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A quantitative speed of sound database for multi-component jet mixing at high pressure

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ABSTRACT

This study is the first to provide a comprehensive speed of sound database for multi-component jet mixing at high pressure. It serves as a unique reference for numerical simulations of mixture preparation processes in future liquid rocket engines and internal combustion engines. We performed quantitative speed of sound measurements in jet mixing zones for five configurations with well-defined experimental conditions. The database covers three different injectant fluids (two alkanes and a fluoroketone) that were brought beyond their critical temperature and pressure prior to injection and discharged into cold nitrogen at supercritical pressure (with respect to the pure injectant properties). Here, we chose the conditions such that subsonic jets were obtained and re-condensation due to cooling of the injected fluid was prevented. Hence, we provide speed of sound data for single-phase jet mixing for three different binary systems. Quantitative data are presented along the jet centerline with sufficiently high spatial resolution to properly resolve the axial decay. In addition, two radial profiles at a position close to the nozzle allow for an assessment of the transversal mixing characteristics. The experimental speed of sound data show consistent trends, which corroborate that mixture effects are correctly resolved in the measurement.

1. Introduction

A high-pressure combustion process is a key feature of modern liquid rocket motors, direct-injection engines and gas turbines. For rocket engines, these high system pressures are essential to generate a sufficiently high specific impulse [1] and can easily exceed the critical pressure p_c of the involved fluids (i.e. fuel and oxidizer). Preparation of the combustible fuel-oxidizer mixture may then occur under near- or supercritical thermodynamic conditions. Such mixing processes have recently become subject of interest also for gasoline direction injection [2–4] and Diesel [5–7] engines. While in classical designs the fuel is typically injected at subcritical temperature, a heat-up to supercritical temperatures is reported to be beneficial for future engine concepts. Ultimately, this shall result in a single-phase mixing process at high pressure, which has shown to feature excellent potential to increase engine efficiency and simultaneously decrease emission. Although evidently desired, practical implications of such strategies impose high complexity to the mixing process resulting from thermodynamic peculiarities of fluids in the vicinity of the critical point. For instance, a fluid in the supercritical region generally features non-ideal behavior that is characterized by steep gradients in the fluid properties when the thermodynamic state approaches the Widom line (sometimes also called pseudo-boiling line). Additionally, heat and mass diffusion including Soret and Dufour effects become significant within multi-component mixtures [8] leading to a strong coupling between thermodynamics and local flow phenomena.

This complex behavior poses huge challenges to a numerical simulation of high-pressure jet mixing being an essential design tool for future combustion systems. Accurate frameworks using sophisticated equations of state (EoS) in combination with non-linear mixing rules are required to reproduce the highly non-ideal mixture properties. Moreover, theoretical models for the heat and mass transport among the individual chemical species are compulsory. Consequently, large effort has been spent over the past years to develop reliable numerical models for the simulation of jet mixing under high-pressure conditions [8–22]. As virtually all of the aforementioned researchers state, quantitative experimental data are strongly required to evaluate the quality of the theoretical models. Compared to the number and variety of proposed numerical codes, it is, however, striking how little experimental data for high-pressure jet mixing exist that are suitable for model validation.

Several experimental studies provide visual information on jets for

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supercritical pressure conditions comprising both single- and multi-component mixing. Here, either shadowgraphy [23–28], ballistic imaging [27] or a combination of shadowgraphy and elastic light scattering [29] was applied. Besides the extraction of topological information (e.g. jet growth rate or dark core lengths), these studies predominantly seek to answer the question whether the mixing process occurs in single- or two-phase state rather than presenting quantitative flow field data (which is not possible due to the principles of the applied techniques).

To the authors best knowledge, available quantitative data are limited to only a few studies in which laser-based spectroscopic techniques, i.e. Raman scattering and laser-induced fluorescence (LIF), were applied. Mayer et al. [30] performed Raman scattering measurements in cryogenic N_2 jets at sub- and supercritical temperature injected into N_2 at supercritical pressure (single-component system). Here, the density field in the mixing domain was inferred from the Raman signals comprising a resolution of the axial centerline decay and radial profiles at distinct axial positions. Over the years, this data set became a quasi-standard validation case for numerical frameworks as it has been used to assess several numerical codes, see e.g. [9,10,14–17]. In a related study, Oschwald et al. [31,32] acquired quantitative density fields with Raman scattering in coaxial LN_2/GH_2 jets and, hence, extended the investigation to binary systems. Similarly, Bassing and Braeuer [33] and Dowy et al. [34] used Raman scattering to extract concentration fields of ethanol jets discharged into CO_2 at supercritical pressure. In addition, Roy and Segal [35] as well as Roy et al. [36] applied LIF to supercritical fluoroketone (FK-5-1-12) injections into N_2 providing planar density fields of the jet mixing zones. These results were later utilized by Qiu et al. [12] as a validation basis for their numerical code (RANS).

Although tremendously valuable for the characterization of high-pressure jet mixing, the to-date available data does not provide the completeness of a well-characterized reference required for validation of numerical tools. Particularly with respect to multi-component mixing, the choice is limited to only a few binary systems, which prevents to develop a universal treatment. Furthermore, existing studies mostly provide jet densities or mixture composition, whereas additional quantities that reflect the thermal characteristics such as the local temperature or the speed of sound would allow for an extended assessment of the mixing process.

This shortage in experimental data is a consequence from the inherent complexity of laser-based spectroscopic techniques when applied to high-pressure mixtures. Both Raman scattering and LIF derive their signals by a measurement of the absolute light intensity or the spectral distribution of intensity. Therefore, the data acquisition is prone to deterioration through parasitic stray light which is indistinguishable from the true intensity distribution that corresponds to the flow properties. In addition, the measured intensities must be converted to the desired flow quantity, which requires a comprehensive calibration at known conditions that are comparable to the actual problem (i.e. temperature and pressure) in order to correctly quantify the excitation and subsequent emission dynamics (for LIF) as well as the intermolecular energy transfer (for Raman) for the relevant thermodynamic states.

Lately, laser-induced thermal acoustics (LITA), better known as laser-induced grating spectroscopy (LIGS), has evolved as a robust alternative to obtain quantitative flow field data. Under harsh experimental conditions, LITA benefits from the fact that flow quantities are directly inferred from a characteristic signal shape (periodic oscillations). In addition, the signal originates from a macroscopic modulation of the bulk media's properties rather than the radiative molecular relaxation. Here, the increased collisional quenching at high pressures is even beneficial for the signal generation. More importantly, however, LIGS allows for data extraction independent from the absolute signal intensity. Flow information is linked to the frequency of the periodic oscillations, which can be separated from contributions of stray light making the technique more robust under the investigated conditions. This link is provided by a simple scaling constant providing a significantly simpler calibration procedure. In recent studies, we proved the effectiveness of LITA for quantitative speed of sound measurements in high-pressure atmospheres [37] and the turbulent far-field zone of extremely underexpanded jets [38].

Combining the results of both studies, it becomes obvious that LITA is an excellent tool to generate an experimental database for high-pressure jet mixing. It must be stressed that LITA provides the local speed of sound in the jets without the use of an equation of state (EoS) or theoretical mixing model. This prevents systematic errors induced by simplified assumptions in the data evaluation. Also, the speed of sound directly reflects the thermodynamic mixture state as it generally depends upon pressure, temperature and composition (for multi-component systems). Both features qualify the speed of sound as a suitable quantity for numerical validation.

In the present study, we performed LITA measurements to provide a comprehensