DEPARTMENT OF MECHANICAL ENGINEERING
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Synopsis Of

Acoustic Forces Acting on Inhomogeneous Fluids: Theory and Applications

A Thesis

To be submitted by

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For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

The primary focus is to provide a theoretical framework and clear understanding of the underlying principles and mechanisms governing the behavior of inhomogeneous fluids under acoustic fields, enabling their effective utilization in heat transfer and droplet manipulation applications. Initially, a unified theory is developed to elucidate the phenomena of acoustic relocation and streaming suppression in inhomogeneous fluids, as well as streaming in a homogeneous fluid. The assumptions on mean Eulerian pressure and consequent formulations of acoustic body forces have resulted in a lack of clarity among the scientific community and our developed theory addresses these ambiguities in the literature. Remarkably, our theory predicts that the acoustic relocation/stabilization of inhomogeneous fluids in a microchannel subjected to standing acoustic waves is possible only if there exists an impedance ($Z = \rho c$) gradient which agrees well with the recent experiments. Also, we successfully separate the streaming term and acoustic relocation term from the generalized acoustic body force thereby enhancing the understanding of the dynamics of the inhomogeneous fluids under acoustic fields. Followed by the theory, using linear stability analysis, we derive the characteristic equation that governs the stability of inhomogeneous fluids (with and without interfacial tension) under an acoustic body force. For fluids with interfacial tension, a non-dimensional number called the acoustic Bond number is obtained theoretically which characterizes the stable and unstable (relocation) regimes.

Followed by the above fundamental works, we exploit the behavior of inhomogeneous fluids under acoustic fields for two key applications.

a) Heat transfer in a minichannel using acoustic waves: When a fluid domain with a temperature gradient is subjected to ultrasonic standing waves, the acoustic body force induces a fluid motion which is shown to be responsible for this heat transfer. The study sheds light on the interplay between the temperature field and velocity field due to the acoustic forces. Remarkably, it is found that acoustic forces can enhance heat transfer up to 2.5 times compared to natural convection and up to 11.2 times compared to pure conduction when the acoustic waves are passed perpendicular to the direction of heat transfer. Suppression of natural convection heat transfer is observed when the acoustic waves are passed parallel to the direction of heat transfer. In this case, acoustic forces could bring down the heat transfer by half or more than half from the natural convection. In continuation to this work, we delve deeper by primarily investigating the effects of acoustic fields on flow patterns and heat transfer for different standing wave configurations (quarter-wave, half-wave, and full-wave) and different temperature boundary conditions in a minichannel. The results of our study suggest that heat transfer using acoustic waves could be a significant technique that can be used to enhance the heat transfer under microgravity environment.

b) Droplet handling using acoustic waves: We use our developed theory of inhomogeneous fluid under acoustic fields to study the behavior of droplets under acoustic fields. The proposed formulation is more comprehensive, resolves the shortcomings of the existing Gorkov formulation, and takes into consideration the effects of interfacial tension, allowing us to fully comprehend the droplet behavior such as droplet deformation under acoustic fields. We validate our theory using silicon-glass microchannel bulk acoustic wave (BAW) experiments. These experiments showcase the previously

unreported, novel technique of droplet deformation and restoration, along with droplet splitting under BAW. The findings of these studies provide fresh insights into droplet behavior and open up new ways of manipulating droplets under acoustic fields.

2 Introduction

When a homogeneous fluid is subjected to an acoustic field, a steady fluid motion is induced by the interaction of sound waves within the fluid medium. This phenomenon is called acoustic streaming. Acoustic streaming can be classified broadly into three types. The streaming that is generated at the bulk due to viscous stresses present in a thin region close to solid boundaries, is known as Boundary-driven streaming or Rayleigh streaming (Rayleigh (1884)). Whereas the steady fluid motion induced within the boundary layer, causing the fluid to move along the surface is referred to as Schlichting streaming (Schlichting (1932)) or inner streaming. On the other hand, Eckart streaming is the flow formed by the dissipation of acoustic energy into the bulk of a fluid also known as "bulk dissipation driven" streaming (Eckart (1948)).

When an acoustic field interacts with an inhomogeneity, it exerts acoustic radiation force on it. This inhomogeneity can manifest as a non-uniform or discontinuous variation of physical properties in the system, such as particles/cells suspended in the fluid, emulsions, co-flowing streams of miscible or immiscible fluids, or a fluid subjected to a temperature gradient. Following the work of Lord Rayleigh, L. V. King (1934) provided a rigorous theoretical treatment of the acoustic radiation force on spherical particles, elucidating the mathematical expressions governing the force exerted by sound waves on solid objects. Followed by this, Yosioka (1955) expanded the theoretical analysis, considering the effect of compressibility on spherical particles in a fluid medium. His work enhanced the understanding of the acoustic radiation force and its implications on particles with different material properties. Later, Gor'kov (1962) developed an elegant approach by formulating the acoustic radiation force as the gradient of a potential (now commonly referred to as the Gor'kov Potential) to replicate the results of Yosioka and Kawasima. The theoretical background of acoustic forces acting on fluids and particles is extensively studied in microscale flows, and this field is widely known as 'microscale acoustofluidics' Friend and Yeo (2011). Over the last two decades, acoustofluidics has found a wide range of applications in the area of biological (Petersson *et al.*, 2007; Wiklund, 2012; Lee *et al.*, 2015; Collins *et al.*, 2015; Ahmed *et al.*, 2016), medical (Augustsson *et al.*, 2012; Li *et al.*, 2015) and chemical sciences (Suslick *et al.*, 1999; **?**; Chen *et al.*, 2021).

