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Posted Date: 25 August 2023

doi: 10.20944/preprints202308.1775.v1

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## Article

# Experimental Investigation of the Influence of High-Frequency Standing Sound Waves on Depth Filtration Using Coarse-Pored Media

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**Abstract:** When a suspension passes through a high-frequency standing sound wave, the particles it contains are manipulated by acoustic forces. In a one-dimensional sound field, these forces lead to a planar arrangement of the particles and the formation of agglomerates. It is known that the combination of these forces and depth filtration can be utilized to significantly increase the filter efficiency of coarse-pored media. So far, this concept has only been used in microfluidics. In this paper, we present the results of a scaled-up filtration channel to test the viability of the industrial application of acoustically assisted filtration systems for the removal of microparticles. The influences of acoustic power input, flow rate, and the porosity of the filter media are investigated. In addition to verifying the scalability, a significant decrease in the large particle fraction in the outflow of the channel was observed when a high-power sound field is applied. Furthermore, the formed agglomerates tend to rise to the fluid surface. The floating particles mostly consist of a large particle fraction.

**Keywords:** ultrasonics; filtration; porous media; acoustic radiation force; microplastics

## 1. Introduction

The removal of particulate contaminations from liquids has gained an increase in attention in recent years due to the prevalent problem of microplastics [1]. Microplastics classifies plastic particles with a diameter of less than 5 mm [2]. Besides their negative impact on the environment, especially aquatic wildlife [3], industrial processes can also be negatively affected by particulate contaminations. In the machining sector, especially in contract manufacturing, manufacturers work with a mix of materials, ranging from steel, brass and aluminium over carbon fiber reinforced plastics and pure plastics, often being machined on the same tool machine. This leads to a contamination of the cutting fluid with plastic particles in the form of chips in various sizes. Especially in the case of carbon fiber reinforced plastics, micro-sized highly abrasive fibers can be introduced into the cutting fluid circuit, that can damage pumps, fluid lines, nozzles, linear bearings and other machine parts they come in contact with. Many standard band filter media for machining are not suitable for separating the fiber fragments from the cutting fluid [4]. While smaller pore size of the filter media can solve this problem, the necessary pressure differential typically leads to high energy consumption of such systems [5]. A different approach is to utilize external fields to manipulate particles [6]. This can be used to improve filter efficiency of regular filters by altering particle trajectory, trapping them in gradient fields, increasing the probability of capture or by influencing attractive forces between fiber-particle and particle-particle. One example of this is magnetic separation, commonly used in machining to remove metal chips from the cutting fluid, where the use of a filter medium becomes obsolete. Since this mechanism can not be applied to polymers due to their lack of interaction with magnetic fields, different physical properties must be considered. While differences in density between particles and fluid can usually be used to cause sedimentation or flotation, the differences in density between polymers and water are too small to overcome stabilizing mechanisms such as electrostatic and steric forces. Only when the forces are

comparatively high, such as in a centrifuge, separation based on density can be achieved. Another method of separation based on density is the use of highly localized gradients in pressure that can form in high frequency acoustic standing waves. By utilizing acoustic forces, particles suspended in a liquid medium can be manipulated [7]. When using a high frequency standing acoustic wave, the local oscillation in pressure leads to a partial segregation of the suspension. This can be attributed to the primary and secondary acoustic forces (PAF and SAF). The primary acoustic force  $F_{pr.ac}$

$$F_{pr.ac} = V_p k E_{ac} \left[ \frac{5\Lambda - 2}{2\Lambda - 1} - \frac{1}{\sigma^2 \Lambda} \right] \sin(2kx) \quad (1)$$

causes the solid phase to be pushed into the nodes or antinodes of the standing wave [8], depending on the density ratio  $\Lambda = \rho_{particle} / \rho_{liquid}$ , the sound velocity ratio  $\sigma = c_{particle} / c_{liquid}$ , particle volume  $V_p$ , acoustic energy density  $E_{ac}$ , wave number  $k$ , and the distance of the particle relative to the nearest node  $x$ . The secondary acoustic force  $F_{se.ac}$

$$F_{se.ac} = \frac{k^2 E_{ac}}{2\pi} \left[ 1 - \frac{\gamma_1}{\gamma_f} \right] \left[ 1 - \frac{\gamma_2}{\gamma_f} \right] \frac{V_1 V_2}{d^2} \quad (2)$$

results from the sound waves being scattered by the solid phase particles and neighbouring particles interacting with the scattered sound field, inducing attractive forces between particles in the suspension [9]. The value of  $F_{se.ac}$  depends on the compressibilities of the interacting particles  $\gamma_{1/2}$  and the fluid  $\gamma_f$ , the volumes of the particles  $V_{1/2}$  and their relative distance  $d$ .

