Active Control of Inter-Scale Energy Transfer in Grid-Generated Turbulence Using Plasma Actuators

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Scientific Background

This research project aims to develop a novel approach to the active control of turbulence based on dielectric barrier discharge (DBD) plasma actuators. These actuators are now widely used for flow control applications, particularly for flow separation delay, drag reduction, and more generally wall-friction reduction. They rely on the rapid electrohydrodynamic conversion of electrical energy into momentum, generating a localized low-speed wall jet. Although the induced flow velocity remains relatively low, the absence of moving parts enables actuation frequencies of several kilohertz, far beyond the capabilities of conventional mechanical actuators.

The project proposes to move beyond these traditional applications by addressing a largely unexplored research question: the direct control of energy-transfer mechanisms within the turbulent energy cascade. The objective is to determine how plasma forcing can modify the spectral characteristics of turbulence, redistribute energy across scales, and influence both production and dissipation mechanisms. Here, the study focused on a canonical flow configuration with well-documented statistical properties (grid-generated homogeneous turbulence configuration). The originality of this approach lies in its ability to inject energy directly into the small scales, within a frequency range usually associated with dissipation, thereby opening the way to a new class of non-equilibrium forced turbulent flows.

Methodology

The PhD project will consist of two complementary research tasks. The first will investigate the effects of spatially homogeneous forcing, achieved through the simultaneous actuation of all plasma electrodes, in order to characterize the influence of forcing frequency, duty cycle, and operating mode (continuous AC or pulsed excitation) on scale-to-scale energy transfer within the turbulent cascade. The second task will explore spatially inhomogeneous forcing through the selective activation of groups of plasma actuators, enabling controlled spatial distributions of energy injection. This entirely novel approach will provide an unprecedented experimental framework for investigating the coupling between spatial inhomogeneities and the turbulent energy cascade, as well as the possible emergence of non-local energy-transfer mechanisms or inverse energy cascades.

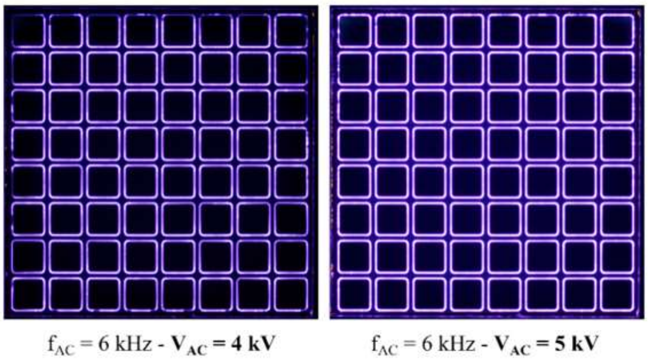

Figure 1 : Système plasma installé sur une grille homogène

Since DBD plasma discharges simultaneously generate an electrohydrodynamic body force and reactive chemical species, the project will also open new perspectives toward forcing strategies combining hydrodynamic and thermodynamic effects. Although this physico-chemical dimension is not the primary objective of the PhD project, it represents a natural extension of the present work toward the active control of reactive flows and combustion processes.

The experimental investigation will rely on advanced time-resolved Particle Image Velocimetry (TR-PIV) measurements. Particular attention will be devoted to the accurate estimation of the smallest turbulent scales and the turbulent kinetic energy dissipation rate, requiring the development of dedicated procedures for background-noise reduction, multi-scale image processing, and velocity-gradient estimation. The resulting datasets will be used to evaluate the different terms of the Kármán–Howarth–Monin–Hill (KHMH) equation, providing a quantitative description of the local mechanisms governing energy transfer across the turbulent cascade.

