Optical Diagnostics of Flows: an Introduction

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Since its founding in 1946 as the major actor in aerospace research in France, Onera has identified the strategic role of optical diagnostics of flows in aerospace development and has achieved recognized expertise in this field. In this first issue of Aerospace Lab, we will describe some recent or on-going developments in the field of optical diagnostics of flows at Onera.

Flows are generated when an object moves in a gaseous environment. It is thus no surprise that we find flow dynamics research in all branches of science and technology: civil and chemical engineering, the automotive industry, energy, etc. Flow dynamics are even more central to aeronautics technology because they provide air lift to planes (non-reacting flow dynamics) as well as moving impetus through combustion (reacting flow dynamics). The great challenges of flow dynamics require the validation of physical models with relevant length ranges spanning dozens of orders of magnitude, from a few Angstroms, at which atoms and molecules collide and bond (particularly in combustion), to a meter range (the size of a combustion chamber or a wing). Optical diagnostics are ideal for addressing this enormous challenge as they can span these different scales, offering both a global view through imaging and a microscopic view through spectroscopy. Moreover, these techniques are non-intrusive, so that they do not disturb the system or bias the measurements as other probing techniques do.

Optical diagnostics of non-reacting flows

In the first part of this Issue, we address the Onera State of the Art in optical diagnostics of non-reacting flows (aerodynamics). Modern problems of Computational Fluid Dynamics (CFD) call for new metrological approaches in terms of spatial and temporal resolutions, measurement precision, etc. which are analyzed in [1]. One aspect of this challenge is to “visualize the invisible”: gaseous flows are transparent so we must devise ways to “materialize” their motion (speed), structures (vortices, turbulences, etc.), and basic parameters such as composition, pressure and temperature fields. This materialization of flows may be provided by micro- or nanoparticles, which are either seeded or naturally present (aerosols) and then carried along by the gaseous flow. These particles diffuse light efficiently, which allows for the use of two-dimensional velocity mapping techniques such as Particle Image Velocimetry (PIV in [3] & [4]), Laser Doppler, Doppler Global Velocimetry (LDV and DGV), and Coherent Lidar [6]. Laser plays an essential role in these techniques due to its outstanding properties of directivity, spatial resolution, optical coherence and spectral linewidth. When no such particles are present in the flow, the intrinsic properties of the gas are used: optical index contrast (Schlieren, shadowgraph, etc.) which makes use of the small variations in the optical index of the gas with temperature [9], or the light emitted or scattered by the air molecules themselves when excited by an electron beam (FFE in [8]) or laser light (Molecular Lidar [7]). Boundary conditions, which are propagated over large distances by the flow, have a fundamental impact on the flow dynamics, so that optical characterization of boundary surface conditions [2] is of the utmost importance for a full understanding of flow dynamics.

Optical diagnostics for reacting flow dynamics

The second part of this Issue is devoted to optical diagnostics for reacting flow dynamics (mostly combustion). Over and above what is needed for non-reacting flows, combustion research calls for quantitative, sensitive and chemical-specific imaging techniques. Combustion science is basically multi-scale (from the molecular level to large scale turbulence) and multi-physics (heat transfer, chemistry, radiation, acoustics, etc.). It is facing new challenges such as environmental protection goals of simultaneously decreasing the consumption of fuel and unwanted emissions (soot, NO_x, CO_x , etc.) or of using alternative fuels with new chemical species. These evolutions call for new approaches in optical diagnostic techniques, such as higher temperature and pressure conditions, greater sensitivity (down to the ppm level for some pollutants), etc., which are described in [10]. For example, multiphase (spray) combustion studies require new techniques to determine the chemical and physical properties of fuel in its liquid and vapor phases (see for instance [5] and [11]). Chemical sensitivity is particularly important and is determined by the spectroscopic properties, particularly line strength, and the temperature of the species. Laser-Induced Fluorescence (LIF in [11]) consists of imaging the fluorescent light emitted by the molecules present in the flow (OH radicals but also seeded tracers such as NH_3, etc.), when they are excited by a sheet of laser light exactly tuned to their molecular resonance. It allows for a direct two-dimensional mapping of the species concentration and temperature. These molecular resonances are also charted by spectroscopic measurements such as Absorption [13] and Non-linear spectroscopy [12]. These techniques allow for the detection of multiple chemical species and provide enhanced knowledge of the gaseous state (rotational and translational temperatures, metastable species, etc.). They require exceptional mastery of tuneable laser technologies, such as dye lasers or more recently optical parametric oscillators, for which the Onera teams have been world leaders since the early 70's.

An ever-evolving technology

This State of the Art is clearly a snapshot of an ever-evolving technology. New developments and technological breakthroughs lie ahead, as Computational Fluid Dynamics will become more demanding with regard to validations. Femtosecond lasers will bring new opportunities, such as the study of ultra-dense media (e.g. high pressure sprays) using undiffused ballistic photons or time-resolved nonlinear scattering [14]. Progress in data processing will give access to three-dimensional reconstructions. High-power high-repetition rate (>10 kHz) lasers will enhance our knowledge of fluid dynamics over short time scales (turbulence formation, etc.). New sources such as wide bandwidth synchrotron radiation or multiplexed frequency comb-based spectroscopy may also prove useful for simultaneously mapping the concentrations of numerous species ■

Voltaire, in his novel "Candide", wrote in 1759 that there will be "many a century before man knows what is a simple flame". This time is now coming.

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