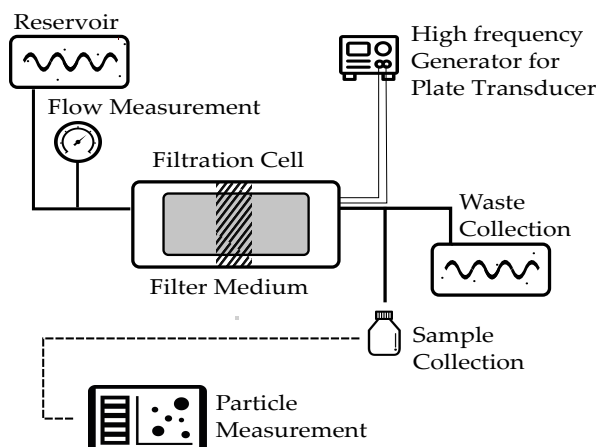
The combination of both forces causes the particles to be first pushed into the wave nodes or antinodes by the PAF and then to agglomerate through the SAF. The influence of these forces on filtration using coarse porous media was first investigated by Gupta and Feke [10]. They were able to show that the filtration efficiency can be significantly increased by applying standing acoustic waves perpendicular to the direction of flow. They explain the increase in filter efficiency by three possible mechanisms: I.) due to the PAF the particles are driven towards the node or antinode plane and can thereby not pass the filter medium freely, II.) the agglomerates of particles caused by the SAF are more easily retained by the filter medium due to the increase in size and are held in the filter medium due to the PAF, and III.) the SAF can act between particles and elements of the filter medium, attracting particles and improving their adherence. By using the sound field, filter media can be used which are normally too coarse-pored for filtration. The deactivation of the acoustic fields allows a large portion of trapped particles to be released from the filter. At a later stage, Gupta and Feke developed a model to describe the trajectory of the particles through the filter medium [11], which was verified by Grossner et al. [12]. A practical application for the filtration concept was found by Wang et al. [13]. They were able to retain mammalian cells in a filter medium with pores that are 2 orders of magnitude larger than the used cells. The acoustic channels and sound fields studied so far have mainly been focused on microfluidics, being rather small and the flow rates investigated have always been less than  $100 \text{ ml min}^{-1}$ . For this reason, the scalability of this filtration concept is to be investigated here in order to test its applicability in industrial applications.

## 2. Materials and Methods

### 2.1. Acoustic Filtration Chamber

The experimental setup is schematically shown in Figure 1 and consists of a reservoir for the inlet of the suspension with a flow measurement to ensure constant flow during the experiment. From there the liquid enters the acoustic chamber, shown in Figure 2. In its center portion, the acoustic transducer *Sonoplate High Frequency* from *Weber Ultrasonics* with the dimensions  $185 \text{ mm} \times 244 \text{ mm}$  is installed vertically on the backside of the chamber. A glass window in front of the transducer acts as the acoustic reflector, while enabling visual observation during the experiments. The distance

between transducer and reflector can be adjusted by 4 screws positioned on the back of the chamber, so the distance correspondes to an integer multiple of half the wavelength  $\lambda$ . They also act as a means to ensure parallelism after the distance is set. The multiple in- and outlets on the sides of the channel are arranged in 3 rows of hose connectors allow the experimentator to make the channel more narrow, disconnecting all the unused in- and outlets. The acoustic field emitted from the transducers surface is limited to an area of  $122 \text{ mm} \times 168 \text{ mm}$  and it is oscillating with a frequency of 1 MHz, which is created by the *SonoPower 3S Megasonic Boost* ultrasound generator from *Weber Ultrasonics*. The generator allows for an adjustment of the power output ranging from 0 % to 100 %, where 100 % corresponds to a power input of 500 W. For the experiments, the distance between transducer and reflector was set to 20 mm.



