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***Abstract*—Hydroelectric power is a clean source of energy, providing up to 20% of the World's electricity. Nevertheless, hydroelectric power plants are plagued with a common problem: silt. The silt causes damage to turbine blades, which then require repairing or replacing.**

In this study, we investigated the possibility to filter micron-sized particles from water using ultrasound. We designed a custom-made *flow chamber* and performed flow simulations and experiments to evaluate its efficacy. We used a 195-kHz ultrasound transducer operating in continuous-wave mode with acoustic output powers up to 12 W.

Our acoustic simulations showed that it should be possible to force a 200-μm particle over 2 cm in flow, using an acoustic pressure of 12 MPa. Our flow simulations showed, that the fluid flow is not drastically decreased with the flow chamber, which was validated by the experimental measurements. The flow was not reduced when the ultrasound was activated. The acoustic filtering was effective between acoustic powers of 2.6 and 6.4 W, where the particle concentration in the clean output was statistically significantly lower than the null experiments.

I. Introduction

Hydroelectric power plants are a highly efficient source of clean energy, to date providing more than 20% of the World's total electric power, and up to 99% in Norway [1].

Nevertheless, all power plants are plagued with a common problem: silt. Silt consists of fine particles of sand or clay carried by running water from natural sources. The damage done by these particles is twofold, 1) high-velocity impact creates micron-sized pits on turbine blades, and 2) these particles also act as nuclei for cavitation [1]. Such damage to the blades result in reduced efficiency [2] or even complete turbine failure requiring shut down and/or replacement [3]. Current solutions employ filters and meshes resulting in reduced water flow and in consequence reduced power output. Unfortunately, such filters cannot filter particles in the micron and sub-micron range. Removing silt from water, would increase the long-term efficiency of hydroelectric power plants, reduce the maintenance costs, and increase the productivity of renewable energy.

Ultrasound is known for its benefits in non-destructive testing and clinical imaging. Modern day research has been taking advantage of ultrasound to manipulate micron-sized particles [4]. Our previous work showed that it was possible to cluster and push micron-sized particles towards a boundary using low power ultrasound (<1W) [5]. Whilst these experiments were performed in micron-sized capillaries and at low flow rates, in this study we attempt to take advantage of this phenomenon, and up-scale it, to force particles to separate from the water into a separate "waste" stream. The benefits of such a methodology is that the resultant product could be a bolt-on solution to existing power plants requiring little to no modification of the existing configuration. In our work here, we perform simulations and experiments to evaluate the efficacy of using ultrasound at low frequencies to radiate particles in flowing regime.

II. Materials and Methods

A. Simulations

Two types of simulations were performed; 1D acoustic radiation force simulations and fluid flow simulations. Knowing the mean primary radiation force working on a spherical incompressible particle in a viscous fluid, assuming a plane progressive wave incident. A second order differential equation was derived to compute the distance a particle can be pushed towards the *waste gate* as it passes through the acoustic field. We study the case $\lambda \ll \delta$. Where λ is the wavelength, and δ is the viscous depth of penetration. Equation 1 was used to compute the radiation distance [6]:

$$m\frac{\partial^2 x}{\partial t^2} = \underbrace{\pi k a^3 f_2 k_0 P_a^2}_{\langle F_{\mathrm{rad}}\rangle} - \overbrace{6\pi\mu a\frac{\partial x}{\partial t}}^{F_{\mathrm{Stokes}}}, \tag{1}$$

where m is the effective mass of the particle, k is the wave number, a is the radius of the particle, f_2 is the dipole scattering coefficient, k_0 is the compressibility of the particle, P_a is the amplitude of the acoustic pressure, μ is the dynamic viscosity of water, $\langle F_{\mathrm{rad}}\rangle$ is the mean acoustic radiation force, and F_{Stokes} is the Stokes drag force acting on the particle. Equation 1 was solved for x, the distance travelled in direction of the acoustic field. Computations were done in MATLAB R2013a (The MathWorks, Inc., Natick, MA).

Fluid flow simulations were performed in order to evaluate the turbulence of the *flow chamber* and the amount of fluid that flow into the waste port (Output I) in comparison the primary port (Output II). Simulations were performed in Solidworks Professional 2014 using FlowXpress (Dassault Systèmes SolidWorks Corporation, Waltham, MA). Simulations were performed using water as the flow media at a flow-rate of 9 L/min. This flow-rate was chosen as it matched the maximum flow-rate possible from the experimental setup.

