On the Evolution of a Neutral Configuration of Inhomogeneous Fluids under Acoustic Fields

Sujith Jayakumar [1,2], **Videsh VK** [1], Jeyapradhap T [1], Hemachandran E [3], and Karthick Subramani [1]

[1] Indian Institute of Information Technology, Design and Manufacturing, Kancheepuram, Chennai, Tamil Nadu, India

[2] Present address: Medically Advanced Devices Laboratory, Department of Mechanical and Aerospace Engineering, Jacobs School of Engineering, University of California San Diego, La Jolla, CA, 92093, USA

[3] National Institute of Advanced Manufacturing Technology, Ranchi, Jharkhand, India

INTRODUCTION

We delve into the evolution of a neutral equilibrium configuration of miscible inhomogeneous two-inlet fluid flow in a microchannel, considered without interfacial tension, when subjected to standing acoustic waves. Intriguingly, acoustic forces result in a spatial bifurcation, stabilizing the neutral configuration in one half of the domain (suppressing Rayleigh streaming) while destabilizing the other half (leading to fluid relocation).

GOVERNING EQUATIONS

An acoustically actuated microchannel containing fluids inhibits a physics developing along two time scales, i.e, fast scale acoustics and slow scale hydrodynamics. We employ the pertubation theory where the fields decompose into the background fields, harmonic acoustic fields and second order fields. Considering the non-linearity of the Navier-Stokes equation, along with the harmonic time dependence of the first order fields, we get the following time-averaged equations upto the second order [1],

$$\nabla . \boldsymbol{v}_2 = 0 \quad [1]$$

$$-\nabla . < \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 > -\nabla p_2 + \eta \nabla^2 \boldsymbol{v}_2 + \rho_0 \boldsymbol{g} = 0 \quad [2]$$

$$\partial_t s_0 + \boldsymbol{v}_2 . \nabla s_0 = D \nabla^2 s_0 \quad [3]$$

where Eq. 1 denotes the mass-continuity, Eq. 2 denotes the momentum and Eq. 3 denotes the advection-diffusion equations. The emergence of second-order slow-scale hydrodynamic flows is a consequence of the divergence of the Reynolds Stress tensor of the first order, which acts as the body force in our study [1],

$$\boldsymbol{f}_{ac} = -\nabla \cdot < \rho_0 \boldsymbol{v}_1 \boldsymbol{v}_1 > \quad [4]$$

The equilibrium configurations can be obtained by taking a curl of the force causing acoustic relocation ($\nabla \times f_{rl} = 0$). Through the stability analysis, the eigenvalue n that determines the initial nature of the stability of the system is found to be [2]

$$n = \sqrt{\frac{k_y}{\rho_A + \rho_B} \Phi E_{ac} (Z_B - Z_A) \sin(2 k_w x_s)} \quad [5]$$

The configuration is in stable equilibrium if the eigenvalue is imaginary and unstable if the value is real. Whereas, when $n = 0$, it describes a configuration with a neutral equilibrium.

NUMERICAL MODEL

The first-order and second-order Navier-Stokes equations are bidirectionally coupled and solved numerically at all slow-time steps employing the Laminar Flow (spf), Thermoviscous Acoustics (ta) and Transport of Diluted Species (tds) physics modules in **COMSOL Multiphysics 6.0.**