**Figure 1.** Schematic of the experimental setup.



**Figure 2.** Rendered model of the filtration cell.

## 2.2. Particle Suspension

The particle suspension consists of polyamid 12 (PA) particles used for additive manufacturing with a particle size distribution centered around  $56 \mu\text{m}$ . The particles are suspended in a mixture of 97.5 wt% water and 2.5 wt% of the synthetic metalworking fluid *Syntilo MR 81 BF* produced by *Castrol*, acting as a surfactant for the particles. 0.5 g/l of PA particles were then added to the solution which resulted in a suspension that remained metastable for a duration of over 24 h, therefore effects of naturally occurring sedimentation and flotation in the course of the experiments can be neglected.

## 2.3. Filter Media

As filter media for the depth filtration, foams made of polyester were purchased from *HIRI - Hildebrand und Richter & Co.* with a porosity of 15, 20 and 30 pores per inch (ppi), with a average pore diameters of 2.54 mm, 1.27 mm and 0.85 mm respectively. Thus, the pores are at least one magnitude larger than the particles in the suspension. The foams were cut to shape to fit inside the acoustic channel. The filter media have a width of 20 mm, equal to the channel width, and reached from the bottom of the channel up to 15 mm above the liquid surface, so none of the suspension could seep over the filter. A filter depth of 20 mm was chosen, as it is sufficiently deep and only fills a small portion of the acoustic field, so non-filter-related acoustic effects before and after the filter medium can be observed aswell. The filter strips are placed vertically in the center of the acoustic channel.

## 2.4. Methodology

Since no previous experiments on an acoustic depth filtration test setup of comparable size are known to the authors, a design-of-experiments (DoE) approach was chosen. Flow rate  $Q$ , acoustic power input  $P$  and the porosity  $\Phi$  were chosen as parameters and their influence on filtration efficiency was investigated. The values of  $P$  serve as a reference value for the acoustic energy  $E_{ac}$  contained

in the standing wave. For the flowrate  $Q$  values of  $0.4 \text{ L min}^{-1}$  and  $0.8 \text{ L min}^{-1}$  were chosen, as they cover a range in which the volume flow is large enough for a reasonable industrial application, but no turbulent flow occurs.  $P$  was varied on the levels 0 %, 10 % and 30 %.  $P = 30 \%$  was chosen as the upper limit because above this threshold, acoustic streaming was observed for the setup present. As for  $\Phi$ , the aforementioned polyester foams with 15 ppi, 20 ppi and 30 ppi were used, bringing the total amount of configurations tested to 18. For each configuration, the flow was initially set to the designated value and a sample of 50 mL was drawn from the effluent via a valve in the tubing for a baseline measurement of particle concentration in the suspension. Then the filter medium was placed in the chamber and the high-frequency generator was activated. From this point on, every two minutes a sample was drawn from the effluent for a total of 20 min, resulting in 11 samples for each configuration.

### 2.5. Sample Analysis

The samples were then diluted with demineralized water by a factor of 5 before being analyzed with the flow cell particle counter *FC 200M* by *OCCHIO*. Dilution was necessary because the device requires a minimum quantity of 200 mL and to reduce overlapping of particles in the measurement cell during a measurement. The device pumps a small quantity of liquid from a reservoir into a cuvette where the liquid within the narrow space is backlit and then photographed. This process is repeated 42 times and the images taken are then analyzed by the software *CALLISTO* provided by *OCCHIO*, where a pixel based particle analysis is performed. For each image the number of particles detected, their equivalent size and shape are saved in a report file. Each measurement was performed three times and high reproducibility between measurements was observed. The fluid in the reservoir was stirred to counteract sedimentation or flotation that could result from possible destabilization of the suspension caused by dilution. With a calibration performed in advance, the concentration  $C$  in g/l can be calculated from the number and size distribution of the particles for each sample. The filter efficiency  $\eta$  is then calculated from the ratio of the particle concentration of the initial sample  $C_0$  and the samples in the course of the experiment  $C_e(t_i)$  with

$$\eta(t_i) = \frac{C_0 - C_e(t_i)}{C_0}. \quad (3)$$

To describe the portion of particle mass that has been retained by the filter up to a certain time  $t_i$ , the retentive filter efficiency  $\eta_{ret}$  is employed, given as