B. Experimental setup

Figure 1 shows a schematic illustration of the experimental setup and the flow chamber. Tap water was contaminated using natural silt filtered through a 200-µm metal mesh at a ratio of 2 g/L. A 60 L bucket was filled with 50 L of particle contaminated water. A Wolfcraft 2207 Super Pump (Wolfcraft, Kempenich, Germany) driven by a RS 14.4V Li-ion drill (RS Components Ltd, Corby, United Kingdom) was used to pump water from the contaminated tank through the flow chamber via a 1" pipe. One-inch diameter, 3-55 L/min variable-area, in-line, waste-water, flow meters (Universal Flow Monitors, Inc., Hazel Park, MI) were placed at the input and output channels of the flow chamber to characterise the flow rates during operation. The processed water from Output I and II were collected in separate containers.

A custom made flow chamber was designed in Solidworks Professional 2014 and 3D printed using a Projet 1500 (3D systems, Rock Hill, SC). Figure 1B shows a graphical rendering of the flow chamber. The main channel (Input I – Output II) had an inner diameter of 1" and a total length of 130 mm. This diameter was chosen to match the piping and flow meter size. Having equal diameters ensurers maximum accuracy of the flow meters and helps reduce turbulence. The ultrasound transducer was positioned 58 mm down-flow from the Input port. Output I had an internal diameter of 15 mm and was position 1" down-flow from the ultrasound transducer at a 145° angle respective to the Input port.

C. Ultrasound generation & characterisation

A custom-made ultrasound transducer was made base on ⌀25 mm, 10 mm thick PZ26 piezoelectic elements (Meggitt A/S, Kvistgård, Denmark). The transducer was fabricated using a previously established technique [7]. The centre frequency of the transducer was measured via impedance measurements at 195 kHz. The transducer was electrically impedance-matched to 50 Ω using a 9-to-1 transmission line transformer to reduce the real resistance.

The ultrasound transducer was driven by 195 kHz continuous sine wave, generated by a 33511B waveform generator (Agilent Technologies, Santa Clara, CA,) and amplified by a 2200L linear RF amplifier (Precision Acoustics, Dorchester, United Kingdom).

The power output of the transducer were measured using an absolute calibration technique with a radiation force balance, based on the standard IEC 61161 [8].

D. Particle concentration measurements

Particle concentration was measured acquiring a minimum of 3 samples from each water reservoir per experimental condition. Samples were stored in 10 mL sealed test tubes for evaluation. From each sample, a minimum of 5 sub-samples were analysed. A 1-mL droplet from each sub-sample was placed on an optical test slide with a 200-µm spacer, and covered with a glass cover slip, generating a precise volume. Sample volumes were imaged using an inverted microscope with a 5×/0.4-NA objective lens (Nikon Corporation, Tokyo, Japan) and a DCC1645C CMOS camera (Thorlabs, Inc., Newton, NJ). This imaging configuration had a maximum resolution of 0.8 µm. The number of particles in the imaging volume was counted using ImageJ. The images were processed by using a rolling ball background subtraction, thresholding, and counting particles. Identical threshold and counting parameters were used for all measurements.