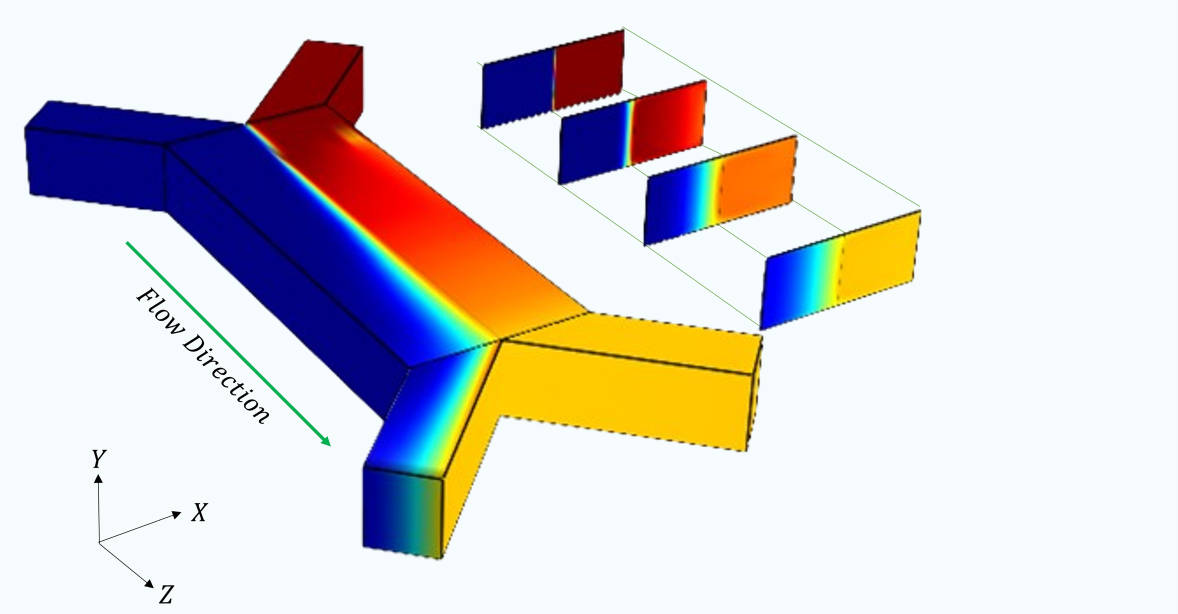


Fig : A 3D illustration of the evolution of neutral configuration fluid flow profile under acoustic actuation

The walls of the microchannel (380μm×190μm) are actuated with a velocity of $(2\Pi f_0)d_0 \approx 10^{-3}\ m/s$, resulting in a half standing acoustic wave being produced horizontally in the microchannel. The properties of the fluids used correspond to Ficoll PM70 and DI (de-ionized) water [3].

