PROPOSITION DE SUJET DE THESE

Analysis of thermoacoustic instabilities in carbon-neutral swirling V-flames

Référence : MFE-DMPE-2025-**18**
(à rappeler dans toute correspondance / include in all correspondence)

Start of PhD : October to December 2025	**Application deadline :** July 2025

Key word

Linear stability, reacting flows, V-flame, flame instability, lean combustion

Ideal candidate profile

Master of science or engineering degree in physics, fluid mechanics or applied mathematics, with a strong background in numerical methods.

Context

The pressing issues of climate change and energy security are driving significant initiatives to transition from fossil fuels to renewable, carbon-neutral energy sources. Hydrogen and ammonia emerge as leading options, as both can be sustainably produced through electrolysis using surplus renewable energy. However, utilizing hydrogen fuel presents distinct challenges, particularly in the lean-premixed combustion mode required by contemporary emissions standards. A notable challenge is the tendency of hydrogen flames to exhibit intrinsic instability more readily than hydrocarbon flames, such as those from methane. Similarly, while ammonia can be used as a hydrogen carrier, it also introduces unique combustion dynamics and potential challenges, including higher ignition temperatures and different flame stability characteristics. These instabilities can cause the flame front of hydrogen to wrinkle into cellular patterns, leading to a considerable increase in surface area and, consequently, a rise in propagation velocity.

Additionally, premixed flames are not merely passive; they are intricately linked to the flow conditions in which they exist. Lean hydrogen flames are particularly sensitive to factors such as flame curvature and stretch caused by hydrodynamic strain. This interaction complicates the behavior of the system, making it difficult to analyze the hydrodynamics and thermodynamics of the reacting flow in isolation. A significant contribution of this study will be to investigate this complex behavior using a straightforward yet fully-coupled (linear and nonlinear) reactive flow model.

State of the art

Laminar flame instabilities are pivotal to understanding turbulent flame propagation, and their relevance to practical combustion issues is well recognized [1]. In addition, the incorporation of swirl in combustion systems is vital for enhancing efficiency and stability [3]. Early studies of the linear stability of swirling flames employed simplifying hypothesis to study the problem: neglect the reaction terms, consider only hydrodynamics or perform local stability analyses. In this line, there have been several studies of the hydrodynamic stability of reacting flow. We find the studies of Juniper [2] and Oberleithner and collaborators [5] of swirling premixed flames and the one by Quadri et al. [6] of lifted jet diffusion flames.

Focusing only on the effect of swirling, recently, [8] studied the effect of swirl of non-reacting laminar jets finding a series of symmetry-breaking bifurcation, including several instances of hysteresis and subcritical behavior, including one that manifests precessing vortex core oscillations. The same authors [9] also analyzed the effect of axial and radial confinement on the flow topology of laminar swirling jets. They find bi-stable states separated by a saddle-node bifurcation when the confinement is made sufficiently important. The results indicate that the hysteresis commonly observed in swirling jets is influenced not only by vortex breakdown but also by confinement resulting from the Coanda effect.

Linear analysis of reacting jets is relatively recent. Blanchard et al. [4] investigated the input-output mechanism of an M-shaped flame. The objective of their work is to develop new methods to calculate and understand the response of an M-shaped flame to small flow oscillations. Global stability of a reacting jet was first performed by [7], who provided a comparison of the temporal growth rates of eigenvalues obtained by four methods, finding that they are very different. More recently, Douglas and collaborators [10] performed a nonlinear bifurcation analysis of burner-stabilized laminar premixed conical flames with varying reaction rates and reactant diffusivities in order to mimic the combustion of hydrogen. They found several saddle–node bifurcations corresponding to spontaneous flash-back and blow-off of the axisymmetric flame. They also identify a symmetry-breaking bifurcation associated with transitions to steady three- dimensional polyhedral and tilted flame state. Concerning V-flames, Wang et al. [11] have analyzed the intrinsic thermoacoustic instability of a premixed annular V-flame. In this case, the spectrum around the steady-state flow, is composed of an arc-branch with the property that the difference in frequency between nearby modes in the spectrum is nearly constant, thus suggesting a non-local feedback. Further analysis shows that the primary bifurcation is a subcritical Hopf bifurcation due to a non-local feedback between the flame base and the flame tip.

