

# Numerical Investigation of a 100-Cavity Acoustofluidic Platform for Parallelized Acoustic Trapping

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## Abstract

We developed a coupled COMSOL Multiphysics® 6.3 model of a glass chip comprising a  $10 \times 10$  network of spherical cavities embedded in a microfluidic network and driven by a bonded Pz26 piezoelectric transducer for parallelized acoustic trapping. Under a 15 V excitation, the forced electrical, structural, and acoustic responses were calculated over the range from 1.75 to 2.00 MHz. The simulations produced structured acoustic fields across the array and recurring frequency-dependent cavity pressure configurations. Precomputed fields were sequentially applied to simulated 15  $\mu\text{m}$  particles in a representative cavity. Switching caused temporary redistribution, but cumulative motion produced a compact central cluster by 0.12 s. During perfusion at  $0.08 \mu\text{L min}^{-1}$ , the shear rate generated at cavities is less than  $0.016 \text{ s}^{-1}$ . In the thermal study, the mean temperature at two monitoring points in the two cavities nearest to the PZT reached 416.8 K after 30 min without cooling and 311.4 K with an effective convective boundary. The maximum temperature of the device without cooling and with cooling condition were approximately 439 K and 312 K, respectively. The results support the feasibility of particle trapping in the proposed microfluidic device with appropriate thermal management.

**Keywords:** acoustofluidics; acoustic radiation force; piezoelectric transducer; particle trapping; thermal management

## Introduction

Acoustic manipulation is an attractive label-free, contactless method for continuous levitation of cells and microparticles in microfluidic systems for microscopic observations. Acoustic forces are suited for cell manipulation, microscopic analysis, studies of cell-cell interactions, and three-dimensional cell culture [1]. In cavity-based acoustofluidic systems, cells or particles can be concentrated within defined observation volumes, while the connected fluidic network can be used for sample loading, medium exchange, and assays [2]. These features enable cell-probing workflows that integrate with microscopy and other methods.

Many acoustic manipulation platforms operate with a single trapping region, while few parallel multi-well implementations have been reported for high-throughput cell and spheroid studies [3]. The CellLEGO acoustofluidic platform allows for scalable arrays and here we report a  $10 \times 10$  array of spherical trapping cavities operated in parallel [4][5]. The layout of the array mimics a conventional multi-well platform, but the cavities connect to form a continuous microfluidic network to maintain sterile cell culture conditions. Scaling from a small number of cavities to one hundred introduces a device-level challenge. A single piezoelectric transducer (PZT) must sufficiently excite the glass to produce usable acoustic fields throughout the array while

maintaining the thermal stability and low shear rate distribution to enable long-term experiment.

In a mechanically coupled transducer-glass-fluid system, varying the excitation frequency changes both the magnitude of the pressure response and the spatial pressure distribution within individual cavities [6]. The position and predominant orientation of pressure nodal surfaces can therefore be manipulated with frequency changing. By sequentially applying complementary pressure configurations, particle-migration components can be generated in different spatial directions, thereby achieving three-dimensional trapping with accurate and drift-free localization of trapped objects attractive for continuous microscopy.

In this work, we report a three-dimensional COMSOL Multiphysics® model of a 100-cavity acoustofluidic platform. The model coupled piezoelectric excitation, structural deformation of the bonded PZT-glass assembly, and frequency-domain acoustics to evaluate pressure-field formation across the complete cavity network. We then analyzed the frequency-dependent cavity responses in terms of characteristic nodal-surface configurations and used a simplified frequency sweep model to investigate particle trapping in a representative cavity. Stationary perfusion and heat transfer were evaluated to assess the hydrodynamic and thermal operating conditions [7]. These simulations provide a numerical basis for designing

and experimentally implementing a parallel acoustofluidic trapping platform.

## Theory and Governing Physics

### Piezoelectric and structural excitation

An electric potential applied across the PZT produces a bulk electric field. Piezoelectric coupling converts this field into strain, causing the disk to vibrate at the drive frequency. The adhesive with relatively matched acoustic impedance transmits the resonant vibration to the glass chip, where elastic deformation distributes the excitation across the chip. In linear stress-charge form, the constitutive relations are

$$S = s^E T + d^T E \quad (1)$$

$$D = dT + \epsilon^T E \quad (2)$$

The strain and stress are denoted by  $S$  and  $T$ , while  $E$  and  $D$  denote the electric field and the electric displacement, respectively. Under the imposed constraint, the following quantities, which are elastic compliance, piezoelectric coupling, and permittivity, are denoted by  $s^E$ ,  $d$ , and  $\epsilon^T$ , respectively. As a result of the continuity conditions for displacement and traction at the bonded interfaces, the PZT is coupled to the glass chip, thereby exciting the fluid confined by the microfluidic glass boundaries [8].