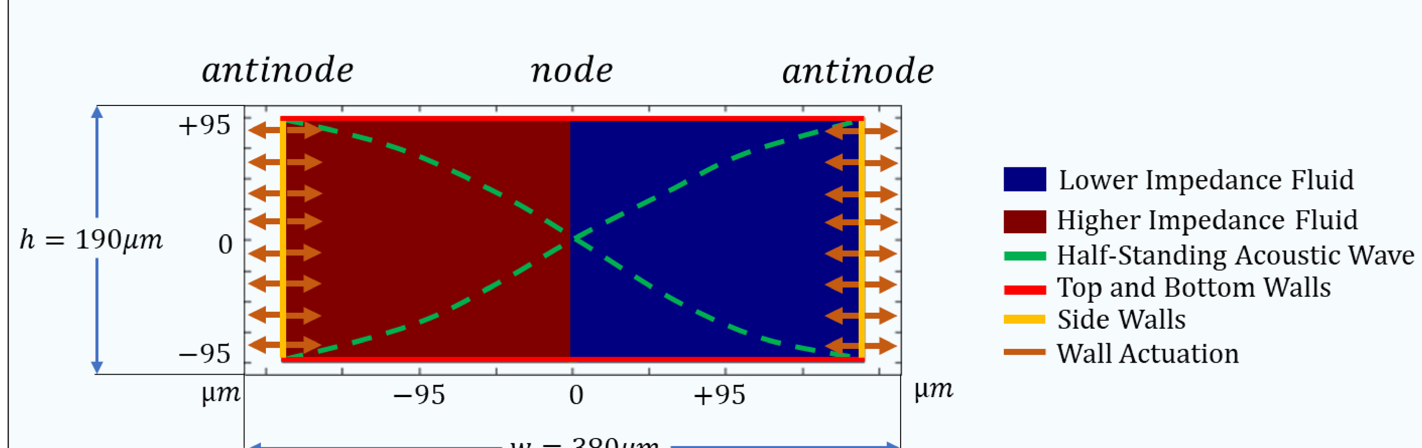
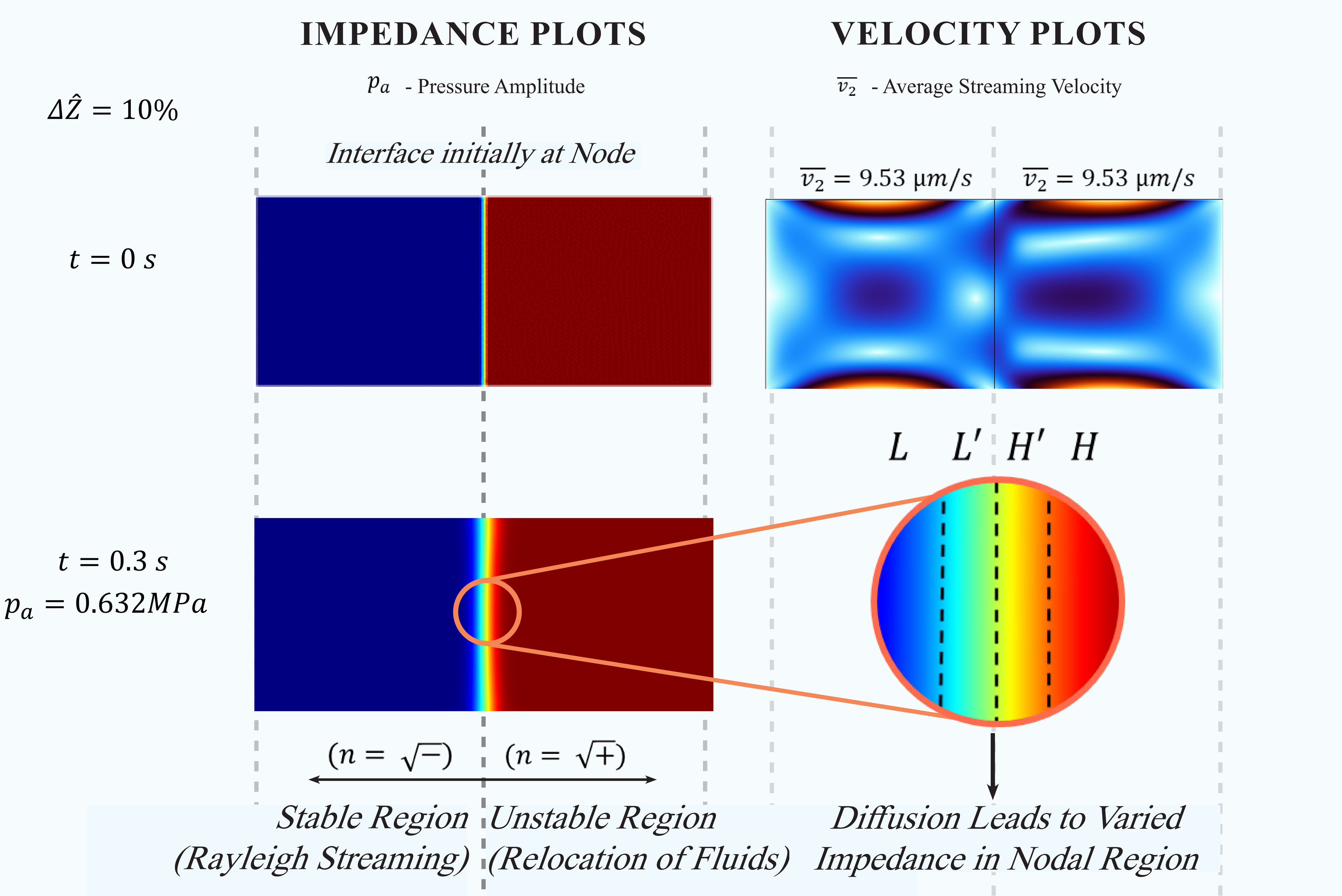


