PhD thesis

Acoustically-driven jets - From 3D water configuration to metallic alloys stirring

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Key words: Experimental and numerical work, acoustically-driven flows, stability, advanced experimental techniques (3D visualization), spectral elements code.

Context: "Not only a jet can generate sound but also sound can generate a jet!" [1]; starting from this idea stated by Sir J. Lighthill, our research team in Lyon has developed theoretical, numerical and experimental skills to observe and model liquid flows generated by ultrasounds. Among several applications, an ultimate goal is the stirring of liquid semi-conductors and metallic alloys or semi-conductors during their solidification; the present study is in the framework of the BRASSOA [2] project working out key points for this issue. Such a way of stirring is for instance of interest in Aluminium alloys industry and in Photovoltaic silicon production processes, which both involve high working temperatures (respectively about 600 °C and 1400 °C). Scaling laws, similarity laws and technical solutions concerning acoustic streaming in liquid metals have already been developed by the international academic and industrial research community [3, 4] and in particular by our team [5–8]

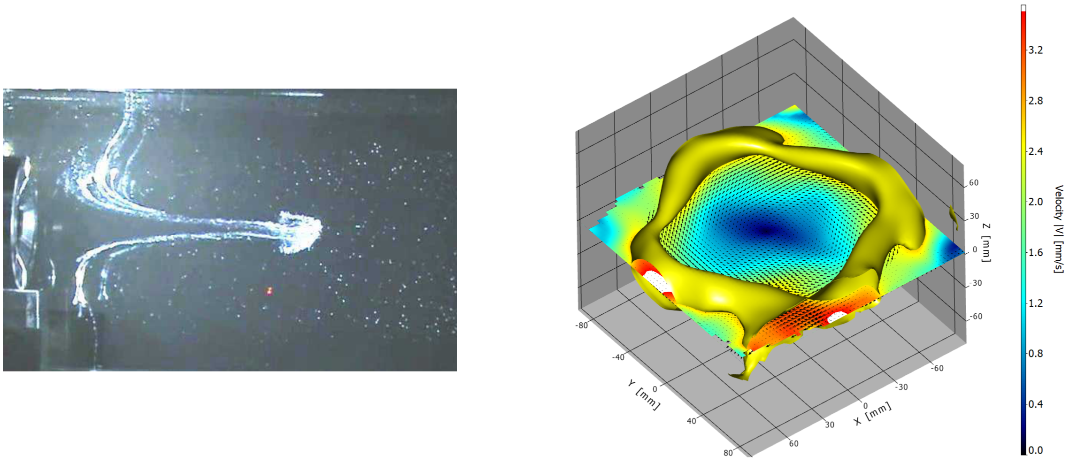
A key ingredient in the generation of acoustic streaming flows is the attenuation of sound in the medium, which is responsible for the conversion of acoustic energy into momentum and increases significantly with the ultrasounds frequency. A common strategy is to use rather low frequencies and high acoustic powers to create a cavitation cloud which significantly increases attenuation, but has the major drawback to break down the acoustic beam coherence. We are most interested in investigating high frequencies and rather low acoustic powers avoiding cavitation regimes, which has been poorly investigated yet.

A very important step is to update the collection of experimental and numerical observations of acoustic streaming in view to extend the scaling and similarity laws over a wide range of frequencies and material properties. This will then provide a strong basis for developing optimization strategies to get the acoustic forcing parameters allowing an efficient stirring, while taking into account the geometrical constraints imposed by the considered processes.
A new approach to identify different streaming regimes is to focus on the dimensionless attenuation parameter $\mathbf{N} = Nf^2L$ (where Nf^2 is the attenuation coefficient for a wave at frequency f in the considered fluid and L is a characteristic length). One of the aims of the PhD is to understand the influence of this parameter on the flow, knowing that, up to now, only the limit $\mathbf{N} \ll 1$ have been explored in our team. A way to achieve this, is to either increase the working frequency or

increase the characteristic length over which the fluid is observed. In particular, the acoustic beam consistency over long distances is a key point to design geometrically complex forcing fields relying on multiple successive reflexions on the container walls. Several velocimetry techniques available in Lyon (UDV/ADV, 2D particle image velocimetry – 3D PTV) will be used to characterize experimentally such streaming configurations in water, while spectral element simulations will be conducted in Coventry with Computational Fluid Dynamics software as NEKTAR++..

Finally a first step towards liquid metals applications is also planned with an experimental campaign in the Helmholtz research center (HZDR), in Dresden (Germany) using galinstan (liquid metal at room temperature) as the working fluid.

These significant steps forward in the use of acoustic streaming for stirring will be done by the present PHD student in the framework of a INSA Lyon – Coventry University **co-tutelle program** involving two research teams, respectively in the LMFA and FCS laboratories.



Visualization of the transient acoustic streaming jet generated with a transducer (left picture). Mean flow is obtained experimentally with reconstructed eulerian field from 3D particle tracking in an acoustic streaming configuration where the acoustic beam is oriented towards the wall of a cubic cavity with a 45° angle, resulting in several reflexions on consecutive walls (right picture).

[1] S. J., Lighthill, *Acoustic streaming*, J. Sound Vibr. **61**, pp. 391-418 (1978).

[2] https://www.ingenierie-at-lyon.org/projet/2020-brassoa-brassage-ecoulement-entraines-ondes-acoustiques/

[3] G.S.B. Lebon, G. Salloum-Abou-Jaoude, D. Eskin, I. Tzanakis, K. Pericleous, P. Jarry, *Numerical modelling of acoustic streaming during the ultrasonic melt treatment of direct-chill (DC) casting*, Ultrasonics Sonochemistry (2019), doi: https://doi.org/10.1016/j.ultsonch.2019.02.002

[4] J-L. Achard, P. Lebrun, *Method for inspecting a liquid metal by ultrasound*, Patent **WO 2016/055729 A1**.

[5] B. Moudjed, V. Botton, D. Henry, H. Ben Hadid, J.P. Garandet, *Scaling and dimensional analysis of acoustic streaming jets*, Phys. Fluids **26**, 093602 (2014). http://dx.doi.org/10.1063/1.4895518.

[6] M. Albaric, V. Brize, V. Botton, S. Miralles, *Sonde acoustique destinée a être utilisée dans un four de solidification du silicium et son procédé de fabrication*, Patent **FR3074908 A1**.

[7] https://www.youtube.com/watch?v=ArpclLD4yP8

[8] https://www.youtube.com/watch?v=ZJBAXHeyuV0 (in French)