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Capturing Microplastics from Aquatic Systems Using Vortex-based Cyclone Technique

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Abstract: Plastic pollution is an acknowledged global problem. As estimated, about 82% of marine litter is plastics, while about 94% of marine plastics are defined as microplastics (MPs), which is less than 5mm in size. MPs have been regarded as widespread emerging pollutants. Different from the commonly used sedimentation, absorption or filtration technologies for aquatic MP capture, this work proposed a cost-effective and scalable solution using the vortex-based cyclone technique for collecting aquatic-borne MPs. Based on a lab-scaled setup and the use of artificial microbeads, the experimental results showed clear and promising evidence of the proposed concept and technology. Different operating conditions are also investigated with the aim controlling the hydrocyclone at its highest separation efficiency, subject to diverse process variations.

Keywords: microplastics, cyclone separation, efficiency, digital microscopy

1. Introduction

Plastics have turned out to correlate with environmental pollution and climate change problems in recent decades due to their low degradation capabilities and potential toxic additives/adsorptions. In addition to large plastic items, the so-called microplastics (MPs), which are defined according to their size in the range of 1 µm to 5 mm, are causing more and more public, societal, and scientific concerns regarding its existence everywhere globally. It has been discovered that about 82% of marine litters are attributed to plastics, and about 94% of marine plastics are typed as MPs [Natalia et al., 2017, Roland et al., 2017].

Wastewater treatment plants (WWTPs) are considered the main source of MP contaminants in the urban aquatic environment [Joana et al., 2019]. It has been discovered that over 98% of MPs in the size range of 10 µm -500 µm in Danish WWTPs has been successfully removed from the WWTP effluent water [Marziye et al., 2023, Márta et al., 2018]. However, most of removed MPs are settled in the sludge stream, which could still raise the risk that MPs will eventually be released back into the natural environment through the leakage of landfills or fertilization usage of sludge. Another challenge correlated to MPs in urban aquatic systems is the management of Storm-Water Runoff/storage/sewer Systems (SWRSs). It has been discovered that MP debris and fibers due to the tire wear-out can account for over 50% of micron-sized pollutants in the urban stormwater runoff/storage systems [Fan et al., 2019]. As evidence of climate change, we are facing more heavy rainfall events than before, like the EU flood that occurred in 2021. The heavy rainfall/storm can not only cause potential threats to human beings and economic losses but also invoke potential pollution problems when the spiking volume is beyond the runoff/storage/sewer system's capability and the retention time must be significantly decreased inside these systems. Though MPs' long-term impacts, sources, transmissions, and fates, are still not fully understood in general, the EU has already put MP management as one of its top priorities in its green strategy [Saskia et al., 2021].

Due to the complex compositions and their additive/adsorbed chemicals, the chemical- or bio-based separation technologies, in principle, are not recommended to handle MPs, particularly in open ecosystems, such as lakes and oceans [Brian et al., 2019, Mohsen et al., 2020]. Furthermore, the popularly used sedimentation processes in WWTPs often require long retention time, which directly limits their capability, while filtration processes often require a large installation footprint and need to frequently cope with the notorious fouling problem, which often leads to the high OPEX and CAPEX. This work aims to prove a new MP-capture method, i.e., the aquatic-borne MPs can be cost-effectively captured using a controlled vortex-based hydrocyclone system. Different from filtration-based separation, the hycrocyclone separates different media according to their different densities using vortex separation and then repels the separated pollutants into a rejection outlet instead of accumulating them on the surface of the penetration channel. As a simple and cheap mechanic device based on the enhanced gravity separation principle, hydrocyclone has been applied in many industrial separation processes [Shaobao et al., 2021, Trygve et al., 2007].

This proof-of-the-method is based on a lab-scaled flow-loop setup and assessed with online MP analysis tools and methods. The effectiveness of the proposed solution is clearly demonstrated, and the best capturing efficiency achieved in the experiment is about 83.6% based on polyethylene (PE) artificial microspheres subject to proper operating conditions.

