Size selective particle filtering on centimeter scale by frequency sweep type dynamic acoustic field

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ABSTRACT

The objective of the study was to investigate and demonstrate the application of frequency-sweep dynamic acoustic fields for size-selective particle filtration on centimeter scale in a regulated continuous flow. The 3D-printed prototype of the acoustic separator has two inlets and two outlets, whereas the dynamic acoustic field is generated between a transducer, operating in the MHz range, and a reflector. The measured frequency response of the prototype was input to computer models, and simulations were carried out to explore the effects of the sweep period and the flow parameters on the filtration performance. A design-of-experiments study showed that the filtration performance is largely affected by the sweep period and the outlet flow rate. Lab experiments with model particle mixtures demonstrated the size selective filtration performance of the prototype with a total flow rate of 1 l h⁻¹. A mixture with unknown properties was also used to demonstrate the selective filtration performance of the prototype.

1. Introduction

Filtration of mixtures is an important step in industrial processes. Such mixtures can be in the form of emulsions or suspensions. For example, pharmaceutical, food, biomedical and water industries commonly incorporate filtration processes of suspensions. Utilizing filtration in a selective manner can improve the quality of the product and process. With the ability to perform filtration in continuous flow without blocking or affecting the flow, acoustophoresis is one of the methods to achieve selective particle filtering in suspensions [1–5].

A particle in an acoustic field experiences an acoustic radiation force. In an acoustic standing wave field this force pushes the particle towards either a pressure node or antinode, depending on the acoustic properties of the particle and the surrounding medium [6,7]. While moving in a fluid due to the combined effect of an acoustic field and flow field, the particle also experiences drag force [7,8]. Consequently, selective particle filtering can be achieved based on the interplay between the acoustic radiation force and the drag force on a particle.

With given surrounding medium and excitation parameters the acoustic radiation force scales with particle volume, density and compressibility whereas the drag force scales with particle size [6–8].

On microscale, this interplay is used to separate particles based on their size [9–13] or acoustic contrast factor, which is a combination of density and compressibility [14–16]. Cells can also be selectively separated using acoustic radiation force only [17–23]. Typically, in microscale acoustophoresis devices an acoustic standing wave field is utilized in a chamber with a width equal to the half-wavelength at the excitation frequency in the medium, referred to as half-wavelength separators. In such devices, the particles are forced towards a single pressure node in the middle of the channel. The amplitude of the acoustic radiation force increases with frequency and pressure amplitude. If the particle size is comparable to or larger than the wavelength of excitation, it cannot be manipulated by the acoustic radiation force. Hence, for micrometer-sized particles the excitation is typically in the MHz range and the channel width of such devices are in the order of hundreds of micrometers [24].

On centimeter scale, acoustophoretic devices become multi-wavelength resonators [25–29]. Instead of one pressure node in the middle of the channel, multiple pressure nodes and antinodes exist in such devices. While the acoustic radiation force is typically due to an acoustic standing wave field, clever arrangement of flow patterns open up possibilities for selective particle filtration in a continuous flow on
microscale [30] as well as on centimeter scale [2,31,32]. Alternatively, application of dynamic acoustic fields on centimeter scale offers more possibilities for selective filtration [33–38]. In dynamic acoustic fields, the pressure nodes are not fixed and their motion can be controlled. One possible way of obtaining a dynamic acoustic field is using frequency-sweep excitation, in which the applied frequency is periodically ramped and the pressure nodes move away from the sound source. Particle separation and concentration using frequency-sweep excitation on centimeter scale and microscale is demonstrated in multiple studies [39–42]. These studies made use of the nodes moving away from the sound source and concentrate the particles in one end.

The controllability of the nodal motion greatly enhances the capabilities of the separator. The acoustic force pattern in the separator and the speed of the nodal movement, hence captured particles, as well as the flow profile in the separator can be adjusted to possibly create a size selective filtration mechanism. This adjustability makes a frequency sweep-based system a good candidate to scale-up selective filtration applications from microscale to centimeter scale. However, such possibilities offered by this type of excitation are not explored yet.