### Forced acoustic response

At all fluid-solid interfaces, the glass surfaces couple with the fluid pressure. Structural acceleration drives the fluid at the surface, while the acoustic pressure exerts a load on the structure. In the case of a homogeneous fluid, expressed in the frequency domain, the complex total pressure,  $p_t$ , is such that

$$\nabla \cdot [(1/\rho)\nabla p_t] + \omega^2 p_t / (\rho c^2) = 0 \quad (3)$$

When  $\rho$  is the fluid density,  $c$  is the sound velocity, and  $\omega$  is the angular frequency of excitation. Each solution represents the system's response to an applied harmonic excitation. Changing the excitation frequency may affect the magnitude and distribution of the pressure.

### Acoustic radiation force and particle motion

The acoustic radiation force is calculated by COMSOL using the first-order pressure and velocity fields, along with the assigned particle and fluid properties. The force can be represented qualitatively as

$$F_{ARF} = -\nabla U \quad (4)$$

where  $U$  is an effective acoustic potential determined by the local field and the density and compressibility contrasts between the particle and fluid[9]. For the 15  $\mu\text{m}$  particles and short time scale considered here, particle inertia was neglected and viscous drag was represented using Stokes' law:

$$0 = F_{ARF} + 6\pi\mu a(u - v_p) \quad (5)$$

where  $\mu$  is the dynamic viscosity,  $a$  is the particle radius,  $u$  is the local fluid velocity, and  $v_p$  is the particle velocity [10].

### Flow and heat transport

Flow represents operating stages separate from the short particle-trapping calculation.

The stationary incompressible laminar flow followed

$$\rho(u \cdot \nabla)u = -\nabla p + \mu \nabla^2 u \quad (6)$$

$$\nabla \cdot u = 0 \quad (7)$$

The rate-of-deformation tensor was defined as

$$D = 1/2[\nabla u + (\nabla u)^T] \quad (8)$$

where  $D$  is the rate-of-deformation tensor.

In the present model, the thermal source term was derived from the calculated PZT losses, while the adhesive was included primarily as a mechanical and thermal coupling layer. Transient heat conduction was solved in the PZT, adhesive, glass, and fluid domains. The temperature field followed

$$\rho c_p \partial T / \partial t - \nabla \cdot (k \nabla T) = Q \quad (9)$$

where  $c_p$  and  $k$  are the heat capacity and thermal conductivity, and  $Q$  represents the sweep-averaged PZT loss. In the cooling scenario, the exposed boundary was assigned as

$$q = h_{air}(T - T_{ambient}) \quad (10)$$

where  $h_{air}$  is an effective convective heat transfer coefficient used to represent heat removal rather than a calibrated description of a particular fan, enclosure, or resolved airflow.

## Numerical Implementation in COMSOL Multiphysics

### Geometry and domains

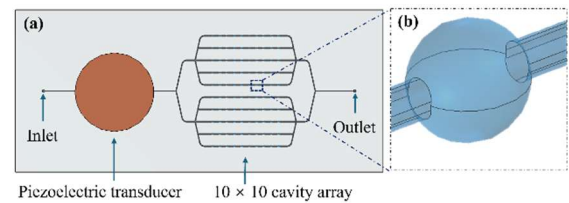


Figure 1. Device geometry of the 100-cavity acoustofluidic platform. (a) Whole-device structure. (b) Enlarged geometry of a representative spherical cavity with in- and outlet channel.

The three-dimensional model comprised a glass chip, a bonded circular Pz26 transducer, an adhesive layer, and a continuous water-filled microfluidic network. One hundred spherical cavities were arranged as a 10  $\times$  10 array and connected by narrow channels between an inlet and an outlet. The cavity diameter is approximately 530  $\mu\text{m}$ , the chip platform is 75  $\times$  33  $\times$  1.1 mm, and the cavity pitch is 1.5 mm horizontally and 2.5 mm vertically. The Pz26 disk is 16 mm in diameter and 1 mm thick. A 50  $\mu\text{m}$  cyanoacrylate layer represented the mechanical and

thermal contact between the PZT and glass. Figure 1 shows the layout and a representative spherical cavity used for the pressure and particle calculations.

