6 months internship (master's level) at Ecole Centrale de Nantes : Physical analysis of Extreme-Scale fluid dynamics simulation data

- **Location:** Ecole centrale de Nantes, GeM – Institut de Recherche en Génie Civil et Mécanique
- **Tutor:** Lucas Lestandi (Assoc. Prof.)
- **Compensation:** ~**630€/months** depending on the latest "Journal Officiel" decree.
- **dates** : 6 months starting between January and March 2025

Context

Understanding the dynamics of turbulent flows with density gradients remains a challenge to this day. It is essential to improve if for advancing both theoretical knowledge and practical applications, from aerospace engineering to weather prediction. During this internship, we will focus on two acamdemic problmes 1. Rayleigh-Taylor Instability (RTI) and 2. Kelvin-Helmholtz Rayleigh-Taylor Instability (KHRTI) as they offer detailed insight into these complex fluid interactions, especially under unstable conditions where density or velocity gradients cause instabilities. However, the level of accuracy required by these simulations means the sheer size of the datasets becomes a challenge on its own be it for visualization or interpretation.

Rayleigh-Taylor Instability (RTI) occurs when two fluids of different densities interact, with the heavier fluid pushing into the lighter one. This instability is common in astrophysics, oceanography, and nuclear fusion research, where fluids of varying densities collide or interact under the influence of gravity. RTI simulations allow researchers to model the complex interplay between these fluids and study how instabilities evolve over time as shown in [1,2,3].

Kelvin-Helmholtz Rayleigh-Taylor Instability (KHRTI) is an extension of RTI, where velocity shear adds another layer of complexity to the fluid interaction. This occurs when there is a velocity difference across the interface between two fluids, creating Kelvin-Helmholtz waves that intensify the instability. The KHRTI phenomenon is crucial in understanding atmospheric turbulence, ocean waves, and plasma behavior in astrophysical settings.

The data used during this internship is obtained by computing Direct Numerical Simulation (DNS) of Navier-Stokes equation. It directly resolves all scales of turbulence by explicitly calculating all potential vortex structures down to a single mesh cell. Consequently, the computation need to use very small mesh size to ensure sufficient accuracy and solve instability without relying on turbulence models. This means that the computational cost of DNS is extremely high, even at low Reynolds numbers and the amount of data produced can be very large. For the RTI simulation, each time step produces 157Gb (2.34 billion mesh points) of data to store pressure, velocity and energy fields. Figure 1 shows the temperature field for the whole computational domain for RTI.

Physical meaning can be gathered from exisiting simulation in a number of ways. For this work, we will

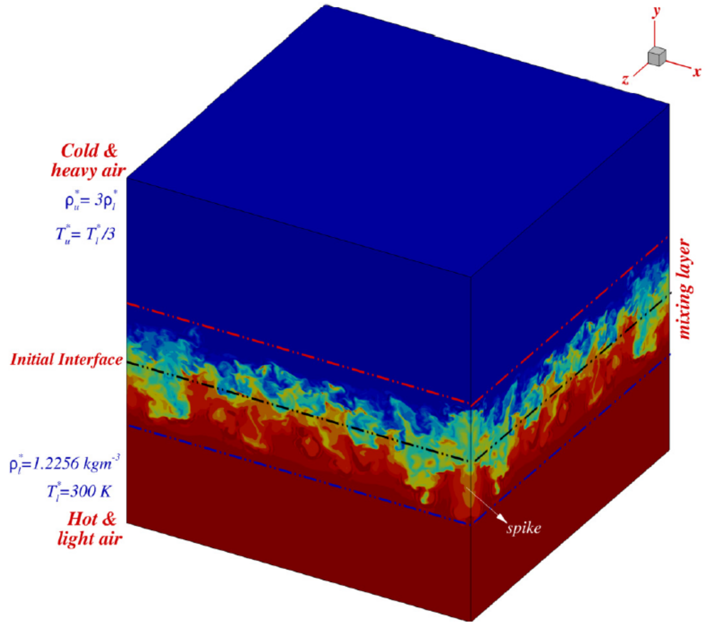

Figure 1: Schematic representation of the computational domain. Reproduced from [1]

focus on characterizing the instability onset. To do so, calculations may be applied to the whole field such as extracting the disturbance pressure field or baroclynic term in order to explain the flow behaviour. Visualisation of the whole field or slices of it is also of interest to the research team in order to visually assess the solution. However, both operations require accessing the whole field which may require super-computer access and long wait time. In order to alleviate this issue, we propose to use decomposition techniques such as POD/SVD in order to extract the *modes* driving the flow evolution. Computing these will enable cheaper storage and data access while enabling energy based analysis of the process (see [4]).