This study aimed to explore and demonstrate the selective particle filtration capability of frequency sweep type dynamic acoustic fields on centimeter scale in a continuous flow separator, by adjusting the excitation and flow parameters. First, the frequency response of the transducer was obtained in the excitation (i.e. MHz) range. Computer simulations were carried out in order to examine the effects of the excitation and flow parameters on the particle size distribution of model polystyrene particles. Subsequently, lab experiments were performed to demonstrate the selective filtering capability of the combination of frequency sweep type field and flow pattern on model polystyrene particles in water and on wheat beer.

2. Materials and methods

2.1. Frequency sweep excitation

In the frequency-sweep method, the excitation frequency is ramped periodically from a starting frequency to a higher frequency within a given period. Excitation by a single sound source, with a reflector placed parallel to that source, generates at each frequency a standing wave field in between. During a frequency sweep, the resulting acoustic wave field can be considered a dynamic acoustic field in which the quasi-standing wave field is contracted by introducing new nodes from the source side. The distance between the source and reflector is kept constant while that distance. Fig. 1 illustrates the change in frequency and the corresponding change in the standing wave pattern.

If the acoustic impedance of the reflector is much higher than the medium it reflects the incoming wave with the same amplitude and phase. Hence, ignoring the attenuation in the medium, the resulting standing wave, as a function of the time-varying frequency $f(t)$, can be expressed as

$$P(x, t) = 2P_i(t)\cos(k(t)x)\cos(\omega(t)t)$$

In Eq. (1), $x$ (m) is the distance of the particle from the reflector (Fig. 1b) and $t$ (s) is time. $P_i(t)$ (Pa) is the pressure amplitude of the incoming wave from the source and it is constant for the case the transducer vibrates equally at every frequency during the sweep period. The function $\omega(t) = 2\pi f(t)$ (rad s$^{-1}$) is the angular frequency of excitation whereas $k(t) = \omega(t)/c_0$ (m$^{-1}$) is the wavenumber and $c_0$ (m s$^{-1}$) is the speed of sound in the medium. Defining the total pressure $P(t) = 2P_i(t)$, the equation of motion for a particle in a frequency sweep type dynamic acoustic field is given by

$$\left(\frac{4}{\pi^2} r^2 \rho \right) \ddot{x} + \left(6\pi r \mu \dot{x} + u \right) + 4\pi k(t) x^2 \frac{P_i(t)}{4\rho_0 c_0^2} \phi(\rho, c) \sin(2k(t)x) = 0$$

In Eq. (2), $r$ (m) is the particle radius, $\rho_0$ (kg m$^{-3}$) is the density of the medium, $\rho$ is the density of the particle, $c$ is the speed of sound in the medium, $\phi(\rho, c)$ is the acoustic contrast factor and $u$ (m s$^{-1}$) is the constant flow velocity of the liquid from the reflector to the source. The first term in Eq. (2) represents the inertial force whereas the second term represents the drag force acting on the particle. The last term, $4\pi k(t) x^2 \frac{P_i(t)}{4\rho_0 c_0^2} \phi(\rho, c) \sin(2k(t)x)$, is the acoustic radiation force acting on a spherical particle in a frequency-sweep type dynamic acoustic field [38].

As new nodes are introduced in the quasi-standing wave pattern with linearly increasing frequency (Fig. 1a), the contraction rate of the pattern is not constant. The velocity of any point in the dynamic acoustic field towards the reflector, hence the negative sign, is a function of time and position and is given, within one sweep period, by:

$$v(x, t) = -\frac{f_0}{(f_0 + 3T)^2} S x$$

In Eq. (3), $S = \Delta f/T$ is the sweep rate. As a particle trapped in the pressure nodes will follow the movement of the nodes, the velocity of a trapped particle can be estimated from Eq. (3) [38].

