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Exploring the Effectiveness of Mini-hydrocyclone Technology for the Removal of Microplastics in Water Matrices

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Exploring the Effectiveness of Mini-hydrocyclone Technology for the Removal of Microplastics in Water Matrices

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Environmental Engineering

by

Gina Habil

Thesis Committee:
Professor Diego Rosso, Chair
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ABSTRACT OF THE THESIS

Exploring the Effectiveness of Mini-hydrocyclone Technology for the Removal of Microplastics in Water Matrices

by

Gina Habil

Master of Science in Environmental Engineering

University of California, Irvine, 2023

Professor Diego Rosso, Chair

Microplastics are inevitable by-products of all plastic uses. Given their size (less than 5 μm in diameter), microplastics are evasive to traditional removal methods and can accumulate in waterways and the environment. Microplastics have been shown to accumulate in wastewater reclamation facilities (WWRFs), and California's new microplastic policies may require monitoring of these Contaminants of Emerging Concern (CECs). Mini-hydrocyclones have been proven to be an effective and energy-efficient method for the removal of microplastics from water. This thesis further studies the potential for this technology to be used in a stormwater context and potential large-scale application. Various mini-hydrocyclone models were used to observe the removal efficiency of microplastics with differing characteristics. Microplastic aging was also considered to further simulate practical applications. Overall, mini-hydrocyclones effectively removed microplastics with minimal energy demand and there was no statistical difference between the removal of new and aged microplastics. Removal efficiency was also increased for the tested stormwater matrix, which is promising for practical applications.

CHAPTER 1: INTRODUCTION

Plastic has been an inherent component of modern society since its creation in 1907. First introduced as an alternative to scarce resources such as ivory and silk, plastic has established itself as a versatile and cheap material and is continuing to fuel innovation (Davis, 2015). Plastics are classified as polymers, which are molecules composed of long carbon chains with repeating chemical structural units (Andrady, 2017; Jacob et al., 2022). There are many types of plastic polymers that are used to produce everyday objects. For example, polyethylene terephthalate (PET) is used for soft drink bottles, low-density polyethylene (LDPE) is used for plastic bags, and polystyrene (PS) is used in foam products. As a result of its widespread use, plastic has become a major source of pollution. Plastic pollution in the environment can have negative effects, such as sea turtles eating plastic straws and six-pack rings suffocating birds. However, plastics also pose a threat on the microscopic level. Over time, plastics degrade and fragment due to biological, mechanical, and chemical weathering and eventually break-down to the microscopic level, producing microplastics. Microplastics are ubiquitous and can be found in our environment, our food sources, and even ourselves (Blackburn et al., 2021; Cox et al., 2019; van Raamsdonk et al., 2020). While research regarding microplastic impacts on human health is still limited, early studies have demonstrated that high concentrations of inhaled or ingested microplastics are correlated to several health risks, which include: decreased immune responsivity, impacted reproduction and development, and transmission of adsorbed contaminants onto microplastic particles (Blackburn et al., 2021; Prata et al., 2020). As the effects of microplastic contamination and its potential health effects are becoming increasingly apparent, governing agencies are beginning to address microplastic pollution. Recently, the

California State Water Resources Control Board approved a plan to test drinking water for microplastics. The potential impact of microplastic pollution on the health of the environment and living organisms requires that methods be developed to mitigate the further spread of these contaminants.

Microplastics are defined as plastic particles that are less than 5 µm in diameter and are classified based on their source as primary or secondary (Lares et al., 2018). Primary microplastics are plastic particles which are purposefully manufactured to be less than 5 µm in diameter, and secondary microplastics are plastic particles which are fragmented from larger pieces of plastic (Lehtiniemi et al., 2018). Legislation has been passed to limit the production of primary microplastics and mitigate microplastic pollution at the source. In California, Assembly Bill 888 has banned the use of primary microplastics for use in personal care products since 2015. However, other forms of microplastics such as glitter are still abundantly generated and commercially available (Yurtsever, 2019). While there is still potential for other forms of primary microplastics to be banned, secondary microplastic pollution will always be a challenge as we continue to use plastic in our everyday lives. To that end, it is imperative to both prevent and remove microplastic accumulation in the environment and living organisms.

Wastewater reclamation facilities (WWRFs), both industrial and municipal, have been labelled as microplastic point-sources given that they are points of accumulation for wastewater collection and discharge (Naji et al., 2021; Talvitie et al., 2015). However, it is important to note that microplastics are likely not generated at WWRFs, or at least have not been proven to be a major contributor to microplastic pollution. Rather, WWRFs are pass-through entities for accumulated microplastics to enter the environment via discharged effluent (Lasee et al., 2017; Mason et al., 2016). A study conducted in 2016 determined that microplastic concentrations (125 – 500 µm) were higher downstream of WWRFs in comparison to upstream concentrations (Estahbanati and Fahrenfeld). Industrial wastewater can contain microplastics in its waste stream if the industry produces or utilizes plastic components and does not have the proper fine-particle filtering technology (Mallow et al., 2020). Municipal wastewater can also accumulate primary microplastics from items such as glitter and personal care products, but also from laundering synthetic clothing (Sun et al., 2019). Another notable source of microplastic discharge to WWRFs is stormwater runoff in combined sewer systems. Stormwater runoff can cover an array of area as it can begin as snowmelt or rain and travel down mountains, hills, and streets. Eventually, stormwater runoff can collect in waterbodies or, in some cases, combined sewer systems (Shruti et al., 2021). Streets have been identified as a major source of microplastics in stormwater runoff as road dust, which results from the degradation of tires and chemicals used in road pavement and pavement markings (Monira et al., 2021). Combined sewer systems then collect this surface runoff to either be treated at a WWRF or, if flows are high, discharged into a neighboring water body without any treatment (Shruti et al., 2021). A study in 2021 analyzed combined sewer overflow from a rectangular channel and found that even with an increased retention storage of 40%, increased runoff flows of 60% resulted in an approximately 200% increase in microplastic discharge (Di Nunno et al., 2021). Existing literature has also indicated that stormwater runoff has caused microplastic accumulation in stormwater treatment methods such as retention ponds and biofilters (Koutnik et al., 2022; Liu et al., 2019).

