High Throughput Membrane-less Water Purification

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Summary
This whitepaper describes a highly scalable fluidic technology that presents a transformative approach to the practice of conventional water treatment. Features include: a high throughput, purely fluidic, continuous flow, membrane-less, size selective method for particulate extraction; and accelerated agglomeration kinetics from mixing and transporting chemicals and raw water in confined channels. The former involves centrifugal force created in spiral flow channels to extract buoyant and denser particles, and transverse hydrodynamic forces to separate neutrally buoyant particles and nested double spirals to focus the bands for extraction. The latter results in reduced coagulant chemical dosage by 30-50% due to the narrow size distribution resulting from fluid shear effects of seed particles for agglomeration. Together, the combined effects allow for extraction of micron sized pin flocs in fluidic structures to potentially eliminate flocculation and sedimentation steps, resulting in significant savings in reduced land and chemical cost, operational overhead, and faster processing time from raw to finished water. This technology is also directly relevant to industrial water purification, waste water reclaim, cooling tower, pre-treatment for RO, and almost any instance where reduction of TSS loading prevents clogging and extends the time between cleaning for many MF and UF filtration membranes.

Transformational Water Purification
Conventional municipal water treatment includes multi-stage filtration and sequential process steps for coagulation, flocculation, and sedimentation. A minimum of two stages of filtration must include coarse 2-5 mm mesh filters at the inlet and 20-40μm multi-media filters for finishing although many utilities have more intermediate filtration steps. Growing concerns about public water safety has highlighted the use of MF as a non-chemical methodology to prevent health and environmental issues. MF for suspended micro particulates is primarily focused on filtration by barriers with average pore size smaller than the particles that are then retained on the membrane. Clogged membrane filters degrade in performance over time and filter materials may lead to contamination hazards. Sedimentation requires long processing times especially for small particles. With heightened awareness for green and renewable resources, the clean technology revolution is getting increased attention. Clean water is an increasingly important mandate that this whitepaper addresses. We will describe a promising technology that is currently being developed to provide low-cost urban water solutions which will likely be translated into practical applications within the next 5 years.

In this whitepaper, we propose the use of spiral fluidic structures with designed size cut-off for membrane-free filtration. The centrifugal force is most effective on particles that have density differences compared with water, thus creating the buoyancy and centrifugal forces necessary for transverse migration. Neutrally buoyant particles, however, can only be filtered or chemically modified for sedimentation, and require additional hydrodynamic considerations for separation. We propose an innovative method in the use of a curved spiral channel to introduce a centrifugal force to perturb the tubular pinch effect most commonly associated with particulate flows in straight channels, resulting in an asymmetric inertial migration leading to focusing and compaction of suspended particulates into narrow bands for extraction. The separation principle is to balance the centrifugal and fluidic forces to achieve asymmetric inertial equilibrium near the inner sidewall.

Here, we also propose a transformational approach to water treatment that incorporates membrane-free filtration with dynamic processing of the fluid to significantly reduce treatment times, chemical cost, land use, and operational overhead. The idea is to provide the hybrid capabilities of filtration together with chemical treatment as the water is transported through the spiral channels. Specifically, the advantages are:
1. Use the spiral particle extraction capability as a front-end to lighten the TSS (total suspended solids) loading on the system;
2. Use the dynamic transport capability to bring reactants together in close proximity within the channel, reducing diffusion length (and time) thus allowing for potentially more rapid bio-chemical kinetic reactions at increased efficiencies;
3. Use the high shear rate to produce uniformly-sized flocs for more rapid agglomeration; and
4. Allow the removal of pin flocs (particle size at transition point between the end of coagulation and start of flocculation) as small as 5µm by the spiral device rather than rely on the conventional practice of allowing them to agglomerate to hundreds of microns in size before settling out in the sedimentation basin. This may allow the elimination of the flocculation step together with all the chemicals as well as the sedimentation step.

![Diagram](image)

**Figure 1** Asymmetric tubular pinch effect in a curvilinear channel. The added centrifugal force induces a slow secondary flow or Dean vortex which perturbs the symmetry of the regular tubular pinch effect. Particles are concentrated in a band at the inner equilibrium position.

**Fluidic Separation Structures**
Fluidic shear in straight channels generate lateral forces which cause inertial migration of particulates. Segré and Silberberg experimentally demonstrated a tubular pinch effect where neutrally buoyant particles migrate to form a symmetric band that is 0.6D wide, where D is the channel diameter. In quadratic Poiseuille flow, three contributions have explained the lateral migration of a rigid sphere. The wall lift, $F_w$, acts to repel particulates from the wall due to lubrication. The second contribution is the Saffman inertial lift towards the wall due to shear slip. Rubinow and Keller showed that the third contribution is the Magnus force due to particle rotation towards the wall. $F_m$ dominates near the wall and achieves equilibrium with the combined effects of $F_w$ and $F_m$ to confine particles in a band. In curvilinear channel geometry, a centrifugal force modifies the symmetric effect. The fluid inertia from this force causes a secondary transverse flow or Dean vortex which is a double recirculation as shown by the dot arrows in Fig. 1. Particles in mid-elevation migrate transversely outward with the Dean vortex, are repelled by the wall lift, and continue to loop back along the top and bottom walls towards the inside wall. The combined Saffman and Magnus forces are large in comparison to the viscous drag of the Dean vortex so particles are trapped in a force minimum located adjacent and closer to the inner wall. More details are contained in Seo et al.
Fig. 2 shows a double-nested spiral embodiment to separate blue polystyrene beads from a sample mixture. After the samples were filtered with different flow rates, the collected samples were diluted to 50 times for coulter counting (Z2™ COULTER COUNTER®, Beckman Coulter, CA, USA). As shown in Fig. 3, the concentration of particles from the outer outlet decreased as the flow velocity is increased. The efficiency of filtration also depends on the corresponding length of the spiral channel. Faster flow velocity improved filtration efficiency (particle capture efficiency) from 64.7% at 23 mm/s to 99.1% at 92 mm/s. The separation factor or ratio of concentrations of the particle and effluent outlets exceeds 300X, and can be further optimized. The important effect of the spiral geometry is to focus the particles into a narrow band through the asymmetric tubular pinch effect. The nested double spiral acts to sequentially compact each side of the band resulting in a much sharper and narrower band than is predicted by the tubular pinch effect alone.