![Fig. 1. Change in the excitation frequency (a) and the corresponding standing wave pattern in the dynamic acoustic field at specific time instances (b). The frequency is ramped from $f_0$ to $f_2 = f_0 + 5T$ within the sweep period $T$ and with $S$ the sweep rate, leading to waves with wavelengths $\lambda_i = c_0/f_i$ with $c_0$ the speed of sound. As the excitation frequency increases, new nodes are introduced from the source (transducer) side, in turn contracting the standing wave pattern.](image-url)
2.2. Experimental set-up

The experimental set-up consists of a dual-channel signal generator (Keysight Trueform 33512B), a custom-made amplifier, an oscilloscope (Tektronix TDS2024C), two syringe pumps for inlets (Aitecs PRO SP-12S), two syringe pumps for outlets (HARVARD Apparatus Pump 33) and a separator prototype with piezoelectric transducer (Noliac NCE41, dimensions 50 mm × 10 mm × 1 mm) and a reflector (stainless steel). The prototype (Fig. 2) includes 3D-printed polylactic acid (PLA) base and walls and a PMMA cover. The X-shaped prototype consists of two inlets and two outlets that can be separately regulated. This ability allows the manipulation of the streamlines, hence the drag force experienced by the particles. Furthermore, the geometry of the prototype was designed such that the pipe entrance is expanding smoothly to the main resonator channel, avoiding turbulence due to sudden expansion. The transducer was coated with a thin layer of polyurethane paint to provide electrical insulation, as polyurethane has a similar acoustic impedance as water.

The transducer was excited by a sweeping frequency signal. The electrical admittance of the prototype was measured by using an HP 4194A impedance analyzer, to check for resonant frequencies in the prototype and the amount of nodes introduced during the sweep period. Each peak and valley introduced in the admittance spectrum corresponds to a resonance in the system, while sharper peaks indicate higher Q factor for those resonances. The generated pressure was derived by measuring the surface velocity of the immersed transducer with a Laser Doppler Vibrometer (LDV: Polytec OFV-5000 single-point vibrometer) during the frequency sweep. During the measurement the transducer was placed on a special stand imitating the fixture in the prototype, immersed in water, outside the prototype to ensure sufficient signal quality. The pressure was calculated by using the specific acoustic impedance of the host medium. Pressure values were calculated by taking the average of 10 recordings for each sweep period and multiplying the velocity with the specific acoustic impedance. This pressure information was used as input for the computer simulations.

For the simulations and experiments polyethylene particles were used (c = 1700 ms⁻¹) of sizes: 36 (red), 56 (cyan), 70 (orange) and 100μm (blue). Densities of the different set of particles are ρ_red = 998 kg m⁻³, ρ_cyan = 1000 kg m⁻³, ρ_orange = 1006 kg m⁻³ and ρ_blue = 1002 kg m⁻³. The particle mixture contained 1 MilliQ water, 0.075g CTAB (hexadecyltrimethylammonium bromide) as surfactant, 0.03g red, 0.08g cyan, 0.2g orange and 0.5g blue particles.

Particle motion was recorded by a microscope with camera and particle trajectories were visualized with ImageJ software [43] and particle size distributions were analyzed using a DIPA [1] 2000 particle analyzer. The DIPA 2000 analyzer uses the laser obscuration time to estimate the diameter of particles. A rotating laser beam scans the mixture and from the corresponding obscuration time the diameter of individual particles is calculated.

2.3. Computer simulations

Computer simulations were done to calculate particle trajectories (COMSOL Multiphysics 5.5) and particle size distributions (MATLAB r2018b). Each set of excitation parameters was an arbitrary combination of a sweep period and input and output flow rates. The sweep range, Δf, was set to 500kHz where f₀ = 1.9MHz. Total flow rate was set to 1Lh⁻¹ and the transducer was excited at 20Vpp. A design of experiments (DOE) study was carried out in order to explore the effect of the variable excitation and flow conditions. As in the lab experiments, the particle mixture was fed from the transducer-side inlet, with flow rate V₁. In the plots presented throughout the article, volumetric percentage refers to the ratio of the volume of particles within a given range to the total particle volume in the mixture. Table 1 presents the range of the variable parameters used in the DOE.

DOE study and analysis were done by using MiniTab 14. The study consisted of in total 27 simulations, which are all possible combinations of parameters given in Table 1. The flow rates were selected such that when the flow rates are unequal at both outlets and inputs, with a preference to have larger flow rates at the transducer-side outlet, the streamlines are bent towards the transducer-side outlet. Hence the drag force resulting from this bending effect in the vertical direction acts against the acoustic radiation force. As the acoustic radiation force carries the particles towards the reflector, the drag force carries the particles mostly towards the transducer-side outlet, in turn enhancing the interplay between those two forces.