Stormwater runoff is evidently a prevalent source of microplastic discharge, however, microplastics are not completely removed once they reach WWRFs. Although microplastic concentrations have been proven to decrease as treatment processes are increased and intensified, microplastic concentrations are still detectable in WWRF effluents at all stages (Liu et al., 2021; Prata, 2018; Ziajahromi et al., 2017). Drinking water has also been proven to have some concentration of microplastics, indicating that microplastics can evade advanced water treatments as well (Eerkes-Medrano et al., 2019; Novotna et al., 2019). Conversely, the microplastics that can be settled accumulate in biosolids and are difficult to remove (Koutnik et al., 2021; Wang et al., 2018). Biosolids that are properly treated to remove pathogens and other contaminants can be used for land application, but the presence of microplastics may pose a health risk and eliminate this reuse method given that microplastic transport has not been greatly investigated (Crossman et al., 2020; Lu et al., 2012; Talvitie et al., 2015). Although the literature has proposed other uses for biosolids such as creating sustainable bricks or biochar (Mohajerani et al., 2020; Paz-Ferreiro et al., 2018), treatment facilities may default to landfill disposal or incineration. Landfill leachate has been shown to contain microplastics and, when left untreated, can further pollute the environment (Shi et al., 2020; Sun et al., 2021).

Microplastics enter WWRFs as industrial and municipal influent, and as stormwater runoff in combined systems. The addition of stormwater runoff to the WWRF influent in combined sewer systems significantly increases the microplastic concentration in comparison to separated sewer systems (Dris et al., 2018; Horton and Dixon, 2017). To this end, stormwater pre-treatment is important to consider when addressing potential microplastic removal methods. Pre-treatment for microplastics may be beneficial for combined sewer systems to prevent microplastic discharge into waterbodies, wastewater effluent, and biosolids.

This thesis explores mini-hydrocyclones (MHCs) as a potential removal method for microplastics from water matrices. Hydrocyclones are apparatuses that are driven by density differentials for solid-liquid and liquid-liquid separation and have been implemented in WWRFs. Hydrocyclones are versatile and can be used in different unit processes by altering the apparatus design paraments. Some applications of hydrocyclones in WWRFs include grit separation, sludge thickening and digester cleaning, and electromagnetic separation of particles (Ali-Zade et al., 2008; Bayo et al., 2015; Mansour-Geoffrion et al., 2010; Senfter et al., 2021). Hydrocyclones are considered to have low energy demands since their operation depends primarily on apparatus design criteria and operational parameters, namely feed flow. Because hydrocyclones are single-bodied vessels with no moving parts, their energy consumption is dependent solely on the energy supplied to pump water through the apparatus (Khatri et al., 2020). To apply hydrocyclone technology for fine particle removal such as microplastics, mini-hydrocyclones must be employed. Mini-hydrocyclones are operated similarly to traditional hydrocyclones, but they differ in the design of the opening diameter. Mini-hydrocyclones have opening diameters that are 15 mm or smaller to target fine particles (He et al., 2022). Studies have previously been conducted exploring mini-hydrocyclone technology for microplastic removal from water matrices (Chen et al., 2021; Cilliers and Harrison, 2019; He et al., 2022; Lv et al., 2018), but the extent of these studies are limited. The objective of this thesis investigates the effects of microplastic density and water matrix on microplastic removal by mini-hydrocyclones, both of which have not been explored thoroughly. Removal efficiency in a synthetic stormwater (SSW) matrix was benchmarked against pure water. These factors were taken into consideration to provide a basis for mini-hydrocyclone technology to eventually be implemented at a large-scale, primarily in a combined sewer context.

CHAPTER 2: MATERIALS AND METHODS

Mini-hydrocyclone Prototypes

The mini-hydrocyclones used for this thesis were originally developed for the experimental set-up conceptualized by Liu et al. (2022). Three mini-hydrocyclone prototypes were produced with EOS Steel 316L via 3D-printing technology (Shanghai Yuerui 3D Technology Co., Ltd.; PR China). The design parameters of the three mini-hydrocyclone prototypes were adopted from literature that also target microplastic separation from water matrices (Bradley, 2013; Yang et al., 2011). Further details regarding specific design parameters of the prototypes can be found in the published paper for the original experiments conducted by Liu et al. (2022).

To observe the effect of microplastic density effect on mini-hydrocyclone removal efficiency, two types of mini-hydrocyclone were designed: one to remove microplastics less dense than water ($<1\ g\cdot cm^{-3}$) and one to remove microplastics denser than water ($>1\ g\cdot cm^{-3}$). **Figure 1** shows the different prototypes created: MHC_H1 and MHC_H2 for microplastics denser than water, and MHC_L for microplastics less dense than water. Two prototypes were created to separate high-density microplastics to determine the effect of main diameter size on removal efficiency. That is, MHC_H1 and MHC_L both have main diameters of 10 mm, while MHC_H2 has a main diameter of 20 mm. The increase in main diameter for MHC_H2 resulted in this prototype being double the size of MHC_H1.

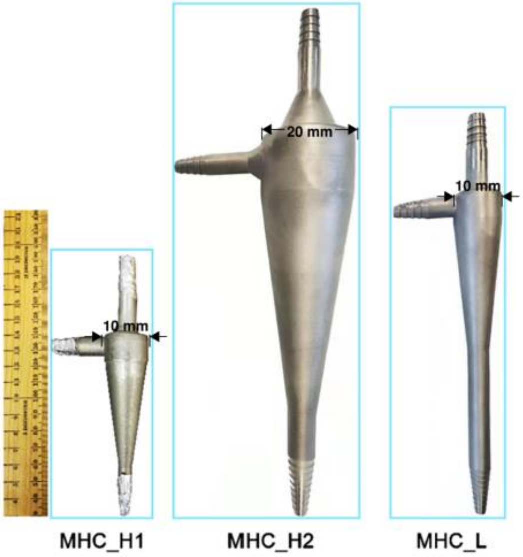

Figure 1: Mini-hydrocyclone Prototypes with Main Diameter Sizes

Optimized Parameters

As previously stated, MHC operation depends primarily on configuration and designated operational parameters. The operational parameters considered for these experiments were microplastic concentration (mg L^{-1}), feed flow rate (gpm), and split ratio (%). Microplastic concentrations were varied by changing the mass of microplastics per volume of suspension. Feed flow rates and split ratios were varied by using flow-control valves within the hydraulic circuit. Parameter optimization was conducted by Liu et al. and referenced for these experiments (2022). **Table 1** summarizes the optimized operational parameters.