$$\eta_{ret}(t_i) = \frac{1}{i} \sum_{k=0}^i \eta(t_k). \quad (4)$$

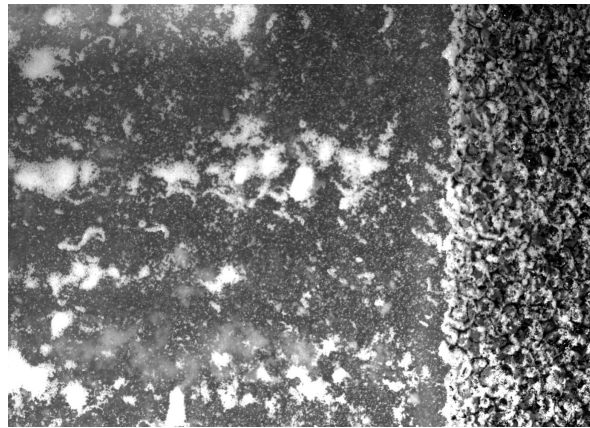
Since the samples in the outflow are taken at regular intervals and the flow rate is kept at a constant level,  $\eta_{ret}(t_i)$  is equal to the average of the  $\eta$  values measured up to that time.

## 3. Results

### 3.1. Visual Observations

In the experimental setup, the filter medium is positioned in front of the center region of the acoustic transducer. Therefore the particles pass through the sound field and are effected by the acoustic forces before coming in contact with the filter medium. This means that the particles can already be manipulated in advance by the PAF and SAF and agglomerate (see Figure 3). Without the influence of the sound field no agglomerates were observed. A large portion of the agglomerates that form are larger than the pores of all the filter media considered, which means they can deposit on the filter surface. This converts the filter media, which were originally used as depth filters, into surface filters.



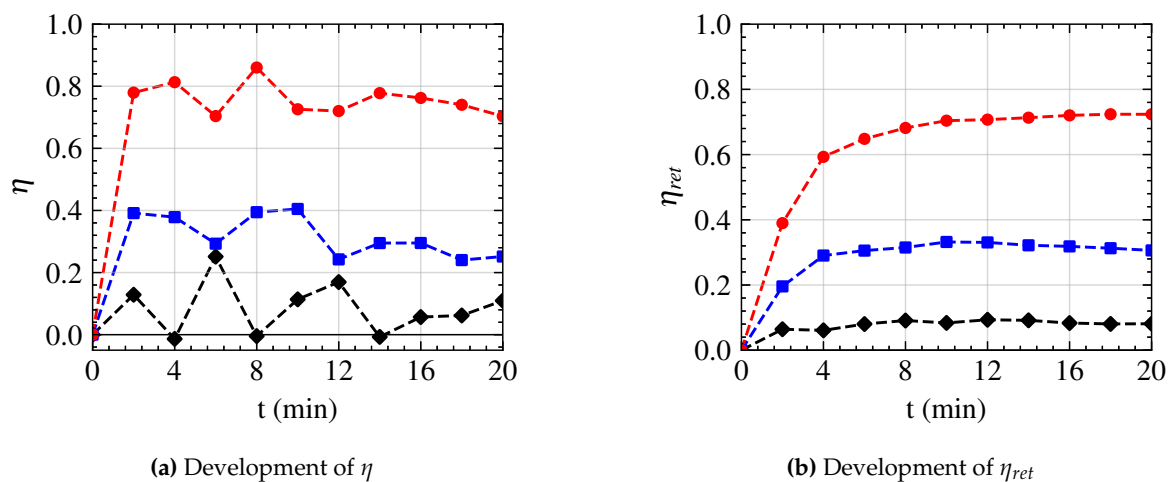


**Figure 3.** Formation of agglomerates in front of the filter medium (whirl); flow direction from left to right, 15 ppi.

The agglomerates that form are more prone to flotation and separate from the suspension at the liquids surface. The measured filter efficiencies therefore do not describe the efficiency of the filter medium but rather the filter efficiency of the entire experimental setup including particle separation due to flotation.