Objectives

The thesis aims to analyze the dynamics of laminar self-stabilized swirling V- flames issued from the combustion of novel fuels such as hydrogen and ammonia, whose thermal to mass diffusivity (the Lewis number) is less than one and thus more sensible to thermo-diffusive instabilities.

The student is expected to apply recent developments from the field of linear instability theory to analyze combustion instabilities, both classical and intrinsic thermoacoustic instabilities in open and enclosed domains. Thus, the purpose of this thesis is to include the effect of swirling and smaller to unity Lewis number to extend the analysis of Wang et al. [11]. In a first step, the student is expected to extend a linearized Navier–Stokes in-house code to include the combustion of hydrogen and ammonia. Then, they will be expected to perform an exhaustive analysis of two configurations: an open and confined domain of the distinct bifurcations in the parameter space (Re, S, Le), being Re the Reynolds number and S the swirl ratio performing continuation of the steady-state and global stability. In addition, the student is expected to determine the importance of non-modal growth using resolvent analysis. These results should be analyzed in order to determine the physical mechanisms responsible for the instability, for instance employing structural sensitivity or endogeneity analysis.

Once the instabilities have been identified the student is expected to design a passive control strategy to mitigate thermoacoustic instabilities, possibly by employing a porous medium, which will be accounted for as a homogenized condition.

References

[1] Gregory I Sivashinsky. “Instabilities, pattern formation, and turbulence in flames”. In: (1982).

[2] Matthew P Juniper. “Absolute and convective instability in gas turbine fuel injectors”. In: Turbo Expo: Power for Land, Sea, and Air. Vol. 44687. American Society of Mechanical Engineers. 2012, pp. 189–198.

[3] Sebastien Candel et al. “Dynamics of swirling flames”. In: Annual review of fluid mechanics 46.1 (2014), pp. 147–173.

[4] Mathieu Blanchard et al. “Response analysis of a laminar premixed M- flame to flow perturbations using a linearized compressible Navier-Stokes solver”. In: Physics of Fluids 27.4 (2015).

[5] Kilian Oberleithner, Sebastian Schimek, and Christian Oliver Paschereit. “Shear flow instabilities in swirl-stabilized combustors and their impact on the amplitude dependent flame response: A linear stability analysis”. In: Combustion and Flame 162.1 (2015), pp. 86–99.

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[7] Alexander Avdonin, Max Meindl, and Wolfgang Polifke. “Thermoacous- tic analysis of a laminar premixed flame using a linearized reactive flow solver”. In: Proceedings of the Combustion Institute 37.4 (2019), pp. 5307– 5314.

[8] Christopher M Douglas, Benjamin L Emerson, and Timothy C Lieuwen. “Dynamics and bifurcations of laminar annular swirling and non-swirling jets”. In: Journal of Fluid Mechanics 943 (2022), A35.

[9] Christopher M Douglas and Lutz Lesshafft. “Confinement effects in lam- inar swirling jets”. In: Journal of Fluid Mechanics 945 (2022), A27.

[10] Christopher M Douglas, Wolfgang Polifke, and Lutz Lesshafft. “Flash- back, blow-off, and symmetry breaking of premixed conical flames”. In: Combustion and Flame 258 (2023), p. 113060.

[11] Chuhan Wang et al. “Onset of global instability in a premixed annular V-flame”. In: arXiv preprint arXiv:2404.17396 (2024).

Environment and collaborations

The student will be enrolled at Ecole Polytechnique and they will be based at Ladhyx as part of the Ladhyx-ONERA collaboration. The thesis is cofounded between Ladhyx and ONERA (ERC-POROLEAF).

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