Table 1: Summary of Optimized MHC Operation Parameters

Parameter	Optimized Value
Microplastic Concentration	25 mg L^{-1}
Feed Flow Rate	0.6 gpm
Split Ratio	35%

Experimental Set-Up

These experiments were conducted on a bench-scale hydraulic circuit, which is depicted in **Figure 2**. The hydraulic circuit was designed to maintain the concentration of microplastics during sample extraction, simulating a continuous stirred-tank reactor (CSTR) configuration. To operate the hydraulic circuit, the reservoir is first filled with the water matrix and microplastic concentration to be sampled. The mixer is turned on to distribute the microplastics and any chemical constituents within the reservoir. The reservoir is modeled as the CSTR control volume, with one outflow and three inflows. The outflow of the reservoir serves as the inlet to the feed pump, which supplies the energy required to power the hydraulic circuit. Feed flow rate is varied depending on how much flow is directed into the feed pump and measured by a flowmeter. The energy required by the hydraulic circuit is measured by a pressure gauge. The flow is then pumped to one of two flow paths: the MHC inlet or a by-pass line. Flow through the MHC inlet is controlled by setting the split ratio to the desired value. Both over- and underflow lines are returned to the reservoir. The by-pass line circulates flow that is not directed to the MHC inlet back to the reservoir.

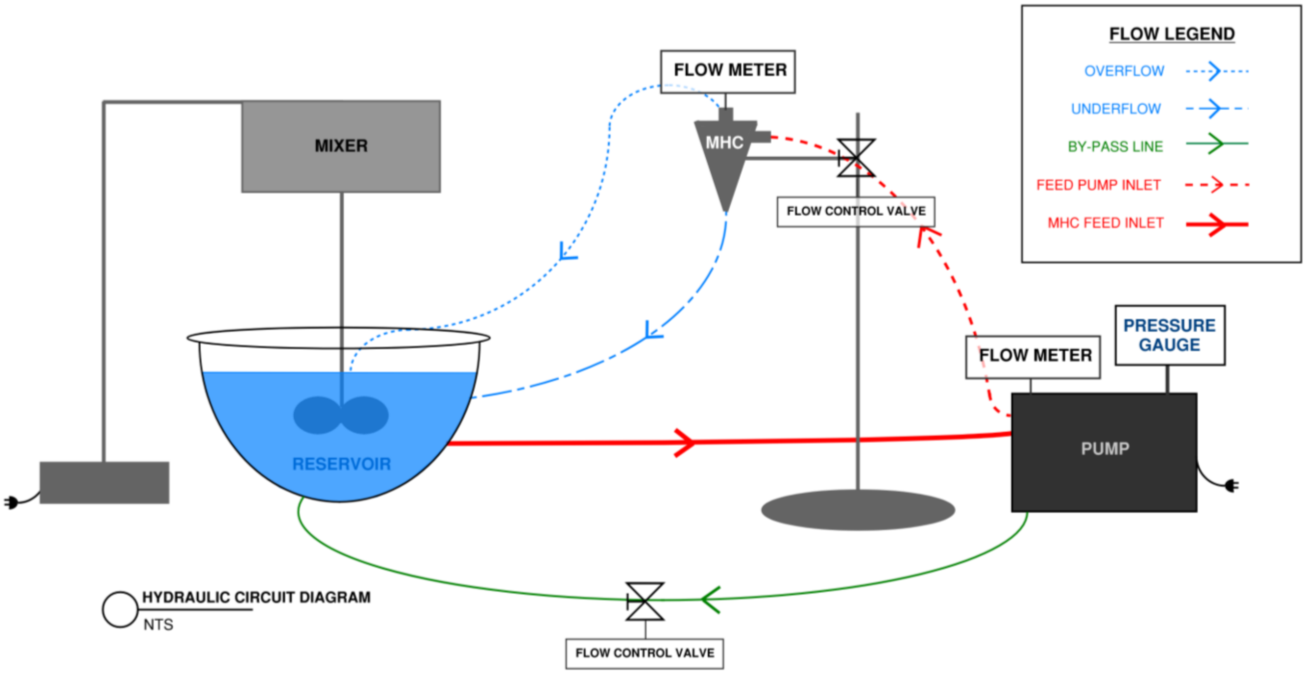

Figure 2: Hydraulic Circuit Diagram

Bench Testing (for validation) and Energy Analysis

Bench testing of the aforementioned optimal operational parameters was conducted as part of this thesis. The original sets of data collected to determine the optimal operational parameters by Liu et al. (2022) were collected in triplicates, so additional data sets were collected to determine the validity of the operational parameters. Validation of the parameters will also serve as a benchmark for determining MHC removal efficiency for the other varied parameters in these experiments: UV-weathered microplastics and the use of a stormwater matrix.

Bench testing performed for this thesis replicated the experimental procedure that was used previously by Liu et al. (2022). Prototype efficiency was also evaluated using the same efficiency calculations as the previous experiments. The previous experiments calculated two types of microplastic separation efficiencies: grade separation efficiency and total mass separation efficiency. Grade separation efficiency analyzes percent removal of microplastics by particle size range, which can identify which particle size ranges are most effectively separated by the MHC prototypes. Total mass separation efficiency compares the total mass of microplastics at the less-concentrated outlet (overflow for MHC_Hs and underflow for MHC_L) to the concentration in the reservoir to determine total microplastic mass removed, regardless of particle size. This thesis only bench marked for MHC prototypes with main diameters of 10 mm (MHC_H1 and MHC_L) since the effect of main diameter on removal efficiency was not considered. The following equations were used to calculated total and grade efficiencies, where "C" is concentration of microplastics (mg L^{-}) and "particles" is the total particle count for a given size range:

$$Total\ Efficiency = 1 - (1 - r\%)\ \frac{C_{underflow}\ or\ C^{*}_{overflow}}{C_{feed}}$$

$$Grade\ Efficiency = 1 - (1 - r\%)\ \frac{Particles_{underflow}\ or\ Particles^{*}_{overflow}}{Particles_{feed}}$$

***Note:** MHC_H1 calculations use overflow and MHC_L calculations use underflow

Energy analysis was also performed to determine the relationship between main diameter size and feed flow rates. Given that only one MHC prototype was created with a different main diameter size (MHC_H2), energy analysis could only be performed for high-density microplastics. Bernoulli's principle was used to calculate energy consumption for these experiments.

MP Selection and UV Weathering

Polyamide (Nylon; GoodFellow) and low-density polyethylene (LDPE; Shiyansanzhou Tech., Inc.) were selected for these experiments due to their physical characteristics as well as their abundance in environmental water matrices (Sun et al., 2019 Talvitie et al., 2017). Nylon and LDPE have densities of 1.15×10^3 kg m^{-3} and 0.92×10^3 kg m^{-3} , respectively. Thus, nylon was used to observe high-density MHC removal efficiency, and LDPE was used to observe low-density MHC removal efficiency. The purchased microplastics were analyzed with a scanning electron microscope (SEM; Magellen XHR 400) to confirm the properties of the microplastics. Both types of microplastics were found to have size ranges of 5-50 µm, with mean sizes of 15-20 µm. Note that the microplastics used in this thesis were the same microplastics purchased for the experiments conducted by Liu et al. (2022).