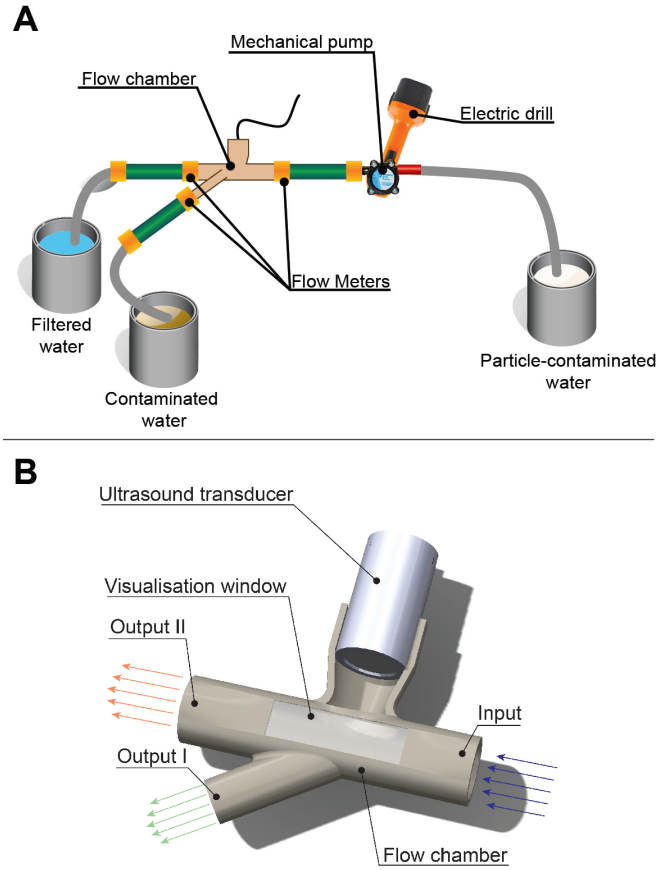

Fig. 1. Schematic illustration depicting experimental configuration used evaluate acoustic filtering of particles in a flow regime (**A**). Graphical rendering of *flow chamber* depicting position of ultrasound transducer and input and output channels (**B**).

E. Experimental procedure

A total of 9 L of contaminated water was pumped through the flow chamber. To prevent dry running and damage to the ultrasound transducer it was turned on several seconds after water flowed through the flow chamber. The processed water was then sampled and then re-mixed and homogenised and used as the input source. This helped prevent large changes in input particle concentrations.

F. Statistics

Statistics were performed using Prism v5.0a (GraphPad Software, Inc., La Jolla, CA). An unpaired Student's t-test was used to compare particle concentration differences. The results were considered statistically significant when $P \leq 0.05$. In all results values indicate mean±SEM.

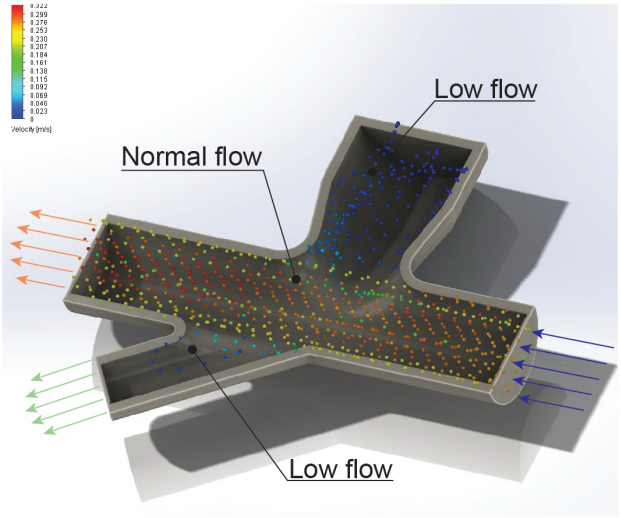

Fig. 2. FloXpress simulation of fluid flow at 9 L per min. Laminar flow can be seen at the center of the chamber. The transducer port and lateral exit port show very low flows.

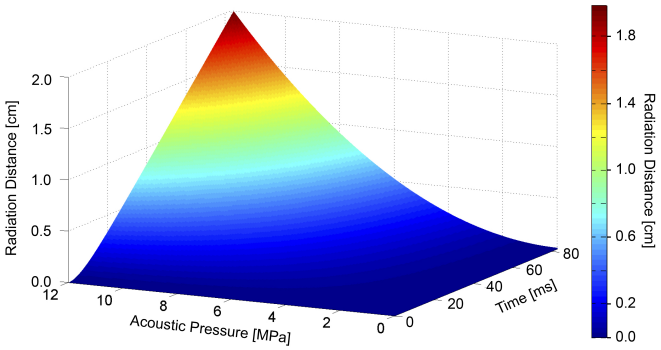

Fig. 3. Results of mathematical simulation. Comparison of radiation distance as a function of acoustic pressure and duration in acoustic field.

III. Results and Discussion

A. Simulations

Fluid flow simulations showed a relatively laminar flow through the primary channel with peak velocities of 0.3 m/s (*c.f.,* Fig 2). The peak velocity into Output II was very low (<0.05 m/s) indicating that the majority of the flow would go through the primary channel. This was a desired result, as we did not want to reduce the velocity of the fluid flow for energy production. Minimal flow was seen also into the transducer housing indicating that there may not be complete water contact with the front face of the ultrasound transducer, resulting in reduced power output. These side chambers (waste channel and transducer housing) induce detached flow resulting in turbulence. Whilst in this case, it is minimal, the design should be optimised to reduce the turbulence and ensure the transducer is in continuous contact with water.