Fig. 3 Coulter counter quantification of particle extraction. At 92mm/s flow velocity, the concentration ratio of extracted particles between the two outlets is 300X with 99.1% efficiency.

**Accelerated Agglomeration Kinetics**

The spiral device may be used to enhance agglomeration kinetics by: improving mixing to result in faster and more complete coagulation; leveraging the shear rate to produce uniform-sized flocs which are more amenable to rapid agglomeration; and allowing 30-50% reduction in dosage to attain the same turbidity reading in a shorter time. Fig. 4 compares turbidity-time measurements for a standard and a modified jar test experiment where in the latter; the sample fluid is flowed through the spiral device at a flow rate of
333ml/min. At this flow rate the average shear rate inside the channel is about an order of magnitude larger than the average shear rate inside the jar test beaker. For the standard jar test, NTU readings drop immediately after the rapid stirring was stopped (red curve in Fig. 4). In the modified jar test, the NTU readings stayed high throughout the 30 minutes while the sample fluid was pumped through the channel, but dropped even more rapidly thereafter. The high shear rate inside the spiral channels appears to completely prevent the growth of aggregates, and break all flocs that may have formed inside the beaker after the coagulant was added. In the standard jar test even at the highest stirring rate loose flocks form that never break up. Because of their large shape, they diffuse slower than more compact aggregates and completion of the growth process is slower. Fig. 4 shows fits of the experimental data to the perikineti
c aggregation model. The fits are excellent; suggesting that the turbidity decrease seems to be closely related to the reduction of total particle number in solution. The more rapid drop-off in the turbidity readings is most likely caused by sedimentation, which is not included in the fit model.

![Figure 4](image-url) NTU readings as a function of time: Black: standard jar test; Red: modified jar test; the solid line is the analytic fit to the data points.

The aggregation dynamics depends crucially on the rate and mode of coagulant addition and pH adjustment. Initial inhomogeneities in the coagulant concentration appear to create large loose flocs that do not break up under the applied stirring rate. These loose flocs have a low diffusion rate due to their large size which leads to a slower growth rate. Step-wise coagulant addition with immediate adjustment of the pH of the sample liquid prevents the uncontrolled growth of large, loose flocs and promotes the formation of more compact aggregates that grow faster due to their faster diffusion rates. Moving the sample fluid through a micro channel at sufficient flow rate (causing sufficiently large shear rate) will prevent aggregate growth and will lead to break-up of the loose flocs that from during coagulant addition. Once the sample liquid is no longer moving through the micro channel, aggregates grow quite rapidly, suggesting again the formation of compact particles.

**Concluding Remarks**

In conclusion, a highly scalable, high throughput, purely fluidic, continuous flow, membrane-less, size selective method for particulate extraction has been described where denser and lighter particles are separated directly by centrifugal forces whilst neutrally buoyant particles are separated and focused using hydrodynamic forces derived from the perturbed tubular pinch effect. Other features include: accelerated agglomeration kinetics from mixing and transporting chemicals and raw water in confined channels; reduce coagulant chemical dosage by 30-50% due to narrow size distribution resulting from fluid shear effects of seed particles for agglomeration; and extraction of pin flocs in fluidic structures to eliminate flocculation.
and sedimentation steps. Advantages include: minimal clogging issues as fast shearing flow is self-cleaning for fluidic structure; low cost solution that piggy back on existing pumping and plumbing infrastructure; lighten TSS loading on membranes (required physical barriers); replacement for intermediate filtration steps; small footprint with elimination of flocculation and sedimentation – particularly valuable for urban scale-up of existing facilities with little expansion room; reduced coagulant dosage and elimination of most flocculant cost; and faster processing or reduced time between raw and finished water leading to reduced holding capacity. Fig. 5 shows a schematic for municipal water treatment using the proposed technology.

![Figure 5](image_url) Insertion of spiral separator behind inlet mesh screen and before final filtration barrier.

In the short term, this spiral device can serve as a front-end to all existing membrane usage to lighten TSS loading; supplanting instances where physical barrier is not mandated or viewed as threat to public safety as in non-potable water applications. In the long-term, this spiral device may transform conventional water treatment by eliminating flocculation and sedimentation steps. Related areas of application include: municipal water treatment, industrial water treatment – for use and reclaim, food and beverage, agricultural, cooling tower water treatment, pre-treatment for RO in desalination of brackish and seawater, and waste water reclaim.

Fundamental experiments are being conducted to generate design rules for device scale-up. Filtration capacity such as filtration rate, cut-off particle size, and concentration factor can be adjusted by changing fluidic parameters. Efforts are on-going to fabricate modular 1 cubic foot units with throughput of 100L/min, 15 psi pressure drop, and 20W friction loss. Multi-stage spiral filtration can be envisioned by simply connecting spiral filtration devices to increase efficiency without major modification. Improvement in the design of outlet collectors and rigid fabrication of devices for faster flow rate should lead to improved separation factors. Future plans also include the addition of electro-coagulation (EC) as a front-end and deionization capabilities as a back-end to the spiral structures for brackish and seawater desalination. More details will be shared in the full proposal.

References