Batches of both microplastic types were also exposed to UV radiation using a simulator (40 mW cm^{-2}; RAYONET) for 15 hours to mimic weathering from the sun in natural environments. Assuming that the average solar energy intensity at any given point on the Earth is 1,360 W m^{-2} (Nasa, 2009), this is equivalent to approximately 4.5 days of average sun exposure. **Figure 3** shows scanning electron microscope (SEM) images of each microplastic before and after being exposed to UV radiation.

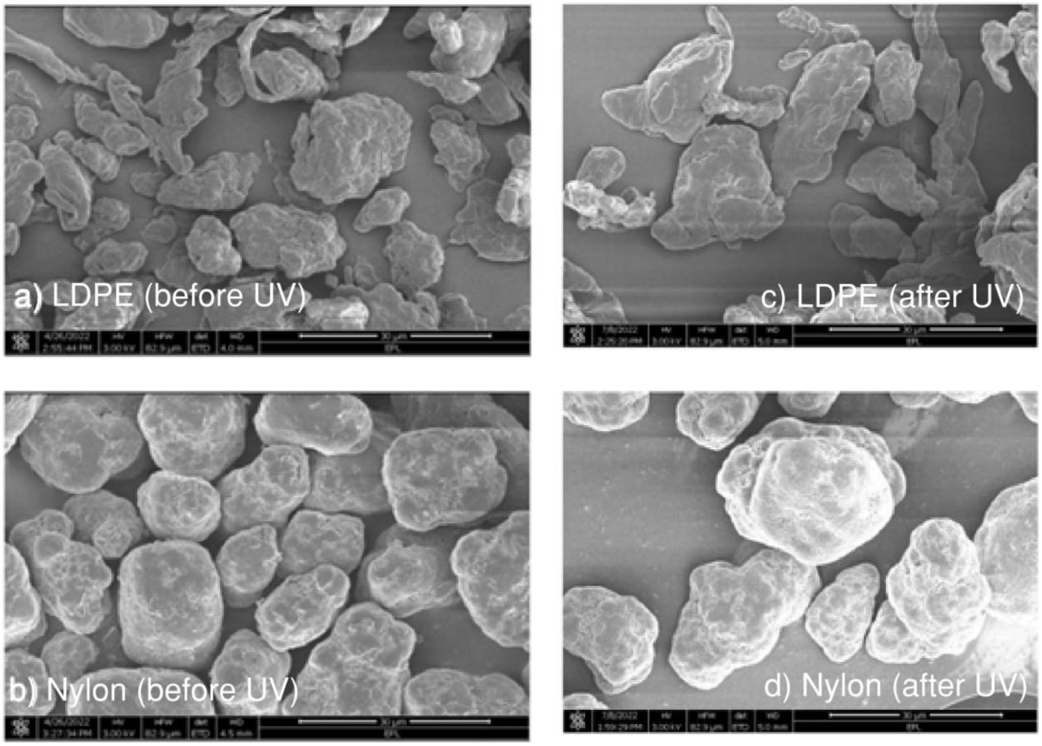

Figure 3: SEM Images of LDPE and Nylon

Stormwater Matrix

In addition to observing the effects of UV weathering on microplastics, these experiments also implemented an environmental water matrix to further test MHC removal efficiency. The synthetic stormwater matrix composition was adopted from Weisbrod et al. (1999) and Dunphy et al. (2007) as the chemical composition of the water matrices in these experiments are characteristic to typical California stormwater runoff (Kayhanian et al., 2019). Collected stormwater runoff was not utilized in these experiments due to low rainfall in the Southern California region. A summary of the chemicals used to create the stormwater matrix is listed in **Table 2**.

Table 2: Synthetic Stormwater Composition

Chemicals Used	Concentration Value	Target Constituent
NaOH	6.8*	pH, Na^+
$NaNO_3$	0.26 mg/L	NO_3^-, Na^+
Na_3PO_4	0.79 mg/L	Total Phosphorous, Na^+
NaCl	23.90 mg/L	Cl^-, Na^+
$CuSO_4$	2.01 mg/L	Cu^{2+}, SO_4^{2-}
$Pb(NO_3)_2$	0.13 mg/L	Pb^{2+}, NO_3^-
$CaCO_3$	12.2 mg/L	Hardness
Humic Acid	15 mg/L	Dissolved Organic Compounds

***Note:** NaOH was used to achieve pH = 6.8 by holding a pellet in solution until the desired pH was reached. Na^+ ions that dissociated during this process were considered to be negligible.

Contamination Control

Contamination control was implemented throughout all stages of these experiments. The use of plastic in this experimental set-up was limited to prevent contamination by other plastic particles, with the exception being the plastic tubing used to transport flow through the system. All other components and tools used for this experiment were comprised of metal, ceramic, or glass. Samples were covered with tin foil before analysis to prevent contamination deposit through the air. The hydraulic reservoir was cleaned with soap and water prior to each set of samples taken. The system was also flushed will Milli-Q water at least 3 times to remove any contamination. Procedure blanks and space blanks were taken and analyzed at the overflow and underflow lines to quantify any residual contamination after cleaning. All blanks showed no measurable mass of residual contamination, and most of the contamination were fibers from the standard blue lab coats.

CHAPTER 3: RESULTS AND DISCUSSION

Bench Test Results

The results of the bench testing found that all samples had a total removal efficiency greater than 70%. **Figure 4** shows the results of each bench test for both LDPE and nylon calculated as total efficiency. Each bench test graphed is a data set taken as part of the triplicate sampling method used for these experiments. The LDPE bench test results had calculated total efficiencies of 82.02%, 88.62%, and 86.50%. The nylon bench test results had calculated total efficiencies of 85.25%, 70.82%. and 79.21%.