### 3.2. Development of the Filter Efficiencies over Time

To illustrate the temporal evolution of  $\eta$  and  $\eta_{ret}$ , three exemplary progressions with varying frequency generator powers  $P$  are shown in Figure 4. The graph of  $\eta$  in Figure 4a shows a large increase in filter efficiency when a sound field is present. Already at 2 min when the first sample is drawn, a much lower amount of particles was measured. The evolution of  $\eta_{ret}$  can take one of three forms for the experiments: (I) the retentive filter efficiency constantly increases up until the end of the experiment at 20 min, (II) after reaching its maximum it stays on a constant level or (III) after reaching a local maximum it decreases slowly over time. In Figure 4b case (I) takes place for  $P = 30\%$ , case (II) can be observed for  $P = 0\%$  and a light version of case (III) can be seen for  $P = 10\%$ .



**Figure 4.** Exemplary temporal developments of the filter efficiencies  $\eta$  and  $\eta_{ret}$  for a porosity of 20 ppi,  $Q = 0.8 \text{ L min}^{-1}$  and  $P$  of 0% (♦), 10% (■) and 30% (●).

### 3.3. Final Retentive Filter Efficiency

In order to qualitatively compare the filter efficiencies of different test series, the final retentive filter efficiency  $\eta_{ret,fin}$  is defined as the retentive filter efficiency  $\eta_{ret}$  that is observed after 20 min. The values of  $\eta_{ret,fin}$  for all configurations can be found in Table 1. An analysis of variance (ANOVA) was performed on the results. With  $\alpha$  set at 0.05,  $P$  and  $Q$  were identified as significant influences with an

increase of  $P$  leading to an increase in filter efficiency, while lower flow rates  $Q$  were also identified as beneficial. The variation of porosity  $\Phi$  in the selected range no significant effect.

**Table 1.** Overview of all values of  $\eta_{ret,fin}$ .

$Q$ $\Phi$	$0.4 \text{ L min}^{-1}$			$0.8 \text{ L min}^{-1}$		
	15 ppi	20 ppi	30 ppi	15 ppi	20 ppi	30 ppi
$P = 30 \%$	0.91	0.78	0.75	0.76	0.72	0.64
$P = 10 \%$	0.83	0.52	0.46	0.19	0.31	0.31
$P = 0 \%$	0.14	0.35	0.28	0.14	0.08	0.23

### 3.4. Temporal Development of the Retentive Filter Efficiency

As described in Section 3.2, some temporal developments of  $\eta_{ret}$  show a stagnant behaviour, while others slowly decline after reaching a maximum or increase until the end. In order to describe this effect, the quantity  $\delta_{10}$  is introduced, which corresponds to the percentage difference of  $\eta_{ret}$  after 10 min and 20 min. Negative values of  $\delta_{10}$  reflect a drop of  $\eta_{ret}$  in the last 10 min, values close to 0 % represent stagnation and positive values indicate that the filter can effectively separate particles until the end of the measurement. All values of  $\delta_{10}$  are presented in Table 2.

With an increase of  $P$ ,  $\delta_{10}$  tends to increase and take on mostly positive values. For the flow rate of  $0.8 \text{ L min}^{-1}$ ,  $\delta_{10}$  takes smaller values than the corresponding measurements for  $0.4 \text{ L min}^{-1}$ . A conducted ANOVA shows that the influences of  $P$  and  $Q$  are indeed significant while an influence of the  $\Phi$  can not be derived.