Recently, the relocation and stabilization of inhomogeneous co-flowing fluid streams in microchannels have gained the attention of the research community which is evident through the following works. Through silicon-glass microchannel experiments, using standing bulk acoustic waves, Deshmukh *et al.* (2014) relocated high-impedance sodium chloride solution to the pressure node (center) and low-impedance water to the pressure anti-node (sides). Following this, using the hypothesis of mean Eulerian pressure, a theoretical framework that explains streaming suppression and relocation of inhomogeneous fluids was developed by Karlsen *et al.* (2016, 2018). Some notable applications using this technique of acoustic forces acting on co-flowing inhomogeneous fluids include sorting of submicron particles such as bacteria and nanoparticles using acoustofluidic systems (Gautam *et al.*, 2018; Van Assche *et al.*, 2020), tweezing and patterning of fluids (Karlsen and Bruus, 2017; Baudoin and Thomas, 2020), and on-demand stream to stream or stream to drop relocation of immiscible fluids (Hemachandran *et al.*, 2019, 2021).

Despite the significant progress made in understanding the physics of acoustic forces acting on inhomogeneous fluids and employing them for various applications, there still remain ambiguities in the theory and require clarification. In this work, we aim to address this problem by developing a comprehensive theory for nonlinear acoustic forces acting on inhomogeneous fluids by deriving it from first principles. The developed theory could explain the acoustic relocation and streaming suppression phenomena which agrees with the recent microchannel experiments. Following this, we delve deeper into the underlying principles to derive the characteristic equation that governs the stability of inhomogeneous fluid systems and establish the necessary and sufficient conditions for the relocation of both miscible and immiscible fluids under acoustic fields. Further, by employing the acoustic relocation phenomena of inhomogeneous fluids, we enhance heat transfer in a minichannel and predict the behavior of droplets. The insights gained from this study can have potential applications in inhomogeneous fluid handling, particle manipulation, handling of cells, droplets, or beads, and heat transfer in outer space environments in the field of acoustofluidics.

3 Objectives

The primary objective of the work is to develop a clear understanding on the dynamics of acoustic forces acting on inhomogeneous fluids and to exploit the acoustic forces on inhomogeneity for applications of heat transfer and droplet manipulation. This main objective can be subdivided as follows,

- To develop a unified theory of acoustic forces acting on inhomogeneous fluids from the first principles that elucidate the phenomena of acoustic relocation and streaming suppression in inhomogeneous (miscible and immiscible) fluids.
- To investigate the stability of inhomogeneous miscible and immiscible fluids under acoustic fields and derive the characteristic equations.
- To utilize the relocation phenomena of inhomogeneous fluids under acoustic fields in heat transfer applications.
- To study the effect of various parameters such as the direction of standing acoustic waves, thermal boundary conditions, and wave configurations on heat transfer in a minichannel under acoustic fields.
- To broaden the scope of the proposed theory of acoustic forces on inhomogeneous fluids to encompass the analysis of acoustofluidic droplet manipulation and validate it using experiments.
- To develop a bulk acoustic wave device for carrying out essential operations such as droplet deformation and splitting.