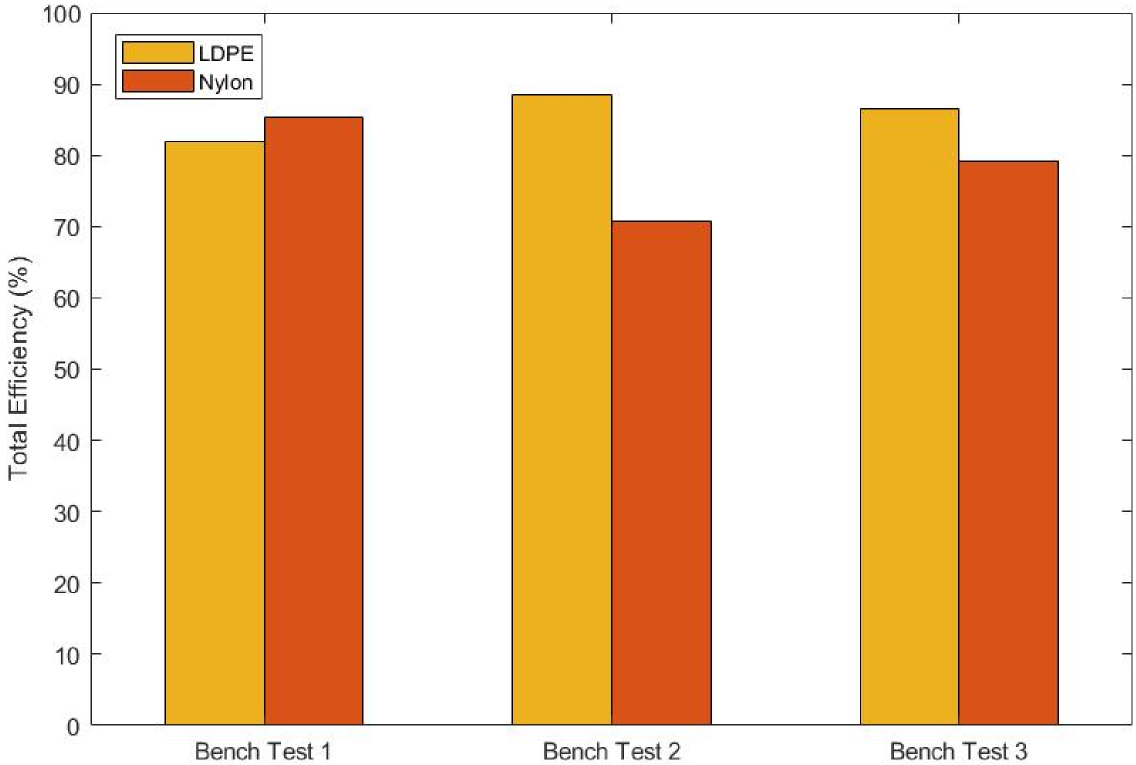

Figure 4: Total Efficiency Bench Test Results

The LDPE and nylon bench tests were each averaged and compared to the original results found by Liu et al. (2022). **Figure 5** graphs the bench test average for LDPE and nylon next to the original experimental results for the optimized operational parameters. The LDPE bench test average was 77.35%, which was higher than the 69.72% LDPE average referenced from Liu et al. (2022). The LDPE bench test average was considered to fall within range with the referenced LDPE average given that it fell within the reference's range of error. The nylon bench test average was 86.79%, which was very close to the 86.65% average referenced from Liu et al. (2022). Thus, it was concluded that the optimized operational parameters did yield similar results when the bench tests were conducted.

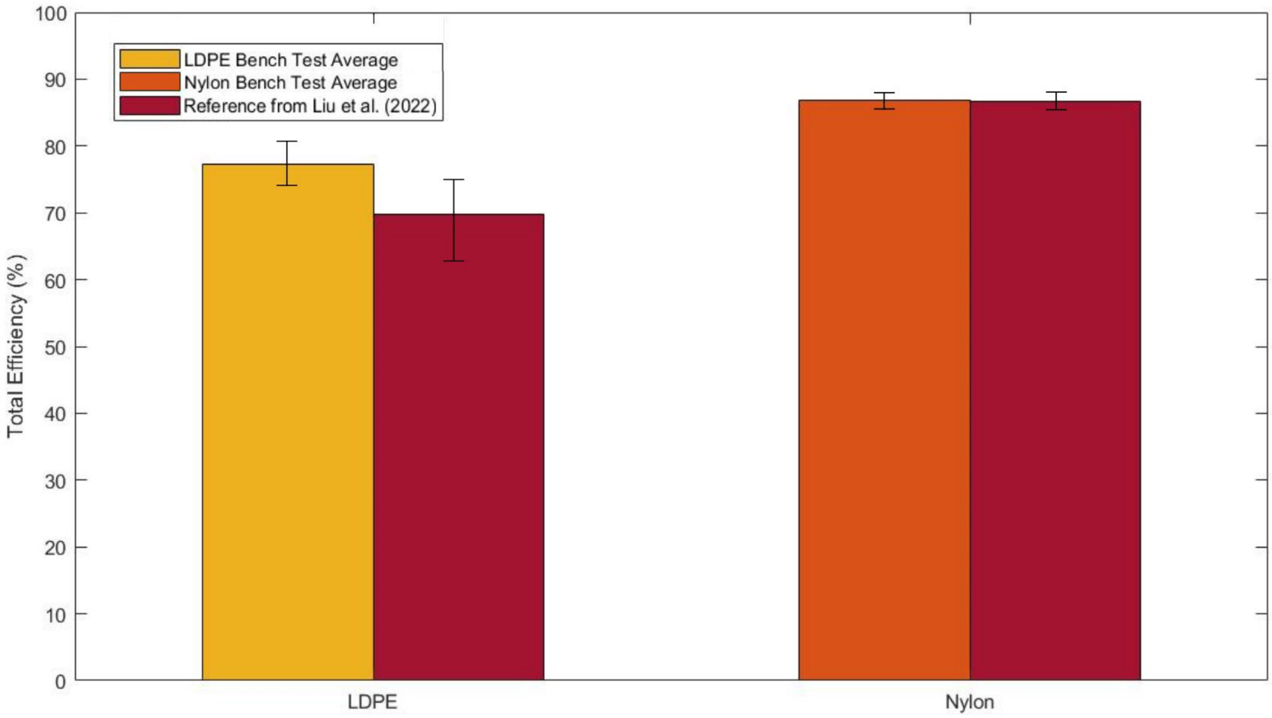

Figure 5: Total Efficiency Comparisons (Bench Tests vs. Original Results)

Given that the total efficiencies fell within range for both MHC_H1 and MHC_L, it was assumed that the grade efficiency would also be similar to the results obtained by Liu et al. (2022). Thus, no samples were analyzed for grade efficiency.

Benchmarking was also performed to observe the removal efficiency of the microplastics exposed to UV-radiation. The results of both the UV-exposed LDPE and nylon were similar to the removal efficiency of the microplastics not UV-exposed, and no statistical difference was found between the two results. Although these experiments did not detect any effect of UV-exposure on MHC removal efficiency, it is important to consider that microplastics may be exposed to sunlight longer than what was simulated for this experiment. Exposure to sunlight may also vary in intensity depending on what region is being investigated. Thus, the effect of UV-exposure on microplastic removal by MHCs is inconclusive.

