

Test	1	2	3	4	5
Initial Reservoir Weight g	381.9	381.9	381.9	382.2	384
Reservoir Final Weight g	391	389.1	397.3	393.8	391.9
Reservoir Weight Change g	9.1	7.2	15.4	11.6	7.9
Average Weight Change g	10.24				

Using a graduated cylinder, the density of the solid mix deposited in the reservoir was found to be 1.22 g/ml. With this density, roughly 8.4 ml of solid material are deposited in the reservoir each wash load. If the reservoir needs to be able to go 30 cycles without being emptied, it will need to be able to hold roughly 252 ml worth of solid material.

5.3 Air Sparge Cyclone Methods and Materials

The other investigation carried out was to understand if adding sparged air to the cyclone would reduce the pump power and make the hydro cyclone work better. This idea has been used in the past for coal flotation in the past (JD Miller, 1988). One of the first iterations of the hydro cyclone design was changed to operate with sparged air. The apex of the hydro cyclone was cut off, and an air sparger was added to the inlet, to introduce bubbles into fluid as it entered the cyclone. The particles behave hydrophobically, so the idea was that the hydrophobic particles would attach to the air bubbles, and when entering the cyclone, the air bubbles would exit out the top of the cyclone, and the clean water would exit out the bottom, which had been enlarged for a greater flow of water. This theory was briefly tested but did not yield great results. Figure 5.1 is a picture of the air sparged hydro cyclone. Figure 5.2 is a diagram explaining how the air and water will enter the cyclone.

Figure 5.1 Air Sparged Hydro Cyclone

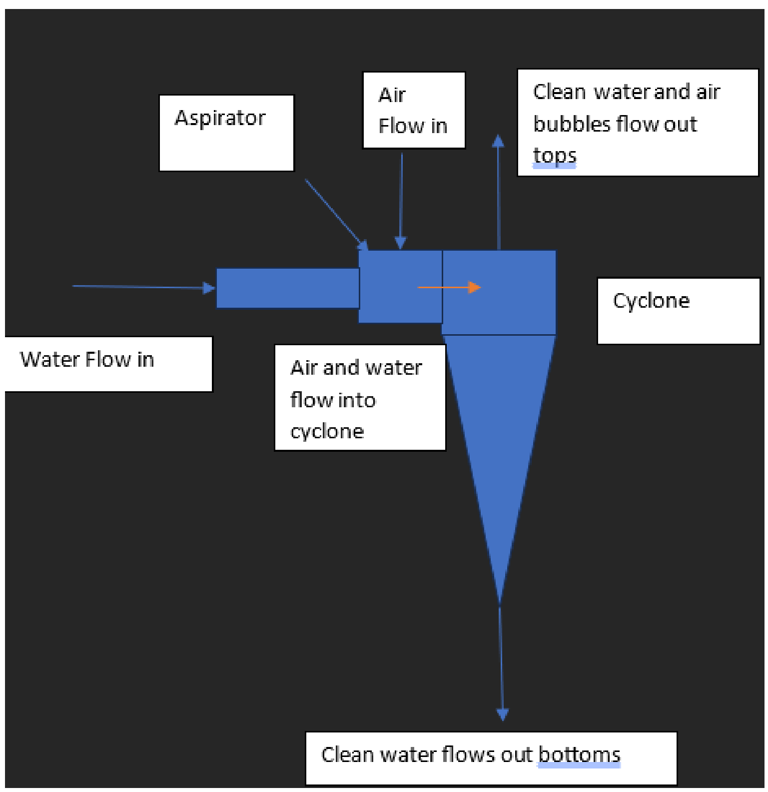

Figure 5.2 Air Sparged Cyclone Diagram

Air Sparged Cyclone test materials can be seen in Table 5.4

Table 5.4 Air sparged cyclone materials

Curtis Matheson 11-inch laboratory filter paper
XS1025 Dual range analytical balance with wind block
Water Source 100 PSI pressure gauge
Sump pump
Fortiflex 66 L MPB plastic tub
Denver Labs pressure filter set up
Braided plastic tubing
Stainless steel plumbing
3d printed hydro cyclone
Isotemp forced air drying oven
Tractor supply 5-gallon bucket
Analog floor balance
Generated microfibers
Air aspirator on feed inlet