For the computer model, particle sizes were randomized in order to represent a continuous particle size distribution. Number of particles used in simulations is given in Table 2. Same set of the particles were used for each simulation. Size and initial position data of the particles can be found in the supplementary material.

The simulations were done in 2D, while taking into account the depth of the prototype for different flow rates. Particle-particle interactions, secondary acoustic radiation force effects, gravity and lift force were ignored. Under these assumptions, all particles were independent of each other, leading to the possibility to release them to the system at the same time. Consequently, the computational load was reduced and the simulation times were shortened.

Assuming that only the acoustic radiation force and drag forces on the particle are significant, COMSOL Multiphysics was used to solve Eq. (2) in combination with the drag forces, resulting from the flow in x and y directions. Eq. (2) was solved for each individual particle, eventually leading to particle trajectories.

Table 1

| T(s) | V₁ (mLh⁻¹) | V₄ (mLh⁻¹) |
|------|------------|------------|
| 3    | 300        | 300        |
| 5    | 400        | 400        |
| 7    | 500        | 500        |

Fig. 2. X-shaped prototype used in the experiment. The transducer is connected to the amplifier. The reflector is a stainless steel plate with the same dimensions as the transducer. Particle mixture is fed from the transducer-side inlet, with flow rate V₁ whereas samples are taken from the transducer-side outlet, with flow rate V₄. Yellow rectangle indicates the area in which the particle trajectories are presented in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Table 2
Parameters of particles used in the simulation.

| Particle color | Diameter (μm) | STD of diameter | Number of particles | Density (kg/m³) |
|----------------|--------------|-----------------|---------------------|-----------------|
| Red            | 35           | 6.36            | 1756                | 998             |
| Cyan           | 50           | 6.34            | 602                 | 1000            |
| Orange         | 71           | 13.11           | 220                 | 1006            |
| Blue           | 99           | 13.11           | 200                 | 1002            |

3. Results and discussion

3.1. Frequency response of the prototype

First, the electrical admittance was measured in the range that covers the range of operation, that is \( f_0 = 1.9 \text{MHz} \) and \( \Delta f = 500 \text{kHz} \), in order to verify the calculations prior to the lab experiments. The electrical admittance of the prototype is given in Fig. 3a. In the electrical admittance plot, every peak corresponds to a resonance frequency of the system. Notice that the resonances in the sweep period have sharp peaks indicating high Q factors. At higher frequencies more pressure nodes in the system are generated, as the number of nodes is given by \( N_{\text{node}} = \frac{2h}{\lambda} \), where \( h \) is the distance between the transducer and the reflector. \( f_r \) is the corresponding resonant frequency and the right-hand side of the equation is rounded down to the closest integer. A small frequency range and low number of nodes may generate a nodal pattern that cannot be contracted fast enough to carry a captured particle to the desired outlet. Based on the ratio of the given start and end frequency, every point in the nodal pattern is approximately 20% closer to the reflector at the end of the sweep period, due to the contraction illustrated in Fig. 1b.

In addition to the admittance measurement, the pressure induced by the transducer was also calculated by measuring the vibrations on the transducer surface (Fig. 3b). Assuming the transducer is only vibrating longitudinally in the thickness direction, the surface velocity of the transducer was measured by a Polytec OFV-5000 single-point laser vibrometer. For this measurement it is implicitly assumed that at the water-transducer interface the water and transducer have the same velocity. Hence, by multiplying the measured velocity with the specific acoustic impedance of water the pressure was calculated. The velocity measurements were carried out for different sweep periods. The corresponding pressure amplitudes for \( T = 5 \text{s} \) are illustrated in Fig. 3b.

Fig. 3a indicates that during the sweep period there were at least 15 new nodes introduced to the standing wave pattern. Pressure values were calculated by taking the average of 10 recordings for each sweep period and multiplying the velocity with the specific acoustic impedance. Calculated pressure values were used in simulations with different sweep periods. The average pressures are 58kPa, 57kPa and 49kPa for 3s, 5s and 7s of sweep periods, respectively.