Synthetic Stormwater Results

The results of the synthetic stormwater data sets were analyzed and compared to the benchmarking data sets in Milli-Q water by Liu et al. (2022). Grade efficiency overall increased for both nylon and LDPE in the synthetic stormwater matrix, which is shown in **Figure 6**. Nylon overall had higher grade efficiencies than LDPE in both water matrices. All data sets demonstrated that larger particles sizes were removed more efficiently than smaller particles. One potential reason for this phenomenon could be that the internal centripetal force within the MHC is affecting smaller particles less than larger particles. Given that each type of microplastic has a certain density, particles with smaller diameters will have smaller volumes, and thus smaller masses to maintain density. Since the centripetal force is dependent on the mass of the particle, it could be likely that particles with small diameters do not possess enough mass to be effectively removed by the MHC prototypes. Another potential reason why smaller particles are less likely to be removed is because they are less likely to collide with other microplastic particles. Microplastics are hydrophobic in nature (Zhang and Chen, 2020), so it is hypothesized that microplastic collisions can cause them to aggregate and form larger particles. Smaller particles may have a lower probability of colliding with another particle given their size, thus preventing their removal.

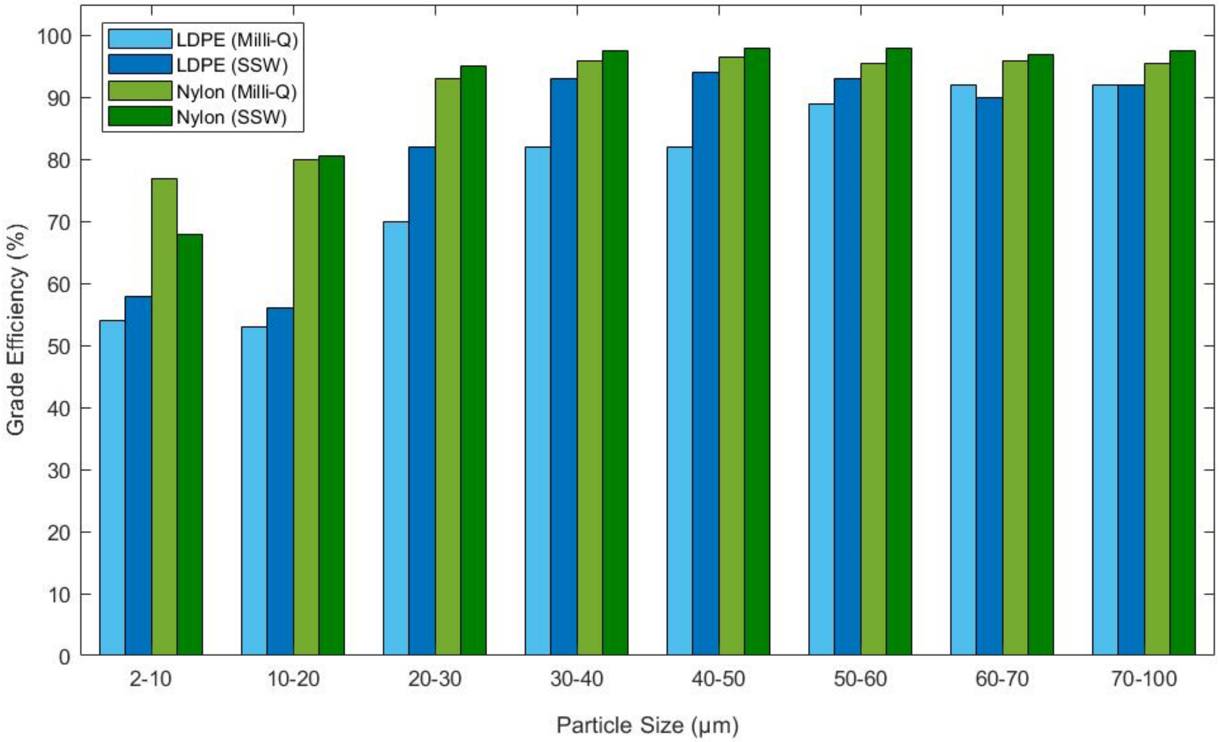

Figure 6: Grade Efficiency Comparisons (Milli-Q vs. SSW)

Total efficiency was also calculated and compared for both nylon and LDPE in Milli-Q water and the synthetic stormwater matrix and is compared in **Figure 7**. Total efficiency increased for both nylon and LDPE in the stormwater matrix, 7.7% for nylon and 3.8% for LDPE. However, only the increase in nylon total efficiency was found to be statistically significant (p = 0.038). It is hypothesized that the increase in total efficiency is due to the increased ionic strength in the synthetic stormwater matrix. The increase in ionic strength could compress the double layer of the microplastic particles, which would result in increased collisions and aggregation (Wu et al., 2007; Zhang et al., 2021). As noted in the grade efficiencies for MHCs, larger particles are more likely to be removed than smaller particles. The chemical composition of nylon and LDPE may also contribute to the differences in total efficiency. Like many polymers, Nylon particles can be altered to have additional functional groups to create desired properties. Nylon surface modifications target the amide group to induce the target reactive functionality (Jia et al., 2006). The amide groups that are characteristic to nylon are electronegatively charged. This is important to note in comparison to LDPE, which is considered a neutral polymer. Studies have shown that polar polymers are more likely to have greater adsorption capacities than nonpolar polymers (Xu et al., 2021). Thus, a potential reason why nylon was more effectively removed in the synthetic stormwater matrix could be due to its polar chemical composition.