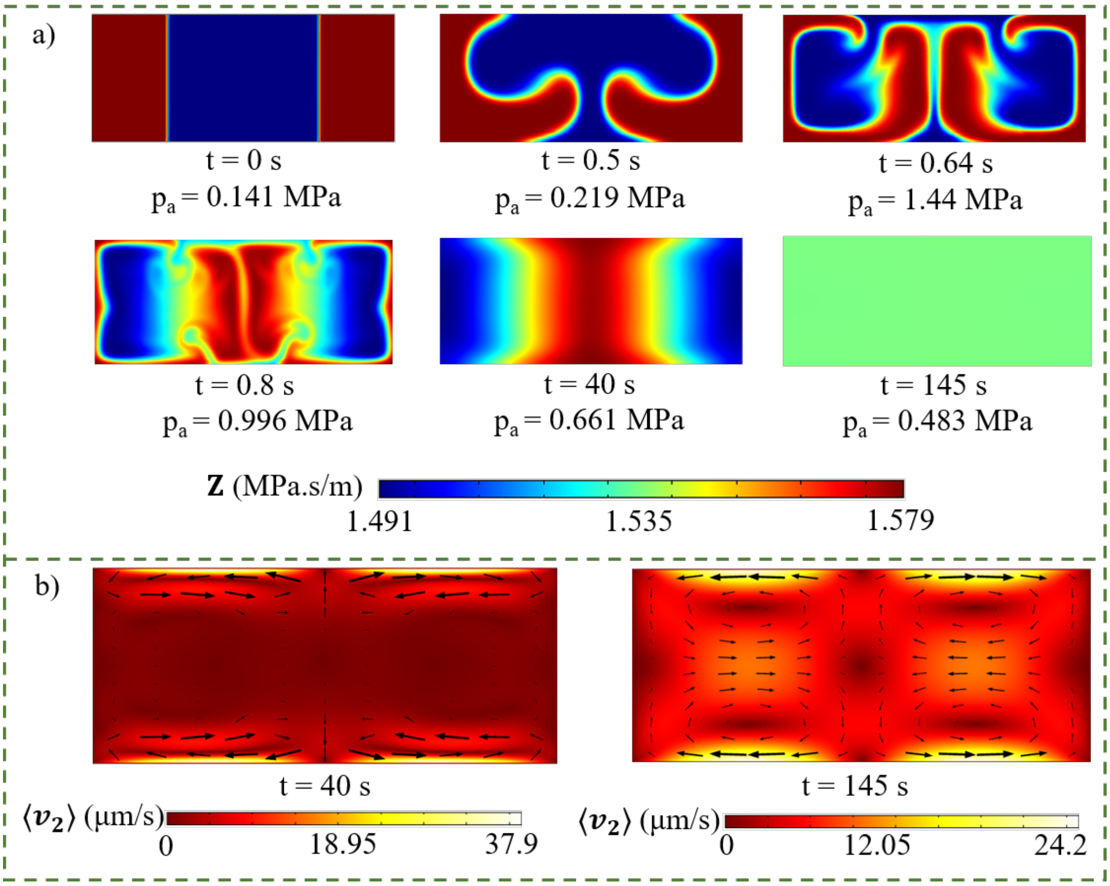


Figure 1: a) Relocation of unstable configuration to stable configuration with wall displacement $d = 0.261\ nm$ in x-direction and frequency $f_0 = 1.96\ MHz$. Initially $(t = 0s)$, low impedance DI Water (blue) at the center and high impedance 10% Ficoll PM70 (red) at the sides. The green image indicates homogeneous fluid profile after relocation and complete diffusion. b) second-order velocity $\langle \boldsymbol{v}_2 \rangle$.

4 Most Important Contributions

4.1 Theory of non-linear acoustic forces inhomogeneous fluids under acoustic fields

We have derived the following equations that govern the dynamics of inhomogeneous fluids under acoustic fields derived from the first principles,

$$\nabla \cdot \langle \boldsymbol{v}_2 \rangle = 0, \tag{1a}$$

$$-\nabla \cdot \langle \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 \rangle + \langle \rho_0 \boldsymbol{g} \rangle - \nabla \langle p_2 \rangle + \eta \nabla^2 \langle \boldsymbol{v}_2 \rangle = 0, \tag{1b}$$

$$\langle \partial_t s_0 \rangle + \langle \boldsymbol{v}_2 \cdot \nabla s_0 \rangle = D \nabla^2 \langle s_0 \rangle. \tag{1c}$$

Where g_0 are zeroth-order (background) fields, g_1 is first-order time-harmonic acoustic fields, g_2 are second-order fields, ρ is the density, $\boldsymbol{v}$ is the velocity, p is the pressure, s is the solute concentration and D is diffusivity and $\langle ... \rangle$ denotes time average over one oscillation period. The body force due to acoustic fields $\boldsymbol{f}_{ac}$ is found to be the divergence of Reynolds stress tensor consisting of the product of first-order fast acoustic fields that creates the second-order slow hydrodynamic flows,

$$\boldsymbol{f}_{ac} = -\nabla \cdot \langle \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 \rangle. \tag{2}$$

The numerical analysis of this study is carried out by employing the above equations in COMSOL Multiphysics 5.6. The following are the important results of this work,

(a) We found that the acoustic body force, $\boldsymbol{f}_{ac}$ is responsible for acoustic relocation and streaming suppression in inhomogeneous fluids as well as acoustic streaming in a homogeneous fluid. Remarkably, in the process of acoustic relocation and diffusion as shown in Fig. 1a, the amplitude of the first-order fields (p_a and v_a) vary significantly as the background ρ_0 and c_0 fields change in slow time-scale. Thus, the acoustic energy density E_{ac} which is a function of p_a, ρ_0, and c_0 also changes significantly (where $E_{ac} = p_a^2/(4\rho_{avg}c_{avg}^2)$).

(b) We showed that the impedance gradient is the prerequisite for the relocation of inhomogeneous fluids which agrees well with the numerical results.

(c) We have analytically separated the purely gradient term (the first term in Eq. (3), the term responsible for streaming (the second term in Eq. (3), and the term causing relocation (the last term in Eq. (3),

$$\boldsymbol{f}_{ac} = \frac{1}{2}\nabla(\kappa_0\langle|p_1|^2\rangle - \rho_0\langle|\boldsymbol{v}_1|^2\rangle) + \langle \boldsymbol{v}_1 \times \nabla \times (\rho_0 \boldsymbol{v}_1)\rangle \\ - \frac{1}{2}[\langle|p_1|^2\rangle\nabla\kappa_0 + \langle|\boldsymbol{v}_1|^2\rangle\nabla\rho_0]. \tag{3}$$

(d) For homogeneous fluid, the Eq. 3 reduces to (Friend and Yeo, 2011; **?**),

$$\boldsymbol{f}_{ac} = -\nabla \cdot \langle \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 \rangle = \frac{1}{2}\left(\kappa_0\nabla\langle|p_1|^2\rangle - \rho_0\nabla\langle|\boldsymbol{v}_1|^2\rangle\right) + \{\rho_0 \langle \boldsymbol{v}_1 \times (\nabla \times \boldsymbol{v}_1)\rangle\}. \tag{4}$$

where κ is the compressibility of the fluid.

(e) A simplified acoustic relocation term is developed which is a part of the generalized force equation (Eq. 2),

$$\boldsymbol{f}_{rl} = -E_{ac}\cos(2kx)\nabla\widetilde{Z}_0. \tag{5}$$

Where impedance $\widetilde{Z}_0 = \widetilde{\rho}_0\widetilde{c}_0$.