**Table 2.** Overview of all values of  $\delta_{10}$ .

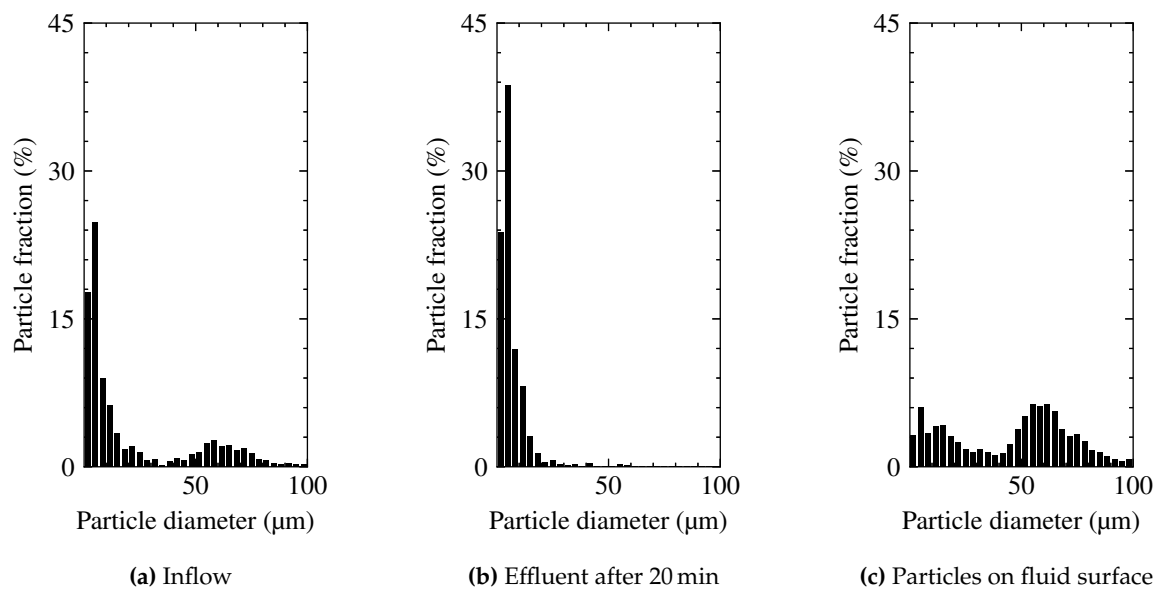
$Q$ $\Phi$	$0.4 \text{ L min}^{-1}$			$0.8 \text{ L min}^{-1}$		
	15 ppi	20 ppi	30 ppi	15 ppi	20 ppi	30 ppi
$P = 30 \%$	+5.8 %	+8.8 %	+6.3 %	+3.0 %	+2.0 %	−0.1 %
$P = 10 \%$	+5.7 %	−3.1 %	+2.4 %	−2.1 %	−2.6 %	−6.3 %
$P = 0 \%$	+1.4 %	−2.1 %	−5.3 %	+1.2 %	−0.3 %	−7.6 %

### 3.5. Change in $P_{sd}$

Since the measurement method used not only measures the particle concentration, but also the particle size distribution, the influence of the parameters investigated on PSD can also be examined. It can be observed that the PSD in the effluent changes under the influence of the sound field. Thereby, the proportion of particles with a diameter of more than  $30 \mu\text{m}$  decreases significantly compared to the input suspension. This significant change in the PSD does not occur in the tests without sound field. For a better understanding, three PSDs of an experiment with  $P = 30 \%$  are visualized in Figure 5. While the input suspension shows particles with diameters under and above  $30 \mu\text{m}$ , the effluent suspension shows nearly no particles with a diameter above  $30 \mu\text{m}$ . In addition a sample of the particle that collected on the fluids surface was taken, where rising agglomerates were floating on top. The sample was diluted and stirred, so that the agglomerates broke down into single, detectable particles. Their PSD in Figure 5c shows that particles that collect on the fluid surface due to flotation have a larger portion of particles with a diameter of more than  $30 \mu\text{m}$  than the inflow suspension. In order to further investigate this observation, the quantity  $\varepsilon$  is derived,

$$\varepsilon = \frac{N_{d < 30 \mu\text{m}}}{N_{total}} \cdot 100 \% \quad (5)$$

which defines the percentage of particles with a diameter  $< 30 \mu\text{m}$  in the total number of particles detected in the effluent from beginning to end of the experiments. The determined values of  $\varepsilon$  can be found in Table 3.



**Figure 5.** PSD of the inflow and outflow suspension and of the particles at the fluid surface for the experiment with 15 ppi,  $Q = 0.4 \text{ L min}^{-1}$  and  $P = 30 \%$ .

**Table 3.** Overview of all values of  $\epsilon$ .

Q $\Phi$	0.4 L min <sup>-1</sup>			0.8 L min <sup>-1</sup>		
	15 ppi	20 ppi	30 ppi	15 ppi	20 ppi	30 ppi
P = 30 %	98 %	96 %	99 %	97 %	95 %	92 %
P = 10 %	96 %	97 %	90 %	83 %	83 %	79 %
P = 0 %	95 %	89 %	97 %	95 %	87 %	89 %

The data shows that for a power output of 30 % more particles with a diameter  $< 30 \mu\text{m}$  can be detected in the effluent than from smaller power outputs. It is noticeable, that  $\epsilon$  does not always increase with a higher power input. For all measurements with a flow rate of  $0.8 \text{ L min}^{-1}$  and a fixed porosity,  $\epsilon$  is the smallest for a power output of 10 %. The same can be observed for the measurements with a  $\Phi = 30 \text{ ppi}$  and  $Q = 0.4 \text{ L min}^{-1}$ . Generally the portion of small particles is larger for the measurements with  $Q = 0.4 \text{ L min}^{-1}$  compared to  $Q = 0.8 \text{ L min}^{-1}$ .