2. Materials and Methods

2.1. Hydrocyclone System

As a typical physical separation method, the hydrocyclone uses the centripetal force, generated from a dedicated mechanical design and the hydrodynamical control, to separate different liquid/solid media from continuous liquid phase based on their different densities [Trygve et al., 2007]. Due to its high mechanical, thermal, and chemical robustness, , small installation footprint and low CAPEX and OPEX, the hydrocyclone technology has been extensively used in different industries. At this proof-of-the-concept phase, we adopted an off-the-shelf commercial hydrocyclone liner (Vortoil D35) produced by Schlumberger. Vortoil D35 was initially designed as a deoiling hydrocyclone for produced water treatment in oil and gas production [Shaobao et al., 2021]. The geometry of a typical hydrocyclone is illustrated in Fig.1.

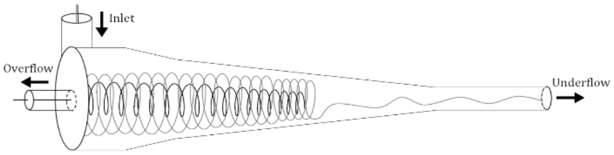

Figure 1. The geometry of a typical hydrocyclone.

2.2 Flow-Loop Configuration

A testing flow loop is constructed as shown in Fig.2. One Vortoil D35 liner (HC) is installed. The microbeads are mixed with the water in the mixture tank. The flow is driven by a centrifugal pump (CP) controlled by its rotational speed. The underflow (Q_u) is controlled by a control valve (V_u), and the overflow is controlled by the control valve (V_o). Two side-stream samplings are deployed for online measures of particles passing through both inlet and water outlet streams using ViPA-1 and -2, respectively. Both sampling streams are controlled via their control valve V_{is} and V_{us}, to keep the flowrate within the ViPA's recommended range. Flowrates and pressures are measured at several locations to study how the hydrocyclone's separation performance correlates to different operating conditions.

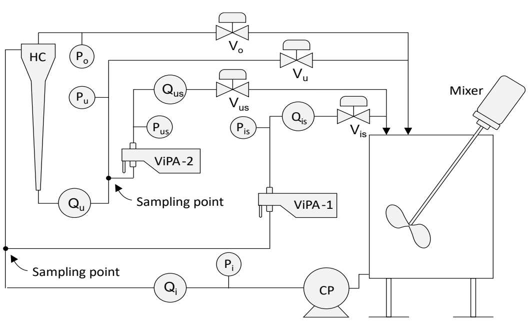

Figure 2. Testing flow-loop with its measurements.

2.3 Microbeads

The microbeads used in the experiment are red PE microspheres produced by Cospheric LLC with a density of 0.98g/cc and two different size ranges: 53-63µm and 70-90 µm. 30g of microbeads and 10g large microbeads were mixed with about 170L tape water in the mixture tank.

2.4 MP Measurements

The hydrocyclone performance is evaluated with two dynamic microscopes (Jorin ViPA) located on side-streams. The dynamic microscopes utilizes a high-resolution video camera to capture images of the particles passing the view cell. This sensor needs to be carefully calibrated to achieve accurate and reliable measurements. We refer to previouswork [Dennis et al., 2021] for details of this calibration issue.

2.5 Experimental Scenarios

The circulation pump is kept at a constant speed to provide sufficient pressure upstream of the hydrocyclone. The underflow control valve (V_u) operates from 50-100% of its opening degree, with an incremental of 5% for each step, as shown in Fig.3. Within each period when the V_u is kept constant, the overflow control valve (V_o) operates from 0-50% of its opening degree in a piecewise constant way with an incremental of 5% as well. Both flowrates of sampling streams for the dynamic microscopes are kept around 2 L/min via its corresponding control valves. Some of the key operating parameters are illustrated in Fig.3.

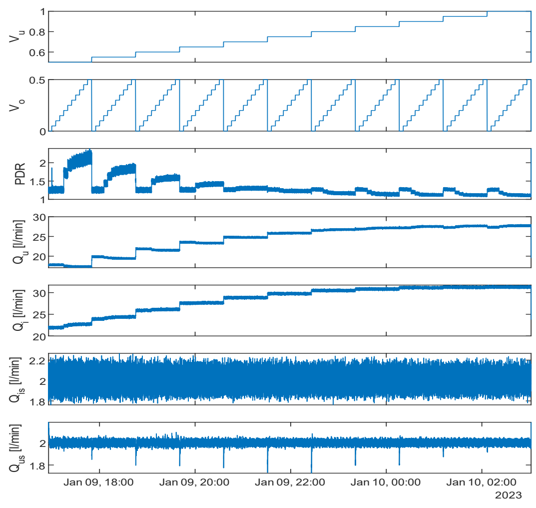

Figure 3. Experimental scenarios & some measurements.