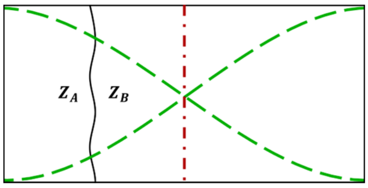
4.2 Stability of inhomogeneous fluids under acoustic fields

We have established the stability criterion for fluids of different acoustic impedances (product of density and speed of sound of the fluid) separated by a plane interface.

The following are the important results of this work,

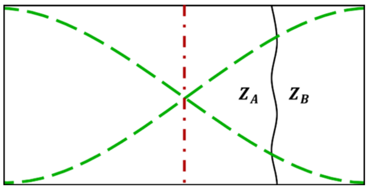
(a). acoustic stability with a single interface

(i)



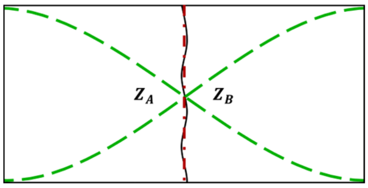
Condition	$sin(2k_wx_s)$	Z_B-Z_A	Fluids without interfacial tension		Fluids with interfacial tension	
			n	Nature of the system	n	Nature of the system
$Z_A < Z_B$	−	+	$\sqrt{-}$	Always Stable	$\sqrt{-}$	Always Stable
$Z_A > Z_B$	−	−	$\sqrt{+}$	Always Unstable	$\sqrt{-}$	Stable when $E_{ac} < E_{cr}$
					$\sqrt{+}$	Unstable when $E_{ac} > E_{cr}$

(ii)



Condition	$sin(2k_wx_s)$	Z_B-Z_A	Fluids without interfacial tension		Fluids with interfacial tension	
			n	Nature of the system	n	Nature of the system
$Z_A < Z_B$	+	+	$\sqrt{+}$	Always Unstable	$\sqrt{-}$	Stable when $E_{ac} < E_{cr}$
					$\sqrt{+}$	Unstable when $E_{ac} > E_{cr}$
$Z_A > Z_B$	+	−	$\sqrt{-}$	Always Stable	$\sqrt{-}$	Always Stable

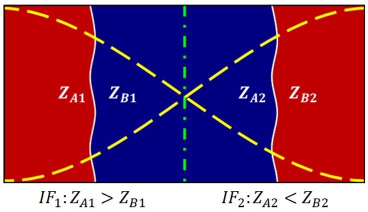
(iii)



Condition	$sin(2k_wx_s)$	Z_B-Z_A	Fluids without interfacial tension		Fluids with interfacial tension	
			n	Nature of the system	n	Nature of the system
$Z_A < Z_B$	0	+	0	Neutral Equilibrium	$\sqrt{-}$	Always Stable
$Z_A > Z_B$	0	−				

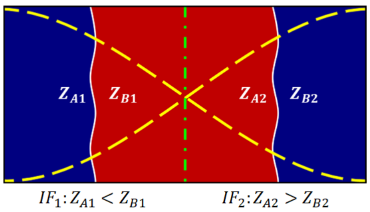
(b). acoustic stability with two interfaces

(i)



Condition	$sin(2k_wx_s)$	Z_B-Z_A	Fluids without interfacial tension		Fluids with interfacial tension	
			n	Nature of the system	n	Nature of the system
IF_1: $Z_{A1} > Z_{B1}$	−	−	$\sqrt{+}$	Always Unstable	$\sqrt{-}$	Stable when $E_{ac} < E_{cr}$
					$\sqrt{+}$	Unstable when $E_{ac} > E_{cr}$
IF_2: $Z_{A2} < Z_{B2}$	+	+	$\sqrt{+}$	Always Unstable	$\sqrt{-}$	Stable when $E_{ac} < E_{cr}$
					$\sqrt{+}$	Unstable when $E_{ac} > E_{cr}$

(ii)



Condition	$sin(2k_wx_s)$	Z_B-Z_A	Fluids without interfacial tension		Fluids with interfacial tension	
			n	Nature of the system	n	Nature of the system
IF_1: $Z_{A1} < Z_{B1}$	−	+	$\sqrt{-}$	Always Stable	$\sqrt{-}$	Always Stable
IF_2: $Z_{A2} > Z_{B2}$	+	−	$\sqrt{-}$	Always Stable	$\sqrt{-}$	Always Stable

High impedance fluid   Low impedance fluid

Figure 2: Different inhomogeneous fluid configurations commonly used in microfluidics and their equilibrium nature. a) Single interface configurations, and b) Double interface configurations. Equations (6) and (7) are used to calculate n for fluids without interfacial tension and with interfacial tension.

(a) Using linear stability analysis, we developed the characteristic equation n, governing the stability of fluids without surface tension,

$$n = \sqrt{\frac{k_y}{\rho_A + \rho_B} \psi E_{ac} (Z_B - Z_A) \sin(2k_w x_s)}. \tag{6}$$

where ρ_A and ρ_B, Z_A and Z_B indicate the densities and impedance of fluids A and B respectively, $k_w = 2\pi/\lambda_w$ denotes the wavenumber, λ_w denotes the wavelength (for standing half-wave, $\lambda_w = 2w$, where w is the width of the channel), k_y is the wavenumber considered along the y-direction, x_s is the location of interface, and $\psi = 2k_w/Z_{avg}$.

(b) The characteristic equation governing the stability of fluids with interfacial tension γ becomes,

$$n = \sqrt{\frac{k_y}{\rho_A + \rho_B} \left(\psi E_{ac} (Z_B - Z_A) \sin(2k_w x_s) - k_y^2 \gamma\right)}. \tag{7}$$

Figure. 2 shows the stable, unstable, and neutral configurations for fluids with and without interfacial tension obtained using equations (6) and (7).