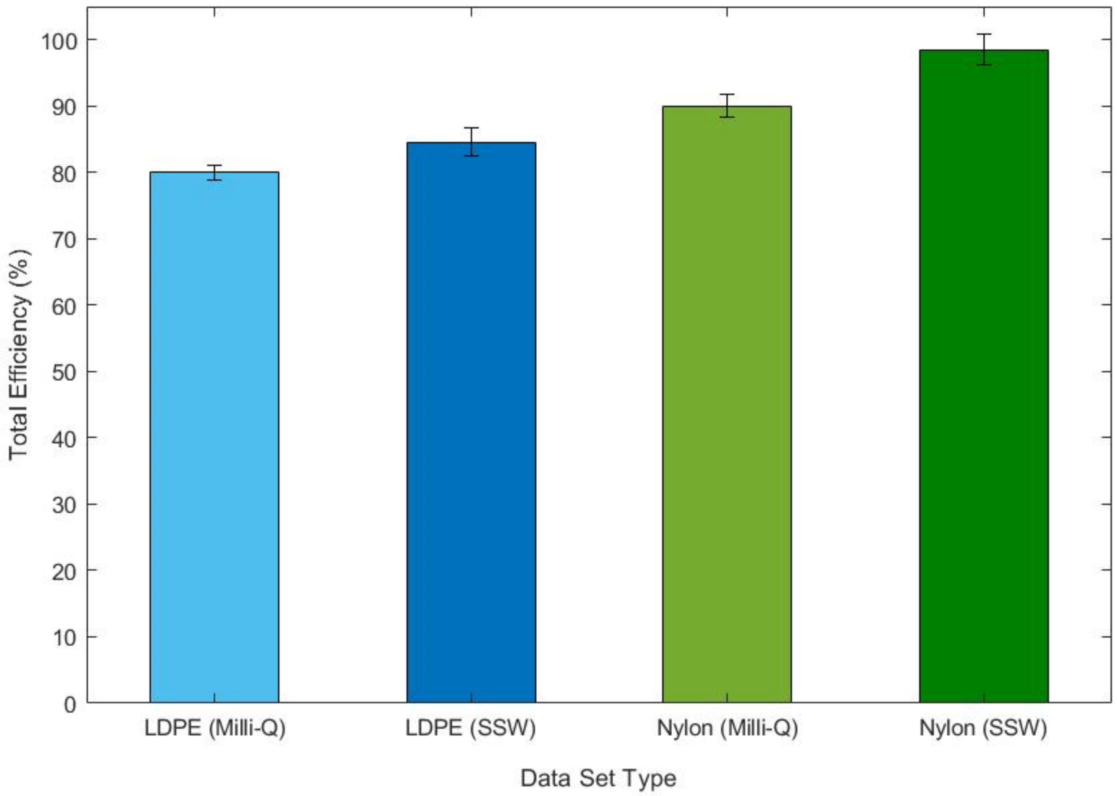

Figure 7: Total Efficiency Comparisons (Milli-Q vs. SSW)

Energy Balance

Energy consumption was also calculated for MHC operation and compared for MHC_H1 and MHC_H2. Energy consumption was compared for the MHC prototypes that targeted high-density microplastics to determine if main diameter size was a factor for MHC energy consumption. Energy consumption was not compared between MHC prototypes that removed different microplastic densities since the design criteria for each protype were different and not scaled equally. **Figure 8** graphs the feed flow rate (gpm) as a function of feed pressure (psi) on the primary axis and energy consumption (J m^3) on the secondary axis.

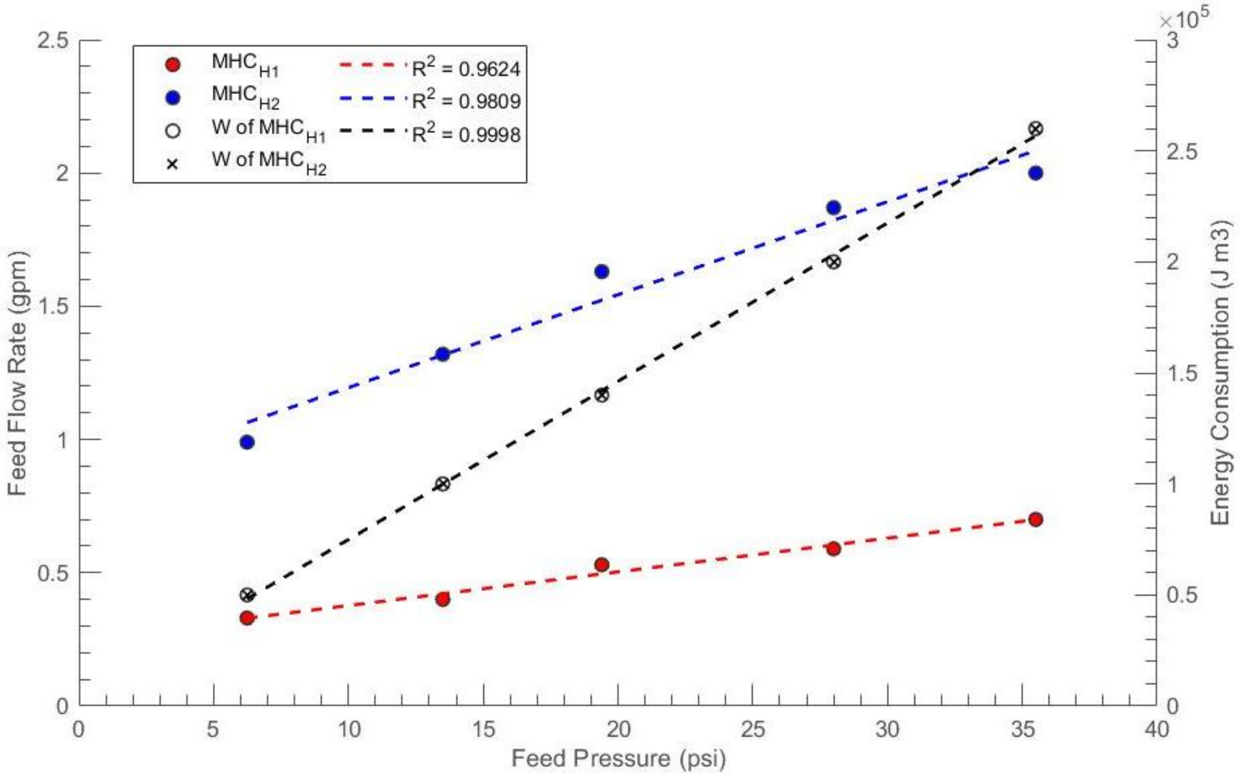

Figure 8: Feed Flow Rate and Energy Consumption Comparison

Both feed flow rates for MHC_H1 and MHC_H2 had a positive linear correlation (R^2 = 0.9809 and R^2 = 0.9624, respectively) as feed pressure increased. Feed flow rate did not increase as rapidly for MHC_H1 as MHC_H2 due to MHC_H1 having a smaller inner cavity. This data indicates that as feed pressure increased, the shear force within the MHC prototypes was also increased. Since MHC_H1 had a smaller inner cavity for fluid flow, the shear force within this MHC prototype was proportionally larger in comparison to the inner cavity of MHC_H2. Thus, the same flow rate would have a larger effect on the fluid velocity of MHC_H1 than MHC_H2.

Figure 8 also graphs energy consumption as a function of feed pressure for MHC_H1 and MHC_H2. Energy consumption was calculated by assuming that both water matrices were ideal fluids and applying Bernoulli's principle. At the highest feed pressure (p = 35.5 psi), energy consumption was calculated to be 250,280 J·m^3 and 250,800 J·m^3 for MHC_H1 and MHC_H2, respectively. Since the energy consumption of MHC operation is largely dependent on feed pressure at the apparatus inlet, benchmarking energy consumption can provide a basis to explore this technology for real life applications.

