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PHD POSITION

Title : Super-resolved temperature-velocity measurements to study turbulent scalar transport

Référence : **MFE-DAAA-2025-33**
(à rappeler dans toute correspondance)

Start date : April 2025-November 2025	**Application deadline :** July 2025

Keywords Turbulent flows, laser-based measurements, luminescent particles, 3D measurements.

Expected profile

Master of science in Mechanical or Process Engineering with a focus on Fluid Dynamics.

Interest for cross disciplinary research and image processing. English proficiency

PhD topic, context and objectives

Understanding and predicting the transport of heat and chemical species in turbulent flows is crucial not only to study the formation and dispersion of pollutants in the atmosphere, for example the evolution of condensation trails or "contrails" in the wake of airplane engines, but also to improve the control of chemical reactors and the thermal management of electric and thermal propulsion systems. Yet an accurate description of turbulent transport remains difficult as many of the flows of interest involve a wide range of length scales preventing the use of Direct Numerical Simulations (DNS). To save computational effort, the smallest scales are not directly simulated and the transport due to subgrid flow structures is modelled by additional equations.

The fluctuations of the velocity u_i' and scalar φ' taking place below the resolution of the simulation and their interaction result in an added scalar flux term $\langle u_i'\varphi' \rangle$ after ensemble averaging within the grid cell. When the scalar is considered passive, i.e. its variations have no influence on the velocity field as in the case of ink concentration in a turbulent water channel, the same transport mechanism across turbulent scales is assumed for the velocity and scalar fields. Sub grid scalar flux is then modelled using the momentum eddy diffusivity and the turbulent Prandtl Pr_t or Schmidt Sc_t numbers for heat and mass respectively. However, this assumption has its limitations, and different Pr_t and Sc_t number must be chosen for different flow configuration, based on the results of experiments [1].

Indeed, for flow configurations found in nature or in reactors where mean scalar gradients are present, the scalar field exhibits a very different phenomenology than the velocity field [2]. The scalar field has a pronounced non-Gaussian distribution, marked anisotropy and a stronger intermittency than the velocity field. Yet a full description of this phenomenology, necessary for the development of more accurate and configuration independent, sub-grid models, remains limited by the range of spatial and temporal scales which either DNS or experiments can cover. Indeed, limited computation power restricts DNS and probe resolution restricts experiments.

The first experimental challenge is to accurately determine the scalar variance and its energy spectrum, as this requires that the measurement technique has a high enough spatial resolution to avoid filtering out the smallest scales of scalar variations. To facilitate measurements, past studies of passive scalar transport targeted flow regions with large Kolmogorov microscales, in the order of 100's of micrometers [2,4], but in turbulent flows of practical interest those microscales can be as small as a few microns. Due to the so called "ramp-cliff" structures in the scalar spatial and temporal variations (see [2]), resolution requirements for the scalar are even stricter than for the velocity. The second challenge is to access gradients and multipoint correlations, for which several measurements in close vicinity are necessary. Measuring the scalar dissipation rate ε_φ, which dictates the rate of mixing, is an ultimate goal but it requires to measure gradients in three directions.

Different approaches have been proposed in the literature to access the scalar dissipation. Multiple probes can be placed in close vicinity for two, three or four-point measurements [2,4] or a laser-based imaging technique such as Laser Induced Fluorescence (LIF) of gaseous tracers applied to determine the 2D mixing scalar field. To derive the full 3D dissipation rate, two-plane LIF measurements were performed [5]. For LIF however, the in-plane resolution is limited by the resolving power of the imaging system, and the out of plane resolution by the thickness of the laser sheet, typically larger than 50 microns. Similarly, the resolution of commercially available micro-resistance probes is limited to the length of their sensing element, which is several hundreds of microns.

To achieve higher resolution and probe the smallest structures, we advocate the use of sub-micron luminescent particles, seeded into the flow as an intricate web of micro-thermometers. Using super-resolution methods, the particles' positions can be localized with a sub-pixel resolution. This can be done by extracting the center of the particle image which size is limited by diffraction using a 2D Gaussian fit, which is positioned with a sub-pixel resolution. The use of super resolution in thermometry has so far been exclusive to the realm of optically trapped nanoparticles for biomedical applications. Here, we expand the horizon of this concept and leverage its potential for multi-point measurements in turbulent flows. Pushing the frontier further, we will strive for the third dimension, localizing the particle through triangulation from two views, akin to 3D particle tracking velocimetry concepts.

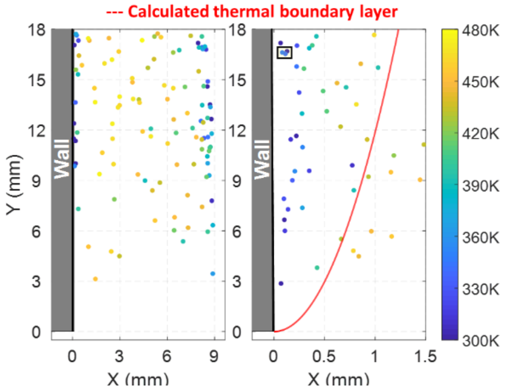

Figure 1 temperature measurements in a hot stream flowing past a cold plate using super-resolution localization [3]

In a recent study, we established the proof of concept of super-resolution temperature measurement using ZnO luminescent tracer particles in a laminar boundary layer [3]. Here the temperature is measured by exploiting the red shift of the ZnO luminescence emission spectrum with temperature using a two-color imaging system. Each point in Fig. 1b) corresponds to an independent temperature measurement positioned by 2D gaussian fits with an in-plane resolution better than 0.1 pixel, or 1 micron over a field of view wider than 10 mm. This corresponds to a spatial dynamic range higher than 1 to 10,000. Thanks to this high resolution, the temperature profile in a 500-micron thin boundary layer could be measured and validated against theory.

In this project, we propose to extend and apply this measurement concept based on submicron luminescent tracers. We will:

1) extend the subpixel localization approach to all three dimensions using stereoscopic imaging

2) measure velocity at the exact same point in space and time to obtain fully coupled scalar-velocity measurements.

3) Describe turbulent transport terms without filtering the smallest turbulent structures (10's of microns) in two turbulent flows: a round heated jet, and an impinging jet on a plate to test and propose new sub-grid scalar models.

The PhD student will work also in close cooperation with a postdoctoral research associate, who will develop optimized luminescent particles with uniform properties.

This project is already fully funded by the French National Research Agency (ANR), and the start date is therefore flexible from April to November 2025

Bibliography:

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[2] Warhaft, Z. Passive Scalars in Turbulent Flows. *Annual Review of Fluid Mechanics*, 32 (2000), 203-240
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[4] Darisse, A., Lemay, J., and Benaïssa, A.. Extensive study of temperature dissipation measurements on the centerline of a turbulent round jet based on the $\overline{\theta^2}/2$ θ 2 ¯ / 2 budget. *Experiments in Fluids*, 55 (2014).
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Foreseen cooperation

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