(c) We showed that the stability of inhomogeneous fluid with interfacial tension is characterized using acoustic Bond number (Bo_a),

$$Bo_a = \frac{F_{rl}}{F_{int}} = \frac{\psi E_{ac} \Delta Z \sin\left(2k_w x_s\right)}{k_h^2 \gamma}. \tag{8}$$

where k_h is the wavenumber considered along the height of the channel. Figure. 3 shows the relocation and non-relocation regime for fluids with interfacial tension predicted using Eq. (8).

(d) The effect of the height of the channel in relocating immiscible fluids is realized. From Eq. (7), it is inferred that the critical acoustic energy density is inversely proportional to the square of the channel height ($E_{cr} \propto 1/h^2$). This inference will be helpful in designing acoustofluidic microchannels where the height of the channel is a crucial aspect to be considered for handling high interfacial tension fluids.

4.3 Heat transfer mechanism driven by acoustic body force under acoustic fields

A novel heat transfer mechanism based on the acoustic relocation phenomenon under acoustic fields is proposed in this work. The effect of acoustic forces on fluid flow and heat transfer is studied with and without the presence of gravity in water and ethanol as shown in Figs. 4 and 5 . The major contributions of this work include,

(a) Investigation of interplay between velocity and temperature fields under the influence of standing acoustic waves.

(b) Enhancement of heat transfer when standing waves are applied perpendicular to the direction of heat transfer. Acoustic forces (without gravity) enhanced heat transfer remarkably up to 11 times compared to the heat transfer due to only conduction. Along with gravity, acoustic force enhanced heat transfer up to 2.5 times compared to natural convection.

(c) Characterization of heat transfer enhancement using modified Rayleigh number

$$Ra_{ac} = -\frac{4E_{ac}h^3\Delta T}{w\eta\alpha}\left(\chi + \beta\right). \tag{9}$$

Where E_{ac} is the acoustic energy density, h is the height of the channel, w is the width of the channel, T is temperature, η is viscosity, α is thermal diffusivity, β is thermal expansion coefficient and χ is the coefficient of the speed of sound.

(d) Suppression of natural convection heat flux by more than half for ethanol and by half for water, when standing waves are parallel to the direction of heat transfer.

4.4 Heat transfer and flow patterns in a minichannel with various acoustic standing wave configurations and thermal boundary conditions.

The proposed heat transfer mechanism and the resulting flow patterns using acoustic body force are analyzed for water and ethanol for different wave configurations and thermal boundary conditions. The significant outcomes of this work are,

(a) From the numerical analysis, it is evident that the rate of heat transfer is highly dependent on the type of fluid used, the direction of the standing wave, the configuration of the standing wave, and the temperature boundary conditions. The resultant heat flux for quarter wave, half wave, and full wave for water and ethanol at different wave directions is found as shown in Fig. 6.

(b) The heat transfer enhancement is maximum for full-wave configuration when the direction of the standing acoustic wave and the direction of the temperature gradient are perpendicular to each other.

(c) The heat flux is minimum for quarter-wave configuration in ethanol and half-wave for water, when the direction of the standing acoustic wave and the direction of the temperature gradient are parallel to each other.

4.5 Theoretical and experimental investigation of droplet manipulation using bulk acoustic waves

By treating the droplets suspended in a continuous medium as an inhomogeneous fluid system, we explain the behavior of droplets under standing acoustic wave fields. The significant contribution of the work includes,

(a) The theory of inhomogeneous fluid discussed in § 4.1 is demonstrated to govern the behavior of droplets beyond the Rayleigh limit.

(b) The theory could well explain various droplet phenomena such as droplet migration, deformation, and splitting under standing acoustic wave fields as shown in Fig. 7.

(c) Validation of the theory using previously unreported bulk acoustic waves (BAW) based droplet deformation, restoration, and droplet splitting experimentations.

5 Conclusions

In this research work, we have developed a unified theory of non-linear acoustic forces acting on inhomogeneous fluids that explain acoustic relocation and streaming suppression. Followed by this, using linear stability analysis we derived the characteristic equations and analyzed the stability of inhomogeneous fluids under acoustic fluids. By employing the relocation phenomena, we investigated the heat transfer mechanism under acoustic fields and showed that acoustic fields can effectively enhance heat transfer under gravity and microgravity conditions. Further, the effect of thermal boundary conditions, and standing acoustic wave configuration on heat transfer under acoustic fields is also investigated to deduce the optimum conditions for heat transfer enhancement. Finally, we employed our theoretical framework of inhomogeneous fluids to understand the behavior of droplets under acoustic fields, and the predictions are validated through silicon glass microchannel experiments. The fundamental understanding from these studies can give new insights into cells/particle sorting in inhomogeneous fluids, acoustic relocation of miscible and immiscible fluids, droplet manipulation, and heat transfer under acoustic fields.

6 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction

(b) Chapter 2: Literature Survey

(c) Chapter 3: Theory of nonlinear acoustic forces acting on the inhomogeneous fluids

(d) Chapter 4: Stability of acoustic forces acting on inhomogeneous fluids.