Figure 3 shows radiation distance, in the acoustic propagation direction, as a function of time and acoustic pressure. Simulations indicated that it was possible to radiate a 200-µm particle over total distance of 2 cm within 80 ms, when using an acoustic pressure of 12 MPa. In general, simulations showed an exponential-like increase in radiation distance with acoustic pressure duration of stay in the acoustic field.

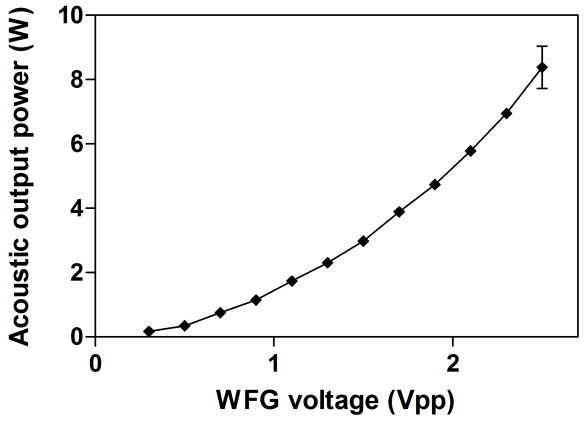

Fig. 4. Power output as a function of peak-to-peak waveform generator (WFG) voltage of the 195-kHz ultrasound transducer measured using a radiation force balance.

B. Acoustics

Figure 4 shows the acoustic power output as a function of waveform generator voltage. The custom-made ultrasound transducer was capable of producing up to 8W of acoustic power in a stable regime. At higher powers, a large deviation between measurements was observed, indicating that the transducer was unstable, either due to cavitation, or due to reaching the maximum excursion possible. For this reason, the results above 8W may have a large deviation and higher uncertainty. Better electrical and acoustic impedance matching may improve the output power. From these resultant powers, estimations to the acoustic pressure were performed. These were used to estimate the radiation force on the particles.

C. Particle concentration

At maximum flow rate, the flow meters indicated a rate of ≈9 L/min, 3 L/min and 6 L/min for the Input, Output I and Output II, respectively. No change in flow was seen when the ultrasound was turned on. Figure 5 shows sample microscope images from the input and output channels. A total of 434 samples were measured. The silt particles can be clearly distinguished as the darker spots within the image. In these sample images we can see that Output II had a three fold lower particle concentration when compared to the Input. Output I had a higher concentration as the flow rate into this channel was approximately half of Output II.

The lower photographs show the water vesicles used. A large amount of silt has sunk to the bottom in the input channel. This was a drawback, as the particle concentration would be constantly varying during water treatment. When

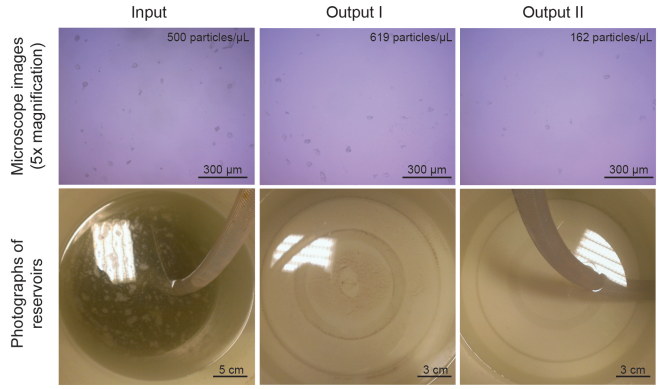

Fig. 5. Micrographs (top row) and photographs (bottom row) of contaminated water before and after treament with ultrasound.

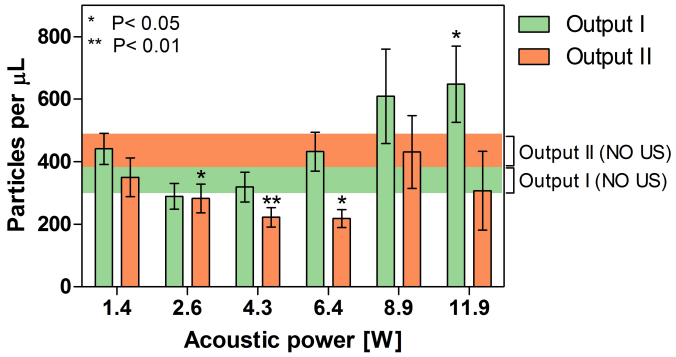

Fig. 6. Paticle concentration as a function acoustic power for flow chamber outputs. Horizontal bars indicate mean particle concentrations with no ultrasound. Stars indicate statistically significant differences.

comparing Output I and Output II, the amount of sunken particles in Output I is substantially higher, as desired.