3.2. Computer simulations

Eq. (2) is a second-order non-linear differential equation that describes the particle motion in a frequency-sweep type dynamic acoustic field. COMSOL Multiphysics was used to calculate the particle trajectories in the prototype. First, the steady state flow field was computed using laminar flow physics. Subsequently, a non-stationary simulation study was carried out in order to calculate particle trajectories for the given laminar flow pattern. For this simulation study, the ideal acoustic pressure field given by Eq. (1), using the average pressure amplitude 55kPa for all sweep periods, was input as a plane wave field and the corresponding acoustic radiation force was calculated by COMSOL.

Fig. 4 illustrates the simulation results for \( V_1 = 300 \text{ml/h} \), \( V_4 = 400 \text{ml/h} \) and \( T = 5 \text{s} \). In order to improve visibility, the number of

![Fig. 3. (a) Electrical admittance of the transducer in the prototype, when the prototype is filled with the mixture. (b) Acoustic pressure induced to the medium by the transducer when excited with 20\( V_{pp} \), for \( T = 5 \text{s} \).](image-url)
particles were reduced to 10% of values given in Table 2.

Fig. 4 indicates that since the flow rate is higher in the reflector-side (bottom) inlet and the transducer-side (top) outlet the streamlines are carrying the particles towards the transducer-side outlet. If the flow rates are all equal at each inlet and outlet, the streamlines in the region of the acoustic field will be horizontal in Fig. 4 and parallel to the pressure nodes, thus the flow does not result in a drag force against the acoustic field. When the flow rates are unequal, with $V_3 > V_4$, the streamlines are always bent towards the transducer-side outlet. The acoustic field, however, pushes particles towards the reflector-side. Hence, in contrast to the case with parallel streamlines where the drag force from the fluid is perpendicular to the acoustic force, the drag force from the fluid flow has a component opposite to the acoustic force. Depending on the position where the particle enters the acoustic field, a small particle in the middle of the channel may not be captured by the nodal pattern but still be affected enough to exit from the reflector-side outlet. Consequently, such a particle potentially exiting from the reflector-side outlet may be pushed to the transducer-side outlet with the help of the additional drag force from the streamlines.

In the example given in Fig. 4, all of the blue (largest) particles (see Table 2) are pushed to the reflector-side outlet. Most of the orange particles and few cyan particles are pushed toward the reflector-side outlet. Red (smallest) particles, on the other hand, all exit from the transducer-side outlet. Particle position data from the simulations in COMSOL was extracted in order to analyze the particle size distribution in the transducer-side outlet and the reflector-side outlet (see Supplementary Material S1 for the initial position and size information). Particle size distributions in terms of total particle volume were calculated with MATLAB and illustrated in Fig. 5. Results presented in Fig. 5 are based on the full number of particles given in Table 2.

In Fig. 5, there is an overlap between the particle size distributions from the transducer-side and reflector-side outlets, indicating that there is not a single cut-off diameter for a clear separation between the two outlets. The interplay between the drag force from the fluid flow and the acoustic forces pushed larger particles towards the reflector-side outlet. In the transducer-side outlet (Fig. 5b) 90% of the particles were smaller than 87 μm whereas the largest particle exited from that outlet was 98 μm in diameter. For the reflector-side outlet 90% of the particles were larger than 88 μm and the smallest particle pushed to that outlet was 83 μm in diameter.

3.3. Effects of flow and sweep period on filtration

In order to explore the effect of the combinations of flow rates and sweep period, a DOE study was carried out using Minitab 14. Simulations without acoustic field were done to check the effect of the flow field only. These simulations did not show any separation, i.e. all particles exited from the transducer-side outlet. The effect of combinations of flow rates and sweep period on the selective separation performance were evaluated based on three metrics, which are (i) the diameter of the largest particle from the transducer-side outlet, indicated as threshold; (ii) $d_{90,T}$, the diameter at which 90% of the particles ends up in the transducer-side outlet; (iii) $d_{10,R}$, the diameter at which 10% of the particles ends up in the reflector-side outlet. Fig. 6 presents the effects of the flow and sweep period on the three metrics, using the average pressure amplitude of 55 kPa for all sweep periods.