(e) Chapter 5: Heat transfer mechanism driven by acoustic body force under acoustic fields

(f) Chapter 6: Heat transfer and flow patterns in a minichannel with various acoustic standing wave configurations and thermal boundary conditions

(g) Chapter 7: Theoretical and experimental investigation of droplet manipulation using bulk acoustic waves

(h) Chapter 8: Summary and Future Scope

7 List of Publications

7.1 Journals

- Varun Kumar. R., Aravind Ram, S., & Subramani, K. On the stability of inhomogeneous fluids under acoustic fields. J. Fluid Mech. 964, A23, (2023).
- Varun Kumar. R., Jayakumar, S., Azharudeen, M. & Subramani, K. Theory of nonlinear acoustic forces acting on inhomogeneous fluids. J. Fluid Mech. 940. A32, (2022).
- Varun Kumar. R., Solomon, J. & Subramani, K. Heat transfer and flow patterns in a minichannel with various acoustic standing wave configurations and thermal boundary conditions. Int. J. Heat Mass Transf. 194, 122923 (2022).
- Varun Kumar. R., Azharudeen, M., Pothuri, C. & Subramani, K. Heat transfer mechanism driven by acoustic body force under acoustic fields. Phys. Rev. Fluids 6, 073501 (2021).

7.2 Conferences

- Varun Kumar, and Karthick. S. Droplet handling using bulk acoustic wave. ICRAFMN 2023.
- Varun Kumar, Aravind Ram SP, and Karthick. S. Stability of immiscible fluids under acoustic fields. FMFP 2022.
- Varun Kumar, and Karthick. S. Acoustic relocation of immiscible fluids. MicroTAS 2022.
- Varun Kumar, Aravind Ram SP, and Karthick .S. Analysis of relocation of immiscible fluids in a microchannel. Acoustofluidics 2022.
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7.3 Patents

- Varun Kumar. R, and Karthick. S. A system for droplet shaping and restoration, unification and splitting using BAW. Intellectual property India –Patent. Published (2023).

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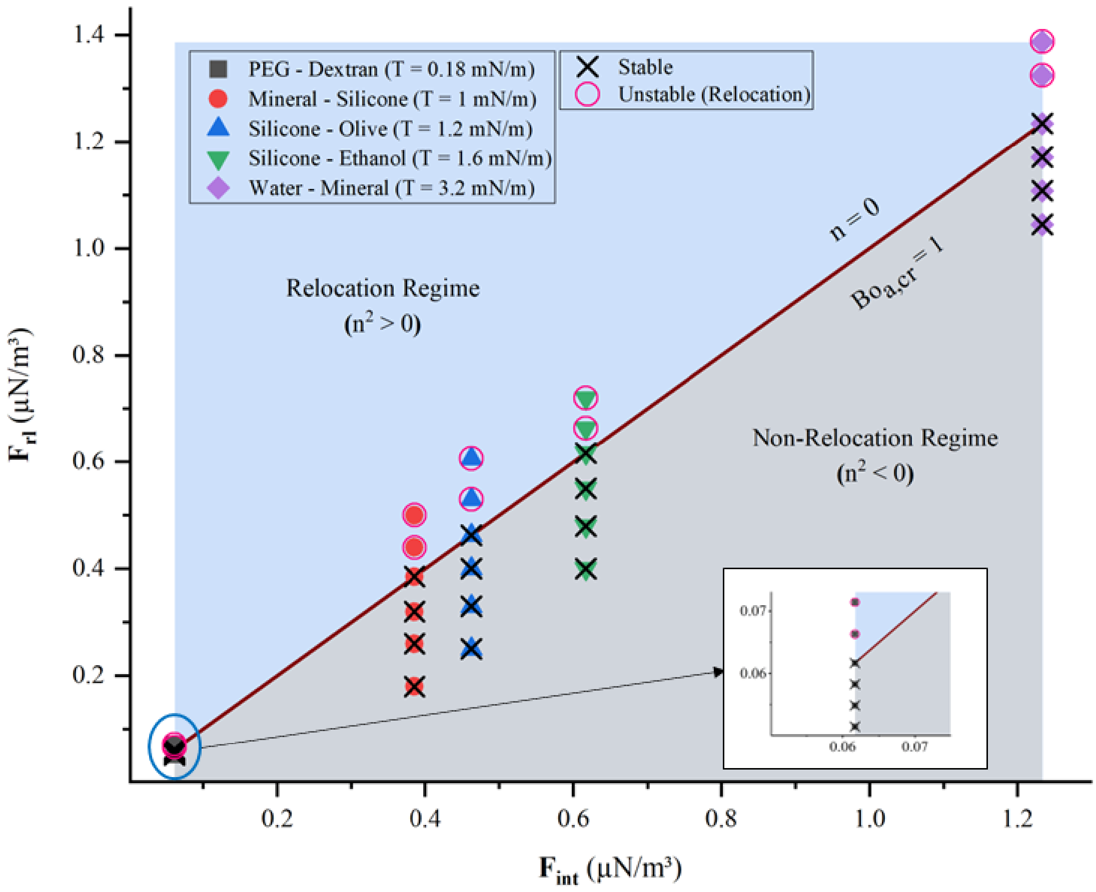

Figure 3: Characterization of relocation and non-relocation regimes of immiscible HLH (High-Low-High fluid impedances) fluid configuration using acoustic Bond number Bo_a and characteristic value n. The blue and grey color indicates theoretically predicted relocation regime ($n^2 > 0$ or $Bo_a > 1$: unstable) and non-relocation regime ($n^2 < 0$ or $Bo_a < 1$: stable) respectively. The line separating these two regimes indicates the neutral configuration ($n = 0$ or $Bo_a = 1$). The data points are obtained through numerical simulations where the open circle indicates relocation and the cross mark indicates non-relocation.