### **Coupled frequency-domain study**

In the acoustofluidic setup, the applied electrical excitation generates deformation of the PZT, which is transferred to the glass through the adhesive layer. Then, the resonance created by the chip affects the water inside the cavities and connecting microfluidic channels. The acoustic response in a cavity depends not only on the trap geometry but also on its position relative to the structural response of the complete device.

Electrostatics defined the electric field in the PZT. Piezoelectricity and Solid Mechanics converted the electrical drive into harmonic displacement of the transducer, adhesive, and glass. The Acoustic-Structure Boundary transferred the normal acceleration of the wetted glass to Pressure Acoustics, Frequency Domain, and returned the pressure load to the structure. The fully coupled system was evaluated from 1.75 to 2.00 MHz in 0.025 MHz increments under a 15 V drive.

Frequency sweeps were primarily interpreted by the spatial organization of the acoustic field, considering the positions and orientations of pressure nodes, rather than by comparing peaks in the pressure field alone. Distribution of acoustic field is critical to the study because particle manipulation relies on the spatial force field generated in each cavity. Mechanical and dielectric losses were included in the PZT response using loss factors of approximately 0.001 and 0.003, respectively. The resulting dissipated power provided the input for the thermal calculation.

### **Particle tracing**

Eighteen particles were released from dispersed initial positions in a representative cavity. The cavity was selected because it exhibited complementary pressure configurations within a narrow frequency range, facilitating the design of a simplified switching strategy. It is possible to examine whether frequency switching alone could provide multi-directional trapping of particles without any changes to the transducer configuration or the introduction of additional actuators. It is evident that the cavity selected was a demonstration case for frequency-based trapping. Each particle had a diameter of 15  $\mu\text{m}$ , a density of 1050  $\text{kg m}^{-3}$ , and an effective speed of sound of 1580  $\text{m s}^{-1}$ . Water was the carrier fluid, its density and the speed of sound within it differ from those of the particles. The Particle Tracing for Fluid Flow interface included the acoustic radiation force and Stokes drag. Then, three frequencies were selected, such that the dominant nodal surfaces corresponding to these three frequencies were approximately orthogonal.

The precomputed fields at three frequencies were applied sequentially for approximately 16.67 ms each, producing a repeating 50 ms switching cycle. The background pump remained stopped. There was no effort to recreate a continuously sweeping frequency in the time domain for this sequence. Rather, the frequency domain solutions were used as precomputed quasi-steady states and applied sequentially to the particles. This approach reduces computational complexity while maintaining the desired effect of continuously varying the acoustic radiation force.

### **Flow, thermal study, and numerical scope**

Stationary laminar flow was solved for with an inlet rate of 0.08  $\mu\text{L min}^{-1}$ , a gauge pressure of 0 Pa at the outlet, and no-slip walls. The thermal analysis was initiated at 310.15 K using an average PZT heat input of 0.162 W. In the case of an effective convective cooling process, the surrounding temperature was considered as  $T_{\text{environment}} = 293.15 \text{ K}$ , and the heat transfer coefficient for the surrounding air as  $h_{\text{air}} = 35 \text{ W m}^{-2} \text{ K}^{-1}$ .

Particle trapping, perfusion, and thermal analyses were treated as separate numerical steps corresponding to different operating conditions of the device. In the case of particle trapping, the fluid flow was turned off so that particle motion was controlled mainly by acoustic fields and viscous forces. Stationary flow analysis was then used to characterize the hydrodynamic field conditions during medium perfusion after trapping. Likewise, thermal analysis was used to investigate temperature buildup over a considerably longer period than particle tracing analysis.

## **Results and Discussion**

### **Coupled electromechanical and array-scale acoustic response**

At a frequency of 1.75 MHz, the magnitude of the electric field across the active PZT disk varied (Figure 2a). The displacement field propagated from the PZT to the glass chip, indicating that the resonant vibration was mechanically transferred from the harmonic source (Figure 2b).

The pressure fields within the cavities and channels across the entire array are shown in Figure 2c. The acoustic pressure field illustrated the harmonic pressure pattern in the fluid domains at that phase. Acoustic waves produced by the vibration of the glass boundaries propagate into the cavities and channels, forming a standing-wave-like distribution due to interference and reflection in these regions. Red and blue regions represent opposite acoustic pressure signs at the displayed phase and are separated by regions where the pressure approaches zero. Since the field is harmonic, the pressure sign reverses after half an acoustic period. Therefore, the

red and blue regions will change with time, whereas the spatial organization of the pressure field and the associated nodal surfaces remain characteristic of the solution at a given excitation frequency. Thus, the red/blue distinction is not a static pressure difference but a representation of a phase-dependent pressure distribution.