Fig. 6a–c show more or less linear relationships between the three metrics and the three factors, $V_1$, $V_4$ and $T$. Fig. 6d shows that the flow threshold and $d_{90,T}$ are affected most by $T$ and to a lesser extent by $V_4$, whereas $d_{10,R}$ is more or less equally affected by the flow rates and sweep period. The combined effects, based on the coefficients in the regression equation which multiplies the product of factors, are all relatively small.

Unequal outlet flows affect particles close to the outlets as indicated in Fig. 4b, thereby, and forced by the streamlines, giving the acoustic

![Fig. 5](image-url)
3.4. Lab-experiments

According to the computer simulations it is possible to manipulate the particle size distribution from the transducer outlet by a combination of sweep rate and flow parameters. In order to determine and confirm such possibilities, lab experiments with polyethylene particles were carried out using the prototype given in Fig. 2. As in the numerical experiments, the particle mixture was fed from the transducer-side inlet and samples were taken from the transducer-side outlet. As in the computer simulations, experiments with only flow manipulation did not result in any separation. Fig. 7 displays the experimentally obtained trajectories of particles, as a result of both acoustic and flow fields. Fig. 7 confirms that the particles are size-selectively following the nodal movement. Trajectories of the particles clearly display the slope.

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![Fig. 6 Effects of the flow parameters V₁ (squares, black line), V₄ (circles, dashed line), T (triangles, dotted line), after averaging the effect of the other factors, on the threshold (a), d₉₀₋ (b) and d₁₀₀ (c) based on computer simulations. Bottom-right panel (d) shows the standardized effects chart based on all 27 simulations, for confidence level of 95% for threshold (squares, black line), d₉₀₋ (circles, dashed line), and d₁₀₀ (triangles, dotted line).](image)

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![Fig. 7. Particle trajectories recorded in the experiments. The transducer is on the top side of the image. The flow is from left to right whereas the acoustic field pushes the particles downwards. V₁ = 300mLh⁻¹, V₄ = 400mLh⁻¹ and T = 5s. Smaller (red, cyan) particles are in general unable to follow the nodal pattern (a), whereas larger (orange, blue) particles are moving downwards with the nodal pattern (b). The images were created by overlaying 300 consecutive pictures taken in a span of 10s.](image)

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difference. Smaller particles, with red and cyan color, are mostly following the streamlines of the flow. The nodal velocity is depending on time and position (Eq. (3)), where for positions further away from the transducer the velocity is lower, as x becomes smaller. As seen in the left bottom corner of Fig. 7a, small (red and cyan) particles, which escaped from the dominant flow towards the transducer-side outlet, have a steeper downward slope of their trajectory than the small particles close to the transducer. As the nodal velocity is higher in the regions close to the transducer, although affected by the acoustic field, small particles were not captured and carried by the nodes. In the regions further away from the transducer, however, the nodal speed becomes lower and the acoustic field moves slow enough to carry these small particles. Consequently, near the transducer the small particles experience the effect of the acoustic field, leading to an increasing downward slope of their trajectories as they get further away from the transducer. Furthermore, in Fig. 7b, large blue particles captured by the field have steeper slope in the regions close to the transducer, as the velocity of the nodal pattern with the trapped (large) particles is highest here. In the regions close to the transducer, however, there are still some large particles unable to follow the nodal pattern. Hence, whether a particle is trapped or not is not only determined by the flow, excitation and size parameters. The location of the particle when entering the acoustic field also affects the particle movement. For example, a large particle close to the transducer and not captured by the nodal movement, as a result of irregularities in the acoustic field, can still follow the streamlines and exit from the transducer-side outlet, whereas a small particle away from the transducer can follow the nodal pattern and exit from the reflector-side outlet. This results in an overlap between the particle size distributions from both outlets, as indicated in Fig. 5.

Fig. 8 displays the particle size distributions from the transducer-side outlet for different combinations of flow and sweep periods.