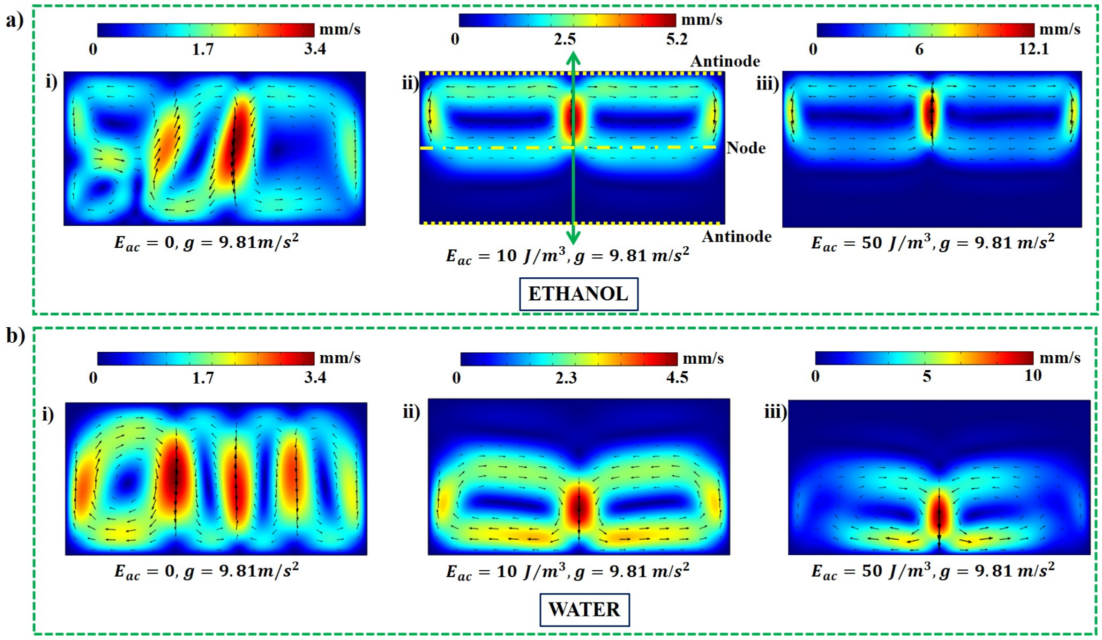

Figure 4: Velocity profile due to the presence of both acoustic and gravity. Standing acoustic wave is applied parallel to the direction of heat transfer. a) Ethanol, and b) Water. The green arrow indicates the direction of the standing acoustic wave.

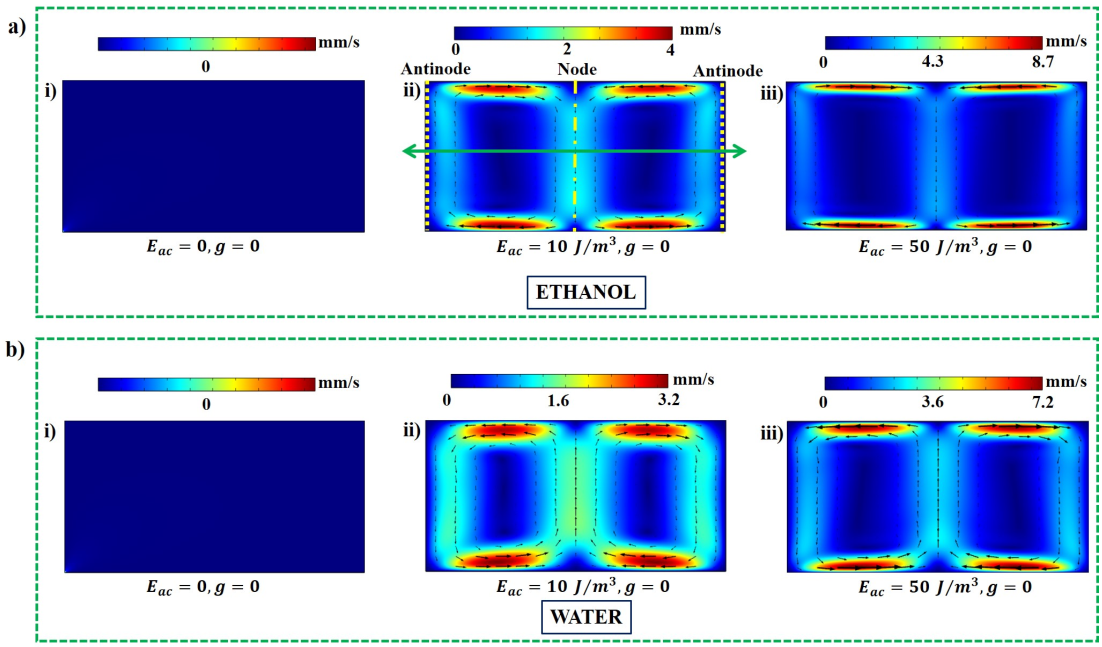

Figure 5: Velocity profile due to acoustic forces at zero gravity condition. Standing acoustic wave is applied perpendicular to the direction of heat transfer. a) Ethanol, and b) Water. The green arrow indicates the direction of the standing acoustic wave.