3 Results

3.1 MP Size Distributions

The size distribution of the detected MPs at the underflow sampling stream for the entire experiment is illustrated in Fig.4. The two grey zones indicate the MP size ranges that was tested. Two peaks appear within these grey zones, but microscopes also counted a lot of small particles between 0-20 μm, which could be due to the other dispersed materials and breakups of microbeads in the flow-loop. The size distributions at both inlet and underflow side-streams during the highest separation efficiency condition are illustrated in Fig.5. It is clearly indicated that the hydrocyclone separation successfully removes all big and half of small MPs.

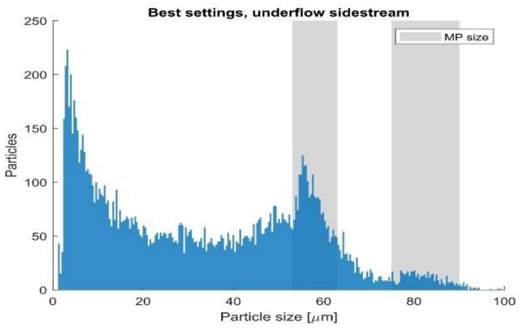

Figure 4. MP size distribution measured at underflow side-stream for the entire experiment.

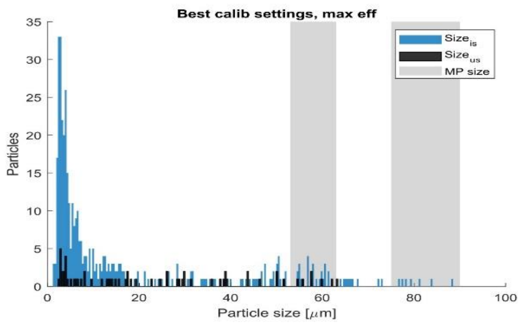

Figure 5. MP size distribution measured at both inlet and underflow side-streams for best efficiency scenario.

3.2 MP Concentrations

The (piecewise) steady-state analysis is committed in this study. The mean values are thereby calculated for each steady-state condition based on microscope measurements. The MP concentrations are calculated based on the size measurement and assuming the particles are spherical. The MP concentrations are shown in Fig. 6.

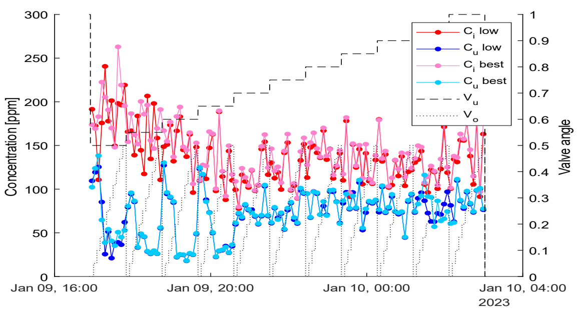

Figure 6. Calculated concentrations at both inlet and underflows for entire experiment (with diff. calib. coeff.)

3.3 Separation Efficiencies

Based on the assumption that MP characters measured in the side-stream are consistent with the main streams (representative issue), the MP removal (steady-state) efficiency, defined as 1 - ratio of underflow concentration with inlet concentration, can be calculated for different operating conditions, as shown in Fig.7. The high efficiency (>80%) can be achieved when the opening degree of V_u is in range of 50-65%. The correlation with the overflow control valve can be seen in Fig.8, which indicates that V_o should operate within the range of 20-45% opening degree, together with V_u within 50-65%, to achieve a high removal efficiency.

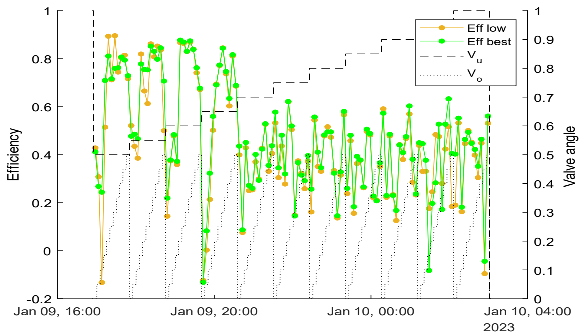

Figure 7. MP removal efficiency by hydrocyclone at different operating conditions (subject to diff. cal. coef.)