The particle mixture used in the experiment was contained in multiple bottles. Even though for each input the particle size distribution is not exactly the same, all input mixtures contained particles sizes in the full range of \(10^{-3} - 120 \mu m\). Fig. 8 confirms the trends indicated by Fig. 6a-c, where for unequal flow rates the threshold decreases from \(T = 3s\) to \(T = 5s\). For the case with equal flow rates, the thresholds were \(103\mu m\) and \(94\mu m\) for \(T = 3s\) and \(T = 5s\), respectively. For the case with unequal flow rate, the thresholds were \(82\mu m\) and \(74\mu m\). The thresholds obtained in the experiments were lower than the thresholds estimated by the simulations. In the simulations, the pressure field was assumed to be a perfect plane wave in the vertical direction, as indicated by Eq. (1). The pressure amplitude in the simulations was \(55kPa\) for all simulations, whereas in the experiments the pressure generated by the transducer is a function of frequency (Fig. 3b) and therefore not constant. The experiments suggest that the actual pressure field generated by the transducer has a stronger effect on particles than the constant peak amplitude field used in the simulations. Nevertheless, experiments confirm that the threshold values can be tuned by the flow and sweep time parameters, enabling selective filtration from the transducer outlet.

3.4.1. Wheat beer experiment

Another experiment, that aimed to further investigate the previous findings using hard model particles, was carried out with wheat beer, containing yeast particles (soft matter) with unknown properties. The prototype has shorter entrance length due to the lower flow rate used. Normally the beer contains bubbles and the bubbles disrupt the acoustic field by creating discontinuities in the medium as well as improving the likelihood of cavitation. Hence, before the start of the experiment the beer was degassed using a vacuum pump. In this experiment, the excitation frequency was swept from 1.9MHz to 2.3MHz. Voltage applied to the transducer was \(20V_{pp}\) while the flow rate was set to \(100\text{mLh}^{-1}\) in total, equal at both inlets and outlets. Sweep periods were set to \(T = 8s\) and \(T = 10s\). Samples were taken from the transducer side outlet. Particle size distributions for each case is given in Fig. 9.

![Fig. 8](image)

Fig. 8. Experimentally obtained particle size distributions of samples from transducer-side outlet with \(T = 3s\) (a) and \(T = 5s\) (b). Black squares connected by black dotted lines and black circles connected by black lines indicate the cumulative percentage of particle sizes for equal and unequal flow rates, respectively. Blue dotted and solid lines give the cumulative percentage of particle sizes for equal and unequal flow rates cases, respectively. Equal flow rates correspond to \(V_1 = V_2 = 500\text{mLh}^{-1}\) whereas unequal flow rates correspond to \(V_1 = 300\text{mLh}^{-1}\) and \(V_4 = 400\text{mLh}^{-1}\). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

![Fig. 9](image)

Fig. 9. Particle size distribution of wheat beer before and after the application. Squares connected by the solid line represents the particle size distribution of the input mixture. Circles connected by the dashed line and triangles connected by the dash-dot line represent the particle size distribution for \(T = 8s\) and \(T = 10s\), respectively.

As the properties of the yeast cells are unknown, we chose a lower flow rate with higher residence time in the separator than in the previous experiments. Together with longer sweep periods the nodes move slower, according to Eq. (3). Such adjustments to the flow and excitation ensured that the yeast cells were trapped. The beer initially contained...
yeast cells up to 21 μm in diameter. After passing through the separator while T = 8s, the sample from the transducer outlet contained yeast cells up to 14 μm in diameter. Similarly, for T = 10s maximum particle size in the transducer outlet was 11 μm.

4. Conclusions

This study explored selective filtering on centimeter scale by frequency sweep excitation and regulation of flow rates. The interplay of the forces on a particle, that is acoustic force and drag force, creates possibilities for selective filtering. A DOE study of computer simulations demonstrated that the filtration threshold can be manipulated by adjusting the inlet and outlet flow rates and the sweep period. The filtration threshold is mainly affected by the outlet flow conditions and the sweep period, as the effects of inlet flow conditions can be countered by the acoustic force. Experiments with a mixture of model polyethylene particles confirmed the tunability of the filtering threshold with a total flow rate of 1 L h⁻¹.

A lab experiment with wheat beer confirmed the applicability of the method on soft matter with smaller particle sizes and using a lower flow rate.

The numerical and lab experiments in this explorative study confirmed the selective filtration capability of dynamic acoustic fields with regulated flows on centimeter scale, and open up possibilities for future optimization studies of the X-shaped separator.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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