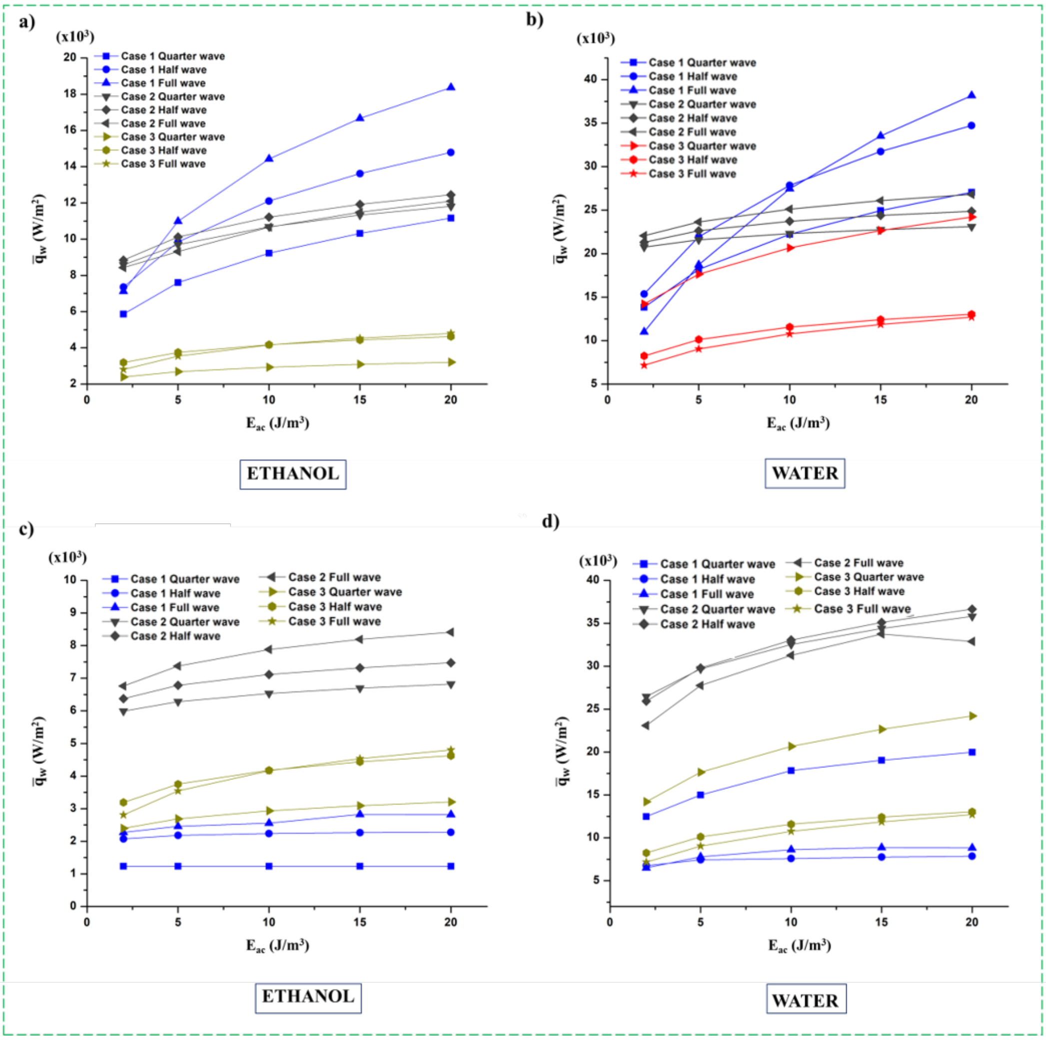

Figure 6: Heat flux at different acoustic energy densities when an acoustic wave is passed along the a) x-direction in ethanol and b) x-direction in water c) y-direction in ethanol d) y-direction in water. Here the x-direction and y-direction represents the direction parallel and perpendicular to the width of the channel respectively.

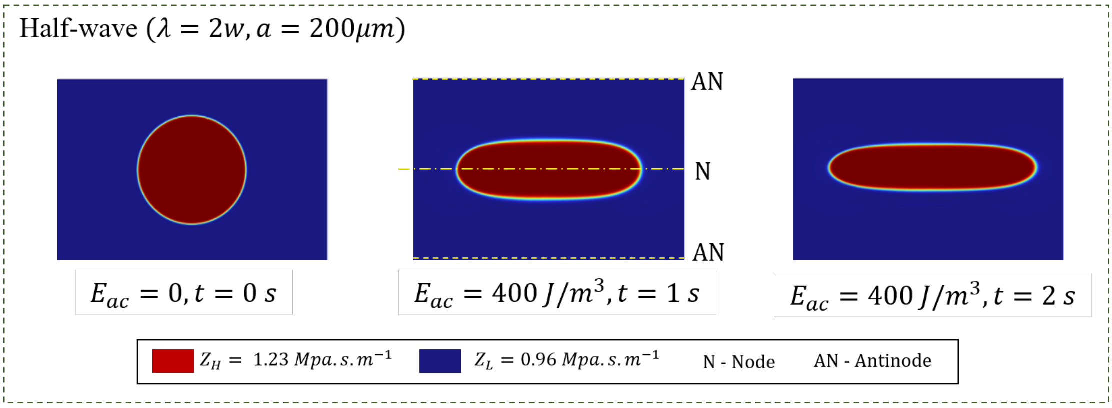

Figure 7: Droplet splitting under acoustic fields. a) Numerical results of droplet splitting (at $\lambda = W$), that demonstrate the theory of inhomogeneous fluid governing the behavior of droplets under acoustic fields and b) Experimental results of droplet splitting at a frequency $f = 1.95362\ MHz$, using bulk acoustic wave silicon-glass microchannel.