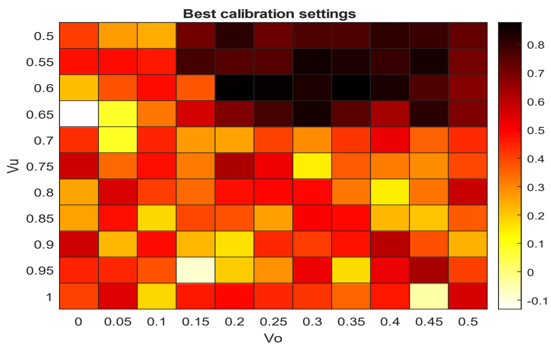

Figure 8. MP removal efficiency correlation with both control valves (subject to best cal. coef.).

3.4 Efficiencies vs. Control Parameters

The hydrocyclone system usually has automatic control of its inlet flow rate and PDR to be stable and robust to unexpected operating variations [Trygve et al., 2007, Shaobao et al., 2021]. Thereby the obtained experimental efficiency correlated with these control parameters is also illustrated in Fig.9. For this specific hydrocyclone, installation and these dedicated experimental conditions, it can be noticed that the PDR, which is defined as the ratio of P_i-P_o with P_i-P_u, should be maintained within the range of 1.5-2.2, and the feeding flowrate Q_i should be in the range of 20-28 L/min, to have high efficiency. The highest efficiency point corresponds to PDR=1.5 and Q_i=26 L/min. These observations are also consistent with the recommendation provided by the Vortoil D35 manufacturer.

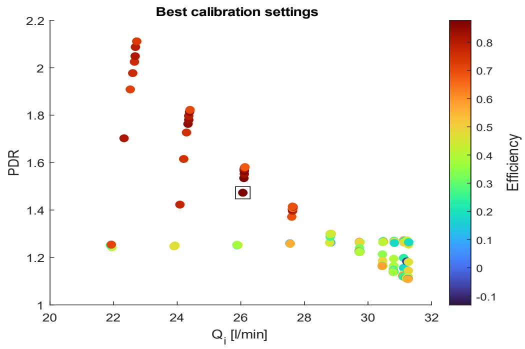

Figure 9. Correlation of removal efficiency vs. control parameters PDR and Q_i (subject to best cal. coef.).

4 Conclusion

Aquatic MP capture using the hydrocyclone technique and system has been experimentally studied. It is clearly demonstrated that the chosen PE-based microbeads can be effectively and efficiently removed from a water stream subject to some proper selected operating conditions of the hydrocyclone system. Due to its simple mechanic structure; complete free of chemical and bio additions; strong robustness to mechanical, thermal, and chemical interruptions; small installation footprint; full flexibility for scaling and mobility; fast processing time (in seconds); as well as extremely low relevant CAPEX and OPEX, the hydrocyclone-based solution for aquatic MP capture can be very promising, particularly towards large open ecosystems.

Hydrocyclone performance can be very sensitive to variations in dedicated operating conditions. Thus, some automatic control mechanism is often necessary to maintain the hydrocycone operating within a satisfactory range subject to these variations. The correlation of the separation efficiency with its PDR and flowrate control loops is also studied in this work.

The geometric and material parameters are another class of key parameters which significantly impacthydrocyclone performance. Vortoil D35 is designed as a de-oiling hydrocyclone for produced water treatment deployed in oil and gas production. The PE-based MPs used in this study are closer to the density of water compared to oil, which the Vortoil D35 is designed to handle. This makes the cyclone's separation more challenging. However, the MPs particulates are more rigid than the oil droplets, which can be easily deformed and even break down into small droplets. Thereby the deployed Vortoil D35 might not be the best hydrocyclone (in terms of removal efficiency) to handle this specific experiment. Moreover, Vortoil D35 cannot effectively handle MPs that are heavier than water due to its dedicated geometric parameters. It could be a very interesting topic to explore how to design a MP-dedicated hydrocyclone system that can handle both lighter and heavier MPs than water. The dynamic microscopes are very sensitive to selected calibration coefficients. The representativeness of the sampling stream to the mainstream (in terms of MP concentration) can be heavily impacted by the sampling mechanism and device (T-junction is used in our setup). To further validate our results and analysis using some offline reference methods will be part of our future work.

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