NON-MODAL STABILITY OF VARIABLE-DENSITY ROUND JETS

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Figure 1 – Schlieren photograph of the side-jets for a pure helium jet, $S = 0.14$ et $Re = 1000$, obtained on the laboratory experimental setup.

1 Context

The current energy market evolution encourages investigations for new forms of energy for land and aircraft propulsion. Gaseous fuels like methane and hydrogen are good candidates. Mixing promotion downstream of jet injectors is a key point of energetic and environmental performance of future engines such as turbojets and ramjets. Indeed, an efficient and fast mixing improves the compactness and efficiency of the combustion chamber. To this end, the understanding and control of transitional mechanisms downstream the injector is an essential prerequisite to the conception of an innovative injector.

In this context, the round jet is the good prototype is of central interest to study theoretically the transitional dynamics of such flows. In addition to the shear effects, local variations of the density field due to the binary mixing between density contrasted fuel and oxidiser
induces strong biases in the dynamics through baroclinic vorticity production. When the density ratio $S = \rho_j/\rho_\infty$ between the jet density $\rho_j$ and the ambient density $\rho_\infty$ is sufficiently low, $S \simeq 0.5$, light jets undergo very specific features with the appearance of side-jets which enhance significantly the spreading of the flow up to angles of $90^\circ$, see figure 1. This phenomenon increases substantially the jet interface and is favourable to mixing. Experiments show that side-jets occur only when the jet primary Kelvin-Helmholtz instability is absolute (Monkewitz et al., 1990). The corresponding flow pulsation arise only below a density ratio threshold which depends on the geometry and the characteristics of both velocity and density exit profiles at the nozzle (Lesshafft et al., 2007). Despite an important literature on the subject, the physical mechanism responsible for such secondary structures is still subjected to conjectures (Lesshafft et al., 2007; Lopez-Zazueta et al., 2016). The aim of the present work is to understand this mechanism with the perspective to develop control strategies for industrial applications.

2 Scientific objectives

The objective of this PhD proposal is to consider the influence of density variations on the development of he round jet secondary three-dimensional instabilities through a non-modal stability analysis (Schmid, 2007). The unsteadiness of the base-flow heads towards a direct-adjoint technique better suited for this purpose than the classic modal analysis relying on a quasi-static assumption conducted so far (Fontane & Joly, 2008). This method consists in an optimisation loop for the perturbation between an injection time $t_0$ an horizon time $t_0 + T$ through direct numerical simulations of the linear Navier-Stokes equations. The algorithm eventually produces the optimal perturbation and give access to its complete evolution which enables to analyse the associated physical mechanisms. The classic use of such methods rely on the optimisation of the perturbation kinetic energy, but it is possible to apply it with different objectives. For example, one can look for the minimisation of density variance for mixing efficiency (Foures et al., 2014) or the minimisation of noise radiation for acoustic furtiveness (Lesshafft et al., 2007).

Within the research team « Dynamique des Fluides Fondamentale », the DAEP (Dépar-
tatement Aérodynamique, Énergétique et Propulsion) has developed over the years a strong expertise in stability analysis for highly density-contrasted mixing flows (jets, mixing layers, vortices). The laboratory also has an experimental set-up of air-helium binary mixing jets aimed to develop complementary studies to theoretical analyses. This ambitious project deals with a complex configuration in direct continuation of previous works conducted in the team over the past years. As a primary step to the jet secondary instabilities, we performed a modal analysis of the variable-density plane mixing layer (Fontane & Joly, 2008) and direct numerical simulations of the non-linear fractal development of the two-dimensional Kelvin-Helmholtz mode, see figure 2, which was awarded the American Physical Society Gallery of Fluid Motion (Fontane, Joly & Reinaud, 2008). Then, the non-modal stability analysis of the variable-density free shear layer (Lopez-Zazueta et al, 2016) exhibited a new mechanism for the flow transition to three-dimensional motions based on the emergence along the braid of longitudinal velocity streaks of opposite sign on either side of the saddle point, see figure 3.

The project is scheduled as follow:

1. The non-modal stability analysis will be first conducted for homogeneous round jets. It will require the derivation of the linear adjoint equations before including them in a linearised version of the pseudo-spectral code available for the simulation of the round jet. The development of an optimisation loop for the maximisation of the perturbation kinetic energy will enable to explore the sensitivity of the optimal perturbation to azimuthal periodicity of the mode as well as the Reynolds number. Through detailed diagnostics of kinetic energy and enstrophy budgets, it will be possible to identify the associated physical mechanisms.

2. The second step will consists in adding the density variations for the direct non-linear simulation of the jet primary Kelvin-Helmholtz instability. The velocity and density fields obtained will be used as the base-flow for the subsequent stability analysis.

3. Then, the methodology derived in the first step will be reproduced for the variable-density
The analysis will be specifically focussed on the influence of the Atwood number on the development of the optimal perturbation.

4. Finally, the non-linear evolution of the optimal perturbations through three-dimensional direct numerical simulation will be considered in order to examine the possible occurrence of side-jets.

To a further perspective and in direct continuation of this project, the control and measure of mixing will be considered through the conception of experimental set-up based on the theoretical results on the air-helium jet test facility of the laboratory.

Références