Air Sparged Cyclone test methods can be seen in table 5.5

Table 5.5 Air Sparged Cyclone Methods

Step #	Step
1	Weighed out 40 L of water in plastic tub
2	0.2g of microfiber added to water
3	Cyclone system was set up pumping water through cyclone, with tops going to empty bucket and bottoms going into plastic tub
4	Water and fibers run through cyclone
5	Bottoms and tops were filtered
6	Filters were dried and weighed

5.4 Air Sparged Cyclone Tests Results:

Due to time constraints, only two tests of the air sparged cyclone were run. The separation efficiency can be seen in Table 5.6.

Table 5.6 Separation Efficiency for Air Sparged Cyclone

Test	1	2
Fiber Addition	0.1830	0.2143
Fiber Weight In Tops	0.0358	0.0471
Separation Efficiency	0.1956	0.2198

Table 5.6 shows that the air sparged cyclone did not reach adequate separation efficiency. Only 20 % of the fibers that were added to the system were separated by the cyclone. While this is a new and interesting way of combining these two technologies, it does not seem to work for this application.

5.5 Conclusions

A series of tests was conducted to predict what the internal volume of the reservoir would need to be to store the solids produced in 30 wash cycles. Wash cycles were performed, and then the wash water was run through the hydro cyclone system to deposit solids in the reservoir. The weight of the reservoir was measured before and after each test, and a graduated cylinder was used to calculate the density of the solid material deposited in the reservoir. Data showed that in 30 cycles, roughly 252 ml of material would be deposited in the reservoir. Calculating in a safety factor, the recommended volume for the reservoir was 300 ml. Unfortunately, that is too large of a footprint, so the actual size of the reservoir is smaller than that.

As an additional investigation, an air sparged hydro cyclone was investigated. A venturi tube was attached to the inlet of the cyclone to introduce air bubbles into the water entering the cyclone. It was thought that this would greatly decrease the required pressure drop across the hydro cyclone. Two tests were conducted with this air sparged cyclone set up but showed very low separation efficiency. While this is an interesting concept that deserves further investigation in other applications, it is not effective for this application.

6. Overall Conclusions

Our project sponsor challenged us to develop a device that could filter microplastics out of washing machine wastewater, that could fit inside the chassis of a washing machine. The device would be able to isolate the plastic particles in a solid state that could be emptied into the trash, and archive a 80% - 90% system based efficiency. Review of the literature in chapter 1 found that there was very little consensus on what kinds of fibers were produced, what sizes, and in what amounts. It was determined that this project would need to include its own size analysis steps.

The first investigation conducted in chapter 2 was to understand the kinds of fibers that were produced in the washing machine and develop a procedure to duplicate those fibers to use for testing. Polyester fleece blankets were washed, and then the wash water was filtered using a pressure filter. The weight of fibers produced during each wash was recorded. Samples of the wash fibers were then put under a microscope and analyzed for length distribution. The weight of fibers created varied greatly from one wash to the next but was always very small, being between 0.05g and 0.15g. A detailed fiber length distribution can be found in figure 5. In general, 86 % of fibers were shorter than 500 microns in length, and 71% being between 100 and 400 microns.

To develop test fibers, a puck mill was used. The puck mill could create more fibers in less time than a washing machine could, and with similar morphology. The puck mill fibers had a greater length distribution, with only 60% to 70% being shorter than 500 microns. This, however, will not greatly affect the results of the efficiency testing.

A hydro cyclone was designed and 3d printed by the funding agency based on the fiber dimensions found in the fiber study stage. Eight investigations were performed on the cyclone and reservoir to determine factors that would affect the separation efficiency. These investigations can be seen in chapters 3 and 4. All these investigations can be summarized in table 6.1.