## 4. Discussion

### 4.1. Flotation

The sound-aided flotation can be explained when looking at the effects that stabilize the suspension in the first place. In general, a differentiation can be made between electrostatic and steric stabilization. Electrostatic stabilization is based on the formation of an electrical double layer on the particle surface, which lead to electrostatic repulsion between the particles. Steric stabilization, on the other hand, results from the absorption of polymer chains on the particle surface, whose interaction with absorbed polymer chains from other particles leads to repulsion. Thus, both stabilization mechanisms depend on the surface area of the particles. The suspension is in a stable state, when these effects can counteract the sedimentation or flotation arising from the density difference between the liquid and solid phase. In the inlet suspension, the stabilization mechanisms and the density-dependent forces are in equilibrium. When the particles interact with the sound field they begin to agglomerate due to the attractive interaction caused by the SAF. Since SAF scales with particle volume, larger particles are more likely to form agglomerates. This results in a shift of the equilibrium between the



particle surface and volume to the detriment of the stabilization mechanisms. Thereby, flotation is enhanced and the particles can be separated from the liquid phase.

#### 4.2. Influence of the Parameters on the Filter Efficiency

Before looking in more detail at the influence of the various parameters on the filter efficiency, it should be pointed out once again that the measured filter efficiency results from the actual filtration and the flotation. The positive effect a reduction of the flow rate has on the efficiency is rather apparent. With lower velocities, the time that particles remain in the sound field and filter medium increases, giving the particles a higher chance to agglomerate and be retained by the filter. Furthermore, the influence of drag forces decreases, which have the potential to release particles from the filter again. The fact that changes in porosity did not result in statistically significant changes of the filter efficiencies can be attributed to the experimental setup where pore size of all the filter media is one magnitude larger than the average particle size. Also a large portion of the agglomerates, that formed in the sound field was larger than the pore size of any of the filter materials. With a smaller ratio of pore size to particle size, a rise in the influence of variation in pore size on filter efficiency is expected. The increase in filter efficiency due to higher acoustic power can be explained by a characteristic of the PAF and SAF. Both behave proportionally to the acoustic energy density of the sound field, which for higher sound power levels promotes the agglomeration of the particles and the resulting effects.

#### 4.3. Change in PSD

In surface and depth filtration, it is almost always the case that large particles can be separated more easily than small ones. However, in the experiments performed, the change in PSD under the influence of acoustic forces is significant. Moreover, it is of interest why especially the particles with diameters  $> 30 \mu\text{m}$  are found in the floating particles. A possible explanation is the dependency of PAF and the SAF on particle volume. As a result, particularly large particles are pushed into the wave nodes or antinodes by the PAF, which promotes their agglomeration by the SAF. Thus, the agglomerates are increasingly composed of larger particles and the surfaced agglomerates have a high fraction of particles with diameters  $> 30 \mu\text{m}$ .

### 5. Conclusions

By using a comparatively large channel, it was shown that the sound-assisted filtration can be scaled-up from microfluidic applications and can be used in larger channels enabling its use for industrial applications. It has been shown that the PAF and SAF promote the separation of the solid and liquid phases of a suspension. This separation is based on the formation of agglomerates, which can be well retained by filter media more easily. The flotation of agglomerates also contributes to the separation of particles from the liquid. The two mechanisms can significantly increase the filter efficiency compared to experiments without a sound field. It is of further interest whether sound-assisted flotation can be instrumentalized and if the filter medium can be replaced by a skimming processes.

**Author Contributions:** Conceptualization, J.H. and R.S.; methodology J.H.; validation J.H. and R.S.; resources R.S.; data curation J.H.; writing J.H. and R.S.; supervision R.S.; project administration R.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
DoE	Design of experiments
ppi	Pores per inch
PA	Polyamid 12
PAF	Primary acoustic force
PSD	Partice size distribution
SAF	Secondary acoustic force

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