Presentation of the team and work environment

This intership is part of a broader international project funded by CEFIPRA (Indo-French Centre for the Promotion of Advanced Research) *Data reduction and surrogate modelling of transition to turbulence of Rayleigh-Taylor instability data obtained by DNS*. The project is headed by Associate Professor Lucas Lestandi at Ecole Centrale de Nantes (ECN, Laboratoire GeM) and Assistant Professor Aditi Sengupta (IIT-ISM Dhanbad, Mechanical engineering dpt.) who has provided data and DNS solvers. The intership will take place at Ecole Centrale de Nantes (France) in collaboration with Lucas Lestandi and Yassin Ajanif who is currently in his 2nd year PhD studies. He is currently developing tools to enable the decomposition of the RTI include preprocessing and SVD.

Work organization

1. Initial Phase:

- Work closely with Yassin to learn how to operate ECN's supercomputing resources.
- Focus on booking resources, scheduling jobs, and using the computational infrastructure effectively.

2. Data Subset Analysis:

- Implement processing pipelines for subset data to ensure proper handling and visualization.
- Develop benchmarks to validate the stability and efficiency of the workflows.

3. Full Dataset Analysis:

- Once the benchmarks are stable, move on to analyzing the entire 2Tb KHRTI dataset.
- If time permits, extend the analysis to the 4Pb RTI dataset.

Goals of the internship

For you

- Develop skills in high-performance computing (HPC): Learn to use the ECN supercomputing facilities, including resource booking, job scheduling, and managing tasks across multiple CPUs and GPUs.
- Gain proficiency in existing software: Familiarize yourself with tools for data analysis and visualization (matplotlib, ParaView, PyVista…)
- Discover international research projects from the inside

For the project

- Implement data processing workflows: Set up and execute the necessary processing steps to handle and visualize the KHRTI and RTI datasets.
- Contribute to better understanding of KHRTI (and RTI) through extensive simulation data analysis

Intern profile

The ideal candidate is looking for a 5 or 6 months internship in a research lab to complete his masters or engineering degree in either of the following major: scientific computing, applied math, mechanical engineering.

Required skills

- **Language:** Proficiency in written English is necessary. French or English for day to day communication
- **Programming:** Good knowledge of programming / scientific programming in **python** or **C++**.
- **Mechanical engineering / Fluid Dynamics:** Highly appreciated
- **Applied math:** Highly appreciated

References: [1] P. Sundaram, A. Sengupta, and T. K. Sengupta, *"A non-overlapping high accuracy parallel subdomain closure for compact scheme: Onset of Rayleigh-Taylor instability by ultrasonic waves,"* Journal of Computational Physics, vol. 470, Dec. 2022, doi: 10.1016/j.jcp.2022.111593.

[2] A. Sengupta, P. Sundaram, V. K. Suman, and T. K. Sengupta, *"Three-dimensional direct numerical simulation of Rayleigh-Taylor instability triggered by acoustic excitation,"* Physics of Fluids, vol. 34, no. 5, May 2022, doi: 10.1063/5.0091109.

[3] T. K. Sengupta, P. Sundaram, V. K. Suman, and S. Bhaumik, *"A high accuracy preserving parallel algorithm for compact schemes for DNS,"* ACM Transactions on Parallel Computing, vol. 7, no. 4, Nov. 2020, doi: 10.1145/3418073.

[4] L. Lestandi, S. Bhaumik, T. K. Sengupta, G. R. Krishna Chand Avatar, and M. Azaïez, *"POD Applied to Numerical Study of Unsteady Flow Inside Lid-driven Cavity,"* Journal of Mathematical Study, vol. 51, no. 2, pp. 150–176, 2018, doi: 10.4208/jms.v51n2.18.03.