Table 6.1 Summary of Investigations

Investigation	Cyclone used	Factor tested	Materials used	Reservoir design	Bleed Line
Initial Cyclone investigation	1st iteration	flow rate and cyclone orientation	polyester	Erlenmeyer flask	no
recirculation vs single pass test	reenforced 1st iteration	recirculation and single pass	polyester	Homemade pvc reservoir	no
Other materials tests	50-watt cyclone	cotton, sand, hair, presence	polyester, cotton, sand, dog hair	Homemade pvc reservoir	no
Reservoir filling tests	50-watt cyclone	How does the reservoir fill with solid particles	cotton, sand, dog hair	Homemade pvc reservoir	no
Push vs pull French Press testing	35-watt cyclone	Which reservoir set up works better	polyester, cotton, sand, dog hair	Push/Pull French Press	no
Bleed Line Investigation	35-watt cyclone	Does Bleed line increase efficiency	polyester, cotton, sand, dog hair	Push French Press	yes
Subsequent Bleed Line Investigation	50-watt cyclone	Does Bleed line increase efficiency	Polyester	Push French Press	yes
Final Efficiency Testing	50-watt cyclone	Does Bleed line increase efficiency	polyester, cotton, sand, dog hair	Push French Press integrated bleed line	yes

The investigations in the third chapter were carried out to understand how the hydro cyclone would behave in a washing machine type environment. Changing the orientation of the cyclone would not negatively affect the separation efficiency, and recirculating the overflow stream back through the system would not improve the efficiency, so the hydro cyclone could be installed in the drain line of the washing machine. The addition of non-plastic solid particles did not significantly change separation efficiency of the hydro cyclone, putting those concerns to rest.

Developing and designing a hydro cyclone that could remove polyester microfibers was only part of the challenge. The other part of the challenge was to develop a reservoir that could collect the material from the underflow of the hydro cyclone and dewater it for disposal. The French press style reservoir was developed and showed promise in its ability to dewater collected solids and collect material.

Multiple investigations were conducted to assess the effect of adding a bleed line to the reservoir. A bleed line would allow water to flow out of the reservoir and back into the system. It was thought that this would increase efficiency significantly.

The final set of trials was to understand the system level performance of the cyclone with French press reservoir and integrated bleed line. Any regulatory tests would be conducted with relation to the weight of microfibers that leave the system. A set of 5 tests was conducted and showed that while the apex-based efficiency was roughly 70%, which is lower than our goal, the system-based efficiency, which is what regulations are concerned with, was upwards of 90%, meeting our sponsors goal of 80% to 90%.

The final recommendation is to use the high-power cyclone with a pump that can supply the necessary power of at least 50 watts. The cyclone inlet pressure and flow rate will need to be about 40 psi and 15 L/minute to get the necessary pressure drop. The cyclone should be in the horizontal orientation, with the apex connecting to the French press push reservoir design, with the bleed line connecting to the inlet of the hydro cyclone pump. With this set up, the system-based efficiency would be upwards of 90%. Figure 6.1 below is a basic diagram of how the cyclone and reservoir will be set up. Figure 6.2 is a basic diagram of how the cyclone and reservoir should fit into the washing machine, and how to integrate the bleed line.