Scientific Challenges and Originality

The project aims to establish a new paradigm for the active control of turbulence based on localized, high-frequency plasma forcing acting directly on the smallest turbulent scales. Unlike conventional flow-control strategies, which primarily target the large energetic structures of the flow, DBD plasma actuators provide a unique opportunity to inject energy directly into a spectral range traditionally associated with viscous dissipation. Rather than controlling coherent flow structures alone, this approach seeks to manipulate the scale-to-scale energy transfer mechanisms that govern the turbulent energy cascade itself. The central objective is therefore to understand how low-amplitude, high-frequency electrohydrodynamic forcing modifies the intrinsic dynamics of the energy cascade, the dissipation process, and the coupling between energy-containing and dissipative scales.

Beyond its potential technological applications, the project provides a unique experimental framework for addressing several fundamental questions that remain largely unresolved in turbulence research. In particular, it will investigate whether energy transfers remain predominantly local in spectral space when forcing is applied directly at the dissipative scales, how such forcing alters the global dynamics of the flow, and whether it can induce non-local interactions, inverse energy transfers, or other departures from the classical Richardson–Kolmogorov cascade. The ability to independently control the frequency, spatial distribution, and intensity of the plasma forcing offers an unprecedented level of experimental flexibility, enabling systematic investigations of turbulent flows maintained under non-equilibrium conditions.

The originality of the project therefore extends well beyond the use of plasma actuators as flow-control devices. It lies in the development of a new experimental discipline at the interface of plasma physics, flow control, and experimental turbulence. By targeting the turbulent energy cascade itself rather than the macroscopic flow structures, this research has the potential to establish a new framework for turbulence manipulation, with significant implications for both the fundamental understanding of turbulent transport and the development of innovative strategies for mixing enhancement, combustion control, and industrial process intensification.

Research Environment

This PhD project is part of the ANR ENRICO project (ANR-25-CE51-0954), funded through the 2025 French National Research Agency (ANR) Generic Call. It is jointly conducted by Institut PPRIME, internationally recognized for its expertise in plasma actuators, electrohydrodynamics, and flow control, and the Lille Fluid Mechanics Laboratory (LMFL, Centrale Lille/CNRS), one of the world's leading research groups in grid-generated turbulence and experimental turbulence physics.

The PhD candidate will work in a highly stimulating research environment alongside a postdoctoral researcher, several Master's students, and the permanent teams from both laboratories. The doctoral research and most of the experimental work will be carried out at Institut PPRIME, located on the Futuroscope campus (Building H2), where the candidate will have access to state-of-the-art experimental facilities, including high-voltage plasma actuation systems, time-resolved Particle Image Velocimetry (TR-PIV), high-speed imaging, laser diagnostics, and advanced data acquisition systems. Regular research visits and scientific exchanges with LMFL will be organized throughout the three-year PhD to strengthen collaboration, share expertise, and jointly develop the experimental programme.

Beyond its scientific objectives, this PhD will provide comprehensive training in experimental fluid mechanics, plasma flow control, turbulence physics, advanced optical diagnostics, image and signal processing, and scientific programming. The candidate will also gain experience in the design of experimental facilities, high-voltage systems, quantitative flow measurements, and the analysis of large datasets in an international collaborative research environment.

Candidate Profile

We are looking for a highly motivated Master's student or engineering graduate with a strong background in fluid mechanics, heat transfer, and/or electrical engineering. Knowledge of turbulence, plasma physics, experimental methods, or optical diagnostics would be appreciated but is not mandatory. Previous experience in signal or image processing, scientific programming (MATLAB, Python, C/C++), or experimental research would be considered an asset.

The successful candidate should demonstrate strong analytical skills, scientific curiosity, and a genuine interest in fundamental and interdisciplinary research. Autonomy, creativity, and the ability to work within a collaborative research team are essential. A good command of written and spoken English is required.

The successful candidate will join an ambitious collaborative project at the interface of plasma physics, turbulence, and flow control, offering the opportunity to contribute to the emergence of a new experimental approach for manipulating the turbulent energy cascade with potential applications ranging from fundamental turbulence research to combustion and process engineering.