Despite their identical nominal geometry, the cavities exhibited different local pressure amplitudes and configurations because they occupied different positions within the distributed structural response of the chip. The distributed response across the array, therefore, motivated the subsequent frequency-dependent analysis of individual cavity configurations.

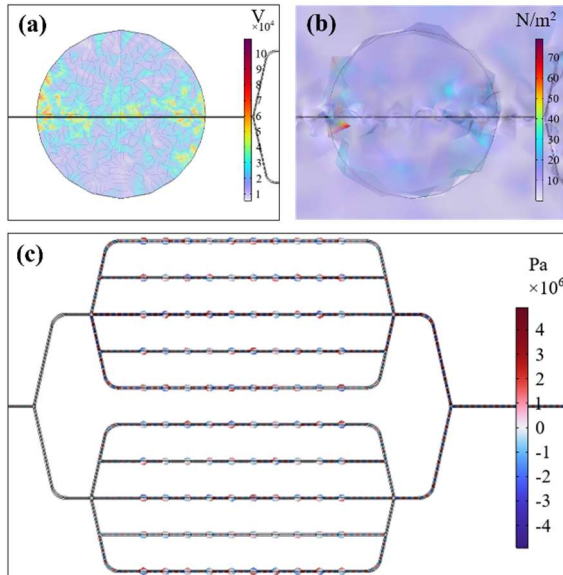


Figure 2. Coupled electromechanical and acoustic response at 1.75 MHz. (a) Electric-field magnitude in the PZT. (b) Displacement magnitude in the PZT and adjacent glass structure. (c) Total acoustic pressure distribution across the 100-cavity array.

### Frequency-dependent cavity response configurations

Figure 3a shows the acoustic field from 1.750 to 1.850 MHz in 0.025 MHz increments. Positive- and negative-pressure regions moved among cavities and reorganized within individual cavities over this range. The changes involved both spatial configuration and amplitude: a change in frequency could also shift the zero-pressure region, rotate the dominant division between pressure signs, or produce a more mixed pattern. The comparison focuses on spatial organization and pressure signs. Recurring cavity patterns were grouped into three categories according to the dominant pressure nodal surface (Figure 3b). In an XY-type response, pressure varies mainly across  $z$ . In a YZ-type response, it varies mainly across  $x$ . And in an XZ-

type response, it varies mainly across  $y$ . The categories describe characteristic forced responses observed in the sweep. Some cavities showed tilted, distorted, or mixed forms, particularly where the chip structural field perturbed the local symmetry. These complementary configurations provide distinct spatial directions for particle trapping and were therefore selected for the particle-trapping analysis described below.

It is important to note that the three classifications described above do not correspond to the ideal cavities' modes of analysis. These categories serve only as a descriptive approach to reveal the orientation of the zero-pressure region in the forced resonant response. In contrast to the isolated ideal spherical cavity, the full PZT-glass-fluid system lacks symmetry, and thus tilted and mixed cavity types can be expected when the cavity response is disturbed by vibrations of the surrounding glass as well as by coupling with the channels.

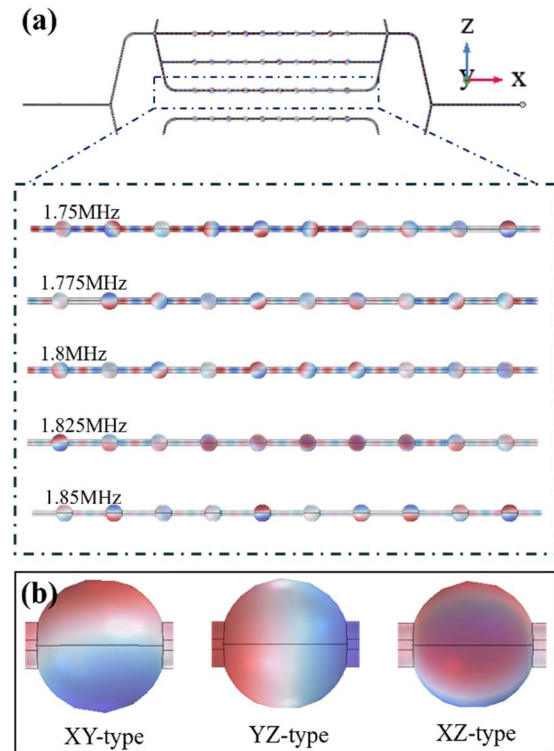


Figure 3. Frequency dependence of the acoustic field and characteristic cavity-scale response configurations. (a) Evolution of the total acoustic pressure distribution across the 100-cavity array with excitation frequency. (b) Three characteristic cavity-scale configurations classified by the predominant orientation of the pressure nodal surface.