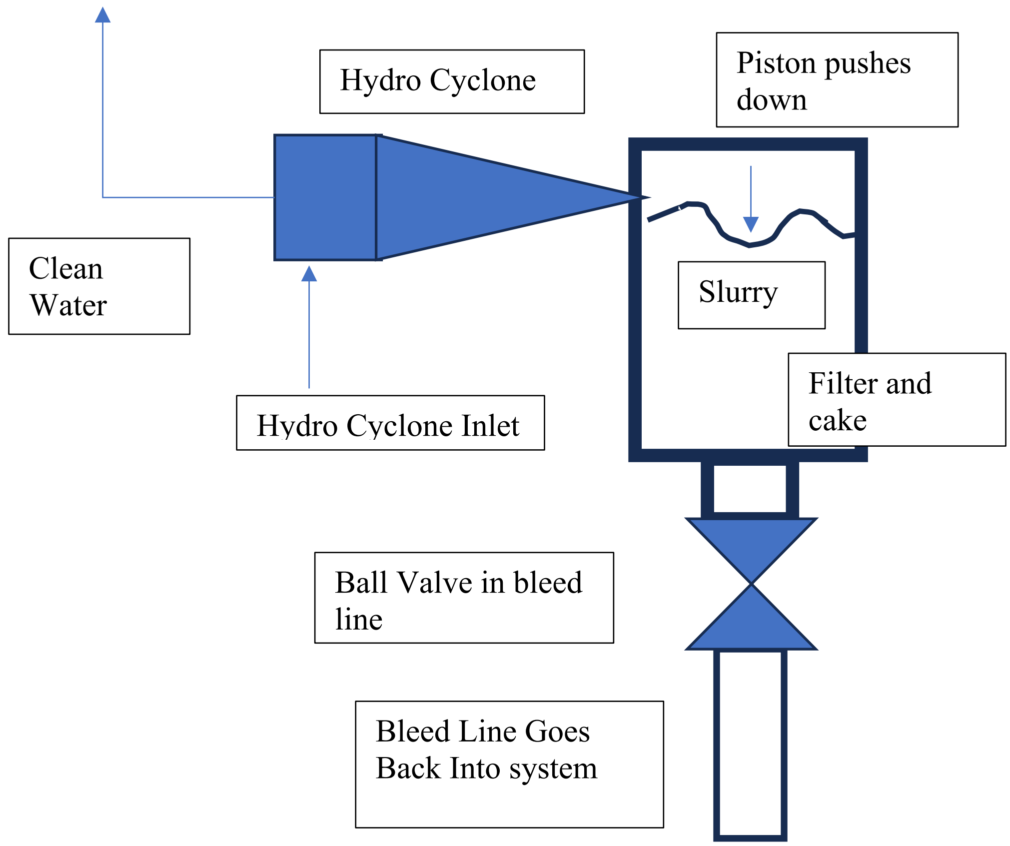

Figure 6.1 Final Recommendation for Cyclone and Reservoir

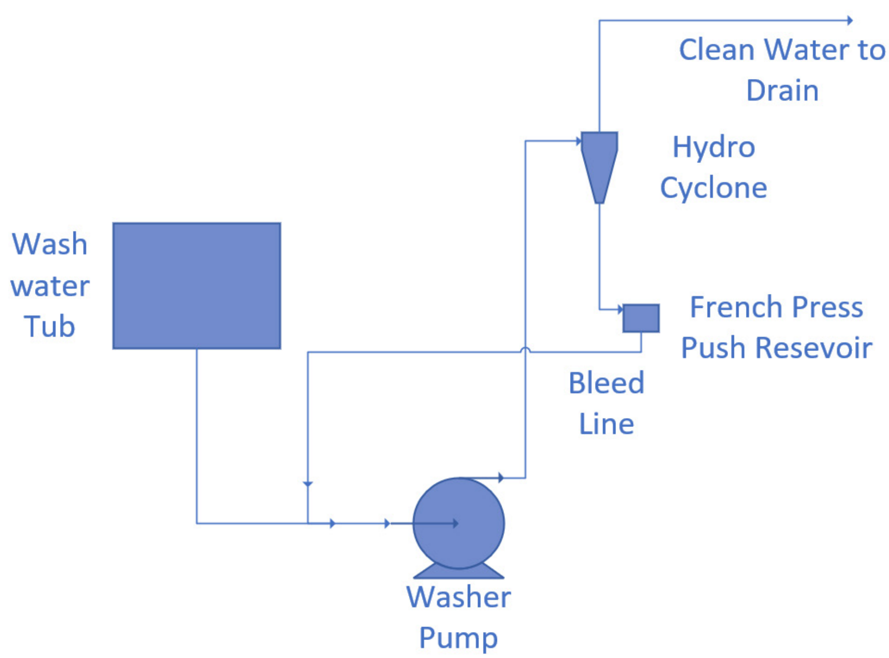

Figure 6.2 Cyclone and Reservoir Integrated into Washing Machin

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