Experimental study and physical modelling of the interaction between injection and acoustics in liquid-gas multi-injection or transcritical real fluid injection conditions

Doctorant·e

OVANDO CASTRO Michael

Direction de thèse

BAILLOT FRANÇOISE (Directeur·trice de thèse)
BLAISOT JEAN-BERNARD (Co-directeur·trice de thèse)

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Rapporteurs de la thèse

DENET BRUNO UNIVERSITE AIX MARSEILLE 1 PROVENCE
SCHULLER THIERRY Université de Toulouse 3 - Paul Sabatier

Membres du jurys

BAILLOT FRANÇOISE, , Université de Rouen Normandie (URN)
BLAISOT JEAN-BERNARD, , Université de Rouen Normandie (URN)
DEMOULIN FRANÇOIS-XAVIER, , Université de Rouen Normandie (URN)
DENET BRUNO, , UNIVERSITE AIX MARSEILLE 1 PROVENCE
SCHULLER THIERRY, , Université de Toulouse 3 - Paul Sabatier
THERON MARIE, , Centre National des Etudes Spatiales

Abstract

Thermoacoustic instabilities in liquid rocket engines (LREs) have been investigated since the 1930s, and are still the subject of vital studies as part of the CNES R{\&}D program strategy. These occur as soon as a coupling loop appears between fluctuations in pressure and those in the rate of heat release. The latter can be disrupted by the impact of pressure waves on physical phenomena such as atomization and mixing, which are involved in the entire combustion process upstream. The work presented in this doctoral thesis is part of this research dynamics. It focuses on the behavior of flows located in the injection zone when subjected to high-intensity transverse acoustic fields following forcing-controlled chamber resonance modes. Fluids are considered either in their subcritical state, or in the vicinity of their transcritical/supercritical state. Three actions are proposed: (i) the development of a theoretical model of the scattered acoustic field in the presence of an acoustically transparent cylindrical object, submitted in turn to nonlinear acoustic radiation effects. The property of acoustic transmission at the object interface, which is not necessary for objects that are heavy relative to their environment (as in the case of a water jet in air), becomes indispensable as soon as its density approaches that of the environment (as in the case of a transcritical jet in nitrogen gas). This must be particularly taken into account when the object is deformable under the action of steady radiation efforts; (ii) adaptation of the HP-5L bench injecting a jet of ethane in the transcritical state into an environment of supercritical nitrogen pressurized beyond the critical point of ethane, in order to accommodate an acoustic forcing system developed specifically within the framework of this study, capable of withstanding these conditions of pressure (50 bar) and temperature (323K). This acoustic system using piezoelectric vibrating elements was tested on the ACoUstic Test bEnch (ACUTE) stand-alone acoustic bench capable of producing a standing transverse acoustic field. Integrated with the HP-5L bench, the injection point can be positioned at will on a pressure, velocity or acoustic intensity antinodes; (iii) the design and installation of an air-assisted multiple water injection dome fitting on the pre-existing MARACA pressurized bench (1 to 5 bar) equipped with an acoustic forcing system comprising four titanium dome loudspeakers and solenoid actuator generating a transverse standing acoustic field of large amplitudes (in the order of 6000 Pa peak-to-peak or 169.5 dB at $P_{ch} = 1 \ bar$ and 14000 Pa peak-to-peak or 176.9 dB at $P_{ch} = 5 \ bar$) and frequency around 1 kHz. Coaxial flows characteristic of the Fiber regime (Re_l = 6600, We_g = 520; Re_l = 3200, We_g = 224) and Rayleigh Non-Axisymmetric regime (Re_l = 3000, We_g = 40) are characterized using diffuse backlighting visualizations (DBI) in two perpendicular directions, captured by two synchronized cameras at high speed (around 1 kfps). The new injection dome has been designed to accommodate multiple injectors, allowing for the simultaneous operation of 4 or 5 injectors. Despite the complexity in visualizing multiple overlapping jets, granulometric measurements (which involve analyzing the size distribution of particles within the jets) can still be performed effectively. At low Weber numbers, which correspond to scenarios where surface tension forces dominate over inertial forces, the influence of acoustics on the jets is more pronounced. The acoustic waves interact strongly with the liquid jets, affecting their breakup behavior. This effect is observed consistently across all multiple injector configurations, indicating that acoustics play a significant role in the dynamics of the jets under these conditions. The impact of acoustic waves on the jets becomes even more significant at a chamber pressure $P_{ch} = 5 \ bar$ due to a decrease of the ampl