The significance of these frequency-dependent configurations lies in their effect on the acoustic potential experienced by the particles. Such behavior explains why several operating frequencies are chosen rather than just one. The field with a single

dominant orientation of the nodal surface is characterized by a good trapping environment for this surface, but not necessarily by restoring components in all directions.

### Particle trapping

Based on the complementary nodal-surface orientations identified above, pressure fields of 1.800, 1.825, and 1.850 MHz were selected and applied to the representative cavity. Sequential application of these acoustic fields redirected the particles along complementary paths as shown in Figure 4. By 0.04 s, the initial distribution had contracted and developed an intermediate alignment. By 0.08 s, the particles had contracted into a small central region, although minor rearrangement continued during subsequent switching. By 0.12 s, the particles had formed a compact cluster near the cavity center.

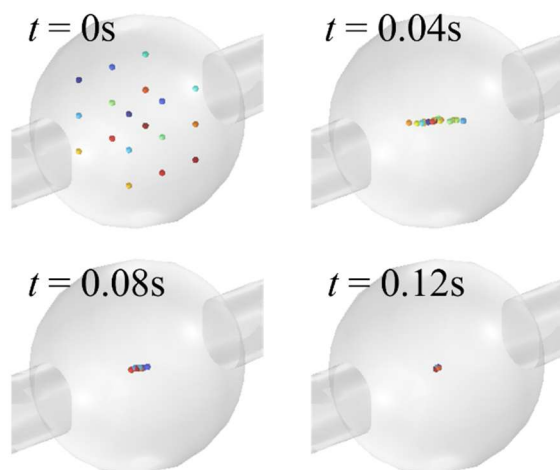


Figure 4. Simulated particle trapping under sequential frequency-programmed acoustic fields. Particle positions are shown at 0, 0.04, 0.08, and 0.12 s.

Changing frequencies led to the emergence of a new force field, which was different from the previous one due to its orientation, allowing the particles which approached one nodal region to temporarily be redistributed in another region. The relevant behavior is the cumulative response over repeated switching cycles. In the present simulation, the spatial distribution area of the particles cluster became smaller with each rearrangement.

It should be noted that the mechanism of trapping performed in the representative cavity does not depend on specific local acoustic behavior. Cavities may not have the same pattern of behavior for a certain excitation frequency since their local behavior depends on their locations within the vibrating chip. However, a range of different acoustic patterns will be generated for every cavity

when sweeping the excitation frequency. The array-scale frequency-domain results indicate that all cavities should encounter pressure configurations capable of providing particle trapping during the sweep. The representative-cavity calculation should therefore be regarded as a demonstration of the trapping mechanism, while the full-array sweep supports its broader applicability across the cavity network.

### Perfusion and shear rate

Perfusion was evaluated after acoustic trapping at an inlet rate of  $0.08 \mu\text{L min}^{-1}$ . The shear-rate map showed that the highest gradients occurred along the channel preceding the primary and secondary junctions, with values of  $0.508$  and  $0.211 \text{ s}^{-1}$ , respectively (Figure 5). Within the cavity-array region, the shear rate ranged from approximately  $0.006$  to  $0.016 \text{ s}^{-1}$ , substantially below the gradients in the channels. The network supported perfusion while keeping the largest hydrodynamic gradients away from most of the cavity interior.

Shear rate spatial distribution depends on the spacing between the narrow channels and the large trapping cavities. High velocity gradients occur in regions of constriction due to the geometry of the channels as well as at network junctions, whereas expansion into cavities reduces the local gradients. It is important to note that this aspect is relevant to the operating sequence intended to be used, which involves high-speed loading and acoustic trapping followed by perfusion with a low flow rate for medium exchange. The present flow calculation therefore characterizes the hydrodynamic environment associated with post-trapping medium exchange rather than establishing a biological shear threshold.