Figure 6 shows the effect of increasing the acoustic power on particle concentration. The horizontal bars indicate the mean particle concentrations when no ultrasound was present. The thickness of the bars indicated the SEM error in measurement. The control experiments (no ultrasound) show that Output II had a higher particle concentration than Output I, indicating that this was the preferred path, consistent with the fluid flow simulations.

Upon applying ultrasound an immediate decrease in particle concentration can be seen in Output II and an increase in Output I. The particle concentration continues to decrease as the acoustic power increases. Output II becomes statistically significantly cleaner at 2.6 W and continues to 6.4 W. From 8 W onwards, the transducer was considered unstable, and this can be seen in the filtration results. At 8.9 and 11.9 W the SEM is much larger. Nevertheless, at 11.9 W, a statistical significant increase in particle concentration is seen in Output I.

D. Future Perspectives

Whilst these preliminary results have shown it is possible to filter particles from water in flow using ultrasound, there are several areas of improvement that should be addressed in order to increase the efficacy of the system. The flow chamber should be redesigned to decrease fluid flow turbulence. Having laminar flow would ensure good coverage of the acoustic propagation face, and would reduce potential particle back-flow into the primary channel. Positioning the transducer closer to the primary channel would also align the acoustic focus, the area of highest acoustic pressure, with the centre of the flow chamber, hopefully forcing more particle into the *waste port*. Fabricating a more stable acoustic source, capable of higher pressures would also improve the acoustic filtering.

In the work presented here, we used continuous-wave ultrasound, this may generate standing waves with nodes and anti-nodes in the wrong locations. Using pulsed ultrasound would prevent standing waves, but would reduce the radiation time. The ideal acoustic conditions need to be evaluated.

In these experiments, particles $<200\mu$m were used. Other particle size ranges and concentrations should be evaluated.

IV. Conclusion

Our setup has shown that filtering micron-sized particles using low frequency ultrasound is possible. Nevertheless, our configuration is far from optimal, resulting in low efficiencies. Major challenges are the overabundance of particles, the turbulent flow in the chamber, the high velocity of the water, and the unstable acoustic output at high powers. Improving these factors should greatly improve the efficacy of this system.

Acknowledgements

This study has been supported by MedViz (http://medviz.uib.no/), an interdisciplinary research cluster from Haukeland University Hospital, University of Bergen, and Christian Michelsen Research AS. The authors would like to thank The Michelsen Centre for Industrial Measurement Science and Technology for their support throughout this project. We would also like to thank Bergenshalvens Kommunale Kraftselskap (BKK) for financially supporting this research.

References

[1] H. J. Wagner and J. Mathur, *Introduction to Hydro Energy Systems: Basics, Technology and Operation*. Berlin: Springer, 2011.

[2] M. K. Padhy and R. P. Saini, "A review on silt erosion in hydro turbines," *Renew. Sustain. Energy Rev.*, vol. 12, no. 7, pp. 1974–1987, 2008.

[3] R. P. Singh, "Silt Damage Control Measures for Underwater Parts - Nathpa Jhakri Hydro Power Station Case Study of a Success Story," *Water Energy Int.*, vol. 66, no. 1, pp. 36–42, 2009.

[4] A. L. Bernassau, C. R. P. Courtney, J. Beeley, B. W. Drinkwater, and D. R. S. Cumming, "Interactive manipulation of microparticles in an octagonal sonotweezer," *Appl. Phys. Lett.*, vol. 102, no. 16, p. 164101, Apr. 2013.

[5] S. Kotopoulis and M. Postema, "Microfoam formation in a capillary," *Ultrasonics*, vol. 50, no. 2, pp. 260–268, 2010.

[6] M. Settnes and H. Bruus, "Forces acting on a small particle in an acoustical field in a viscous fluid," *Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys.*, vol. 85, 2012.

[7] S. Kotopoulis, H. Wang, S. Cochran, and M. Postema, "Lithium niobate ultrasound transducers for MRI-guided ultrasonic microsurgery," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 8, pp. 1570–1576, 2011.

[8] International Electrotechnical Commision, "Radiation force balances and performance requirements (IEC 61161)," Tech. Rep., 2013.