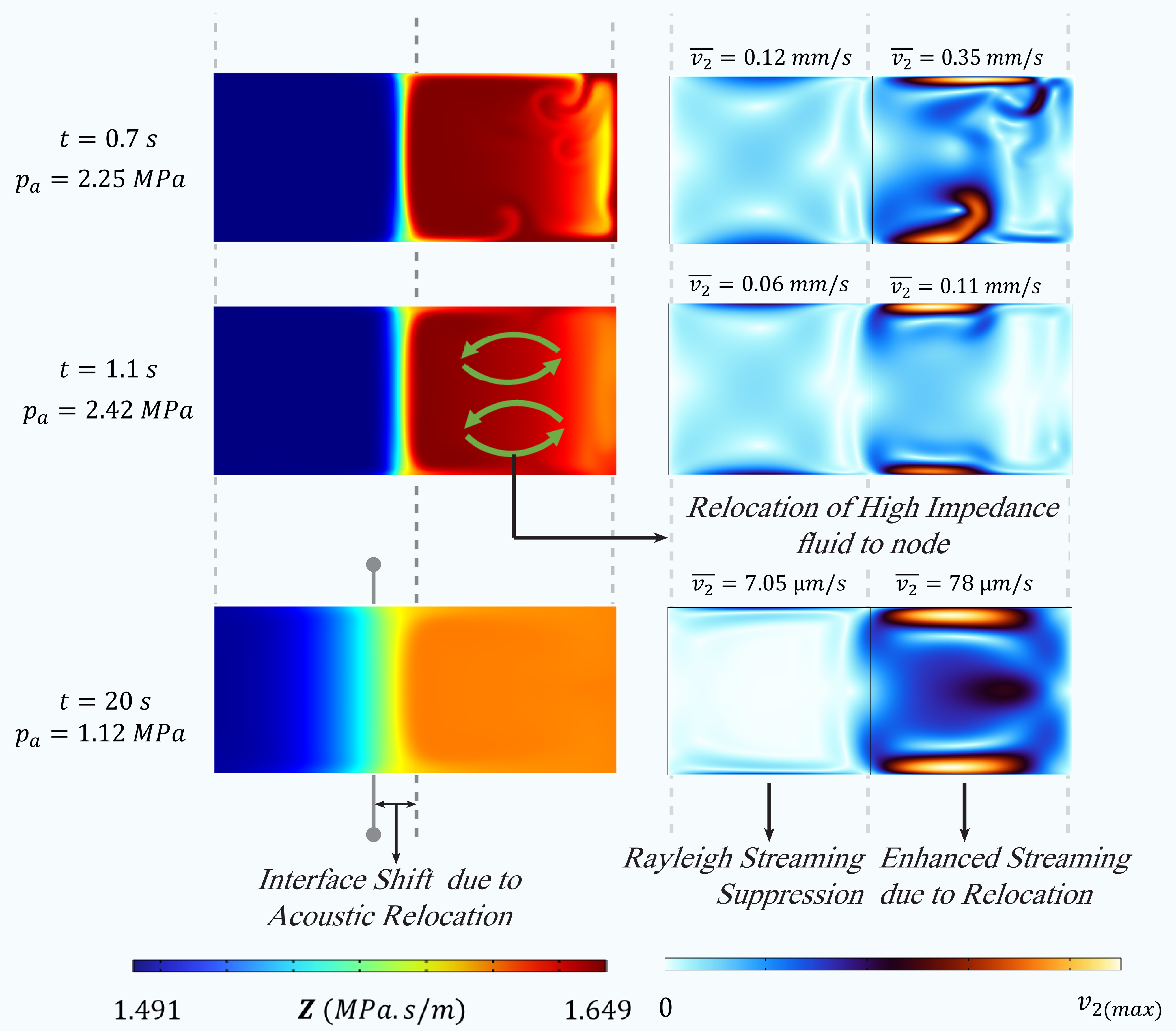
Fig : A 2D cross section of the acoustofluidic microchannel with a neutral configuration ($n = 0$) subjected to acoustic standing half-wave (in the x-y plane).

RESULTS

Acoustic forces acting in the microchannel drive the inhomogeneous fluids to a stable configuration where the higher impedance fluid relocates to the node and the lower impedance fluid to the anti-node.



A **spatial bifurcation** arises with i) a **stable configuration at the left half of the domain**, with the lowest impedance fluid (L) at a pressure anti-node and a higher impedance fluid (L') occupying the nodal area and ii) **an unstable configuration at the right half of the domain** with the highest impedance fluid at the pressure anti-node (H) and a lower impedance fluid (H') near the node.



This results in **increased fluid flow in the right** of the domain while the **left side experiences nearly still or minimal flow**, indicating that when employing a two-inlet acoustofluidics microchannel for particle sorting applications, it is crucial to have the cells or particles suspended within a low impedance fluid medium while ensuring that a high impedance fluid serves as the sheath.

SUMMARY AND OUTCOMES

The discovery was made that upon actuation at the appropriate frequency, the **neutral configuration bifurcates** into a Rayleigh Streaming suppressing **stable domain** and an **unstable domain** resulting in the relocation of fluids with a velocity magnitude one order higher than Rayleigh streaming velocity. The findings and knowledge gained from this research will be helpful for **particle sorting** and fluid manipulation applications in acoustofluidic devices.

References :

[1] V. K. Rajendran, S. Jayakumar, M. Azharudeen, and K. Subramani, Theory of nonlinear acoustic forces acting on inhomogeneous fluids, J. Fluid Mech. 940 (2022), 10.1017/jfm.2022.257

[2] V. K. Rajendran, S. P. A. Ram, and K. Subramani, On the stability of inhomogeneous fluids under acoustic fields, J. Fluid Mech. 964, A23 (2023)

[3] S. Jayakumar and K. Subramani, An investigation of acoustic relocation phenomenon in a microchannel under acoustic fields, Phys. Fluids 34 (2022), 10.1063/5.0100386.

eMpTy Lab
Microscale Transport Laboratory