Given that MHC technology is a passive process as it has no mechanical parts and depends only on feed flow rate, it is hypothesized that it is a more energy-efficient alternative in comparison to other advanced treatment options that are used today. For example, reverse osmosis is not a passive process given that it operates via a pressure differential (Malaeb and Ayoub, 2011). When used for desalination, reverse osmosis has been cited as having a minimum specific energy consumption of 0.71 kWh m^{-3} for 0% recovery, which corresponds to no freshwater recovery (Gude, 2012). For reference, the calculated energy consumption for MHC_H1 and MHC_H2 are both approximately 0.069 kWh m^{-3}, which is an order of magnitude lower than the cited minimum specific energy consumption for a reverse osmosis process. Although seawater and stormwater runoff are different in compositions, both are subject to transporting and accumulating multitudes of contaminants that should be removed prior to being considered for human use. Reverse osmosis waste has also been observed to be ineffective at removing microplastics under 10 μm (Fortin et al., 2019). Thus, processes like reverse osmosis are likely not ideal methods to implement as pre-treatment for stormwater.

Scale-Up

Analyses of the performed bench tests and synthetic stormwater matrices have indicated that MHCs can effectively remove microplastics of particles larger than 20 µm. Analyses of energy consumption also provide a basis to consider MHC technology with respect to anticipated feed flows at large-scale. At large-scale, MHCs cannot be made physically larger since their geometric parameters cannot be upscaled. However, MHC technology can be scaled-up by placing them in-series to accommodate larger flow volumes. Although it is not ideal to have numerous individual MHCs in-series, one potential application could be to 3D print the cavity of MHCs into a wall designed to accommodate projected flows. **Figure 9** provides a schematic of the proposed configuration.

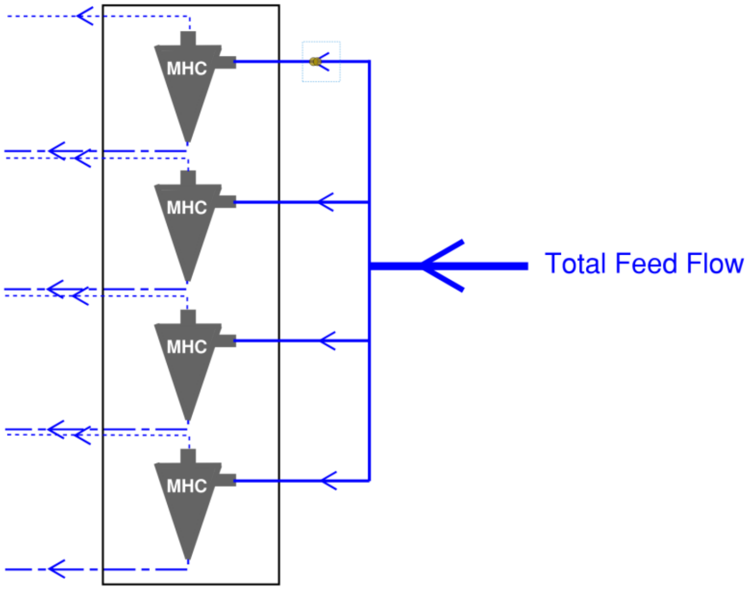

Figure 9: MHCs Configuration in Parallel

A configuration similar to that presented in **Figure 9** would prevent maintaining each individual MHC since water would flow through a wall of MHC cavities. With further research, the MHC wall design could be optimized to handle anticipated flow volumes, isolate certain sections for cleaning, or be fitted to accommodate treatment facilities with limited space.

Another potential scale-up of MHCs is a UU-type parallel configuration, which has been applied for oil-water separation (Lv et al., 2020). Lv et al. placed 150 MHCs in parallel vertically in a chamber that was designed to distribute the flow rate and pressure drop of the system (2020). As depicted in **Figure 10**, the MHCs are placed between plates with holes with the over and underflows exiting collectively from the configuration. This configuration was found to satisfy the industrial requirements for oil-water separation and was also hypothesized to extend the useful life of such separation devices (Lv et al., 2020).

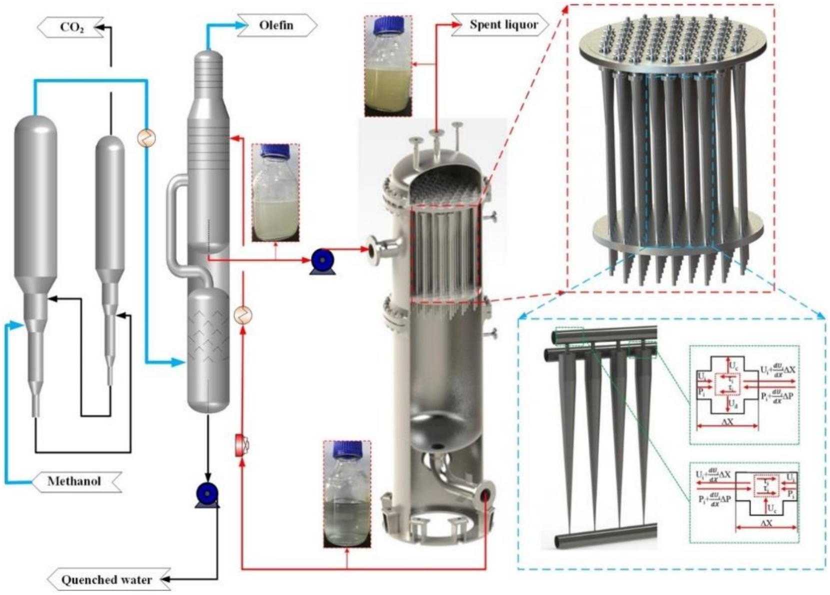

Figure 10: UU-Type Parallel Configuration (Lv et al., 2020)

CHAPTER 4: CONCLUSIONS AND LIMITATIONS

Mini-hydrocyclones were proven to remove Nylon and LDPE of particles sizes ranging from 20 – 100 µm. Removal efficiency was also shown to increase for microplastics in the synthetic stormwater matrix, which is promising for practical applications in stormwater pre-treatment. However, there are still many limitations to MHCs as a potential removal mechanism for microplastics. Microplastics smaller than 20 µm are still not as effectively removed by MHCs as microplastics larger than 20 µm are, and further research should be done to understand and address this issue. In addition, the synthetic stormwater matrix implemented in this study and the selection of microplastics may not be representative of microplastic contamination in areas outside of Southern California, so this must also be considered. Removal efficiency should also be observed with collected stormwater samples as synthetic matrices may not encompass the true nature of stormwater runoff. The parallel configuration of MHCs and energy analysis for low-density MHC prototypes can also be further investigated and optimized.

Microplastic contamination is understood to be widespread and potentially harmful to the health of the environment as well as living organisms. With microplastic regulations fast approaching, this thesis serves as a basis for future research in developing effective microplastic removal technologies. While there is still a research gap to be filled, this is a first step in addressing microplastic pollution and will hopefully propel microplastic research in the future.

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