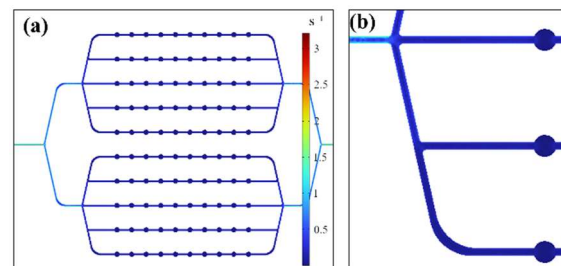


Figure 5 (a) Shear-rate distribution during post-trapping perfusion at  $0.08 \mu\text{L min}^{-1}$ . (b) Enlarged shear-rate distribution in a representative cavity region.

### Thermal management

Figure 6a shows the mean temperature at two monitoring points located in the two cavities nearest the PZT, in rows 5 and 6 of the first column. The monitored points started at  $310.15 \text{ K}$ . Without cooling, their mean temperature rose throughout the 30 min calculation, reaching  $360.73 \text{ K}$  at 15 min and

416.76 K at 30 min. With effective convective cooling, the corresponding mean values were 311.15 K at 15 min and 311.40 K at 30 min. The cooled response approached a stable trend, whereas the uncooled temperature continued to rise over the modeled duration.

The 30 min spatial fields provided a complementary device measure. Without cooling, the maximum temperature reached approximately 439 K at the center of the PZT (Figure 6b). With effective cooling, the field remained close to the initial operating temperature, and the device maximum was approximately 312 K (Figure 6c).

Based on the simulated dissipated power of 0.162 W, the resulting temperatures were above the acceptable range for cellular culture setup. These results indicate that external heat removal is required to maintain temperatures compatible with experiment.

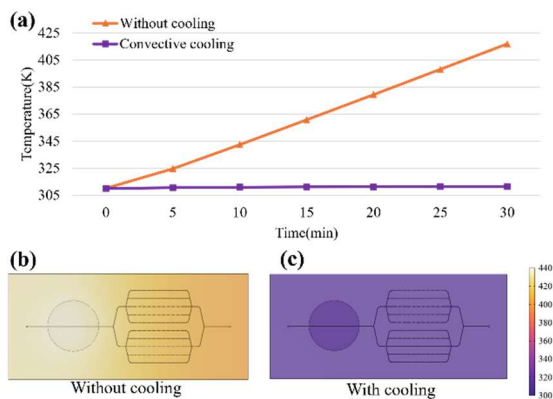


Figure 6. (a) Mean temperature of two monitoring points located in the cavities nearest the PZT. (b) Temperature distribution after 30 min without cooling. (c) Temperature distribution after 30 min with cooling.

The thermal response acts on a larger time scale compared to the numerical acoustic trapping simulation. Contraction of particles takes place after 0.12 s, while thermal accumulation developed over minutes. Hence, transient heat transfer does not seem likely to play a dominant role during the numerical trapping experiment, but it becomes critical in case of prolonged device operation, especially when the platform is used for long-term cell cultures.

It should be emphasized that the cooling process is just an abstract way to describe heat dissipation, and not the simulation of a particular cooling mechanism. The chosen convection coefficient describes heat energy dissipation from the device perimeter. A clear difference between cooled and non-cooled solutions indicates that the heat management process cannot be overlooked if the losses due to electromechanical effects of PZT are accounted in the device model.

## 5. Conclusions

This study established a coupled numerical framework for the proposed 100-cavity acoustofluidic structure. The bonded Pz26-glass structure transformed the applied 15 V excitation voltage into resonant mechanical response and produced acoustic waves in the fluid network. Changing the frequency altered the cavity-scale pressure configuration rather than only its magnitude. Sequential application of three precomputed fields contracted an initially dispersed particle cloud despite transient redistribution, and a compact central cluster formed by 0.12 s in the representative-cavity calculation. During perfusion, the larger shear-rate gradients occurred in channels preceding junctions rather than in the cavity interiors. Effective cooling strongly suppressed the thermal accumulation observed in the uncooled case. The findings further indicate that parallel operation is not dependent on similar cavity responses to the same frequency. It is actually the use of varying frequencies that helps to access complementary local pressure configurations. The particle-tracing result shows how these different complementary pressure configurations can be exploited for creating multidirectional trapping, and the entire array scan demonstrates that the above statement holds true not only for the chosen cavity but also for the whole array. These results support the numerical feasibility of trapping in the proposed structure and provide a basis for device fabrication, further numerical refinement, and experimental validation, and also broaden the scope for the development of acoustic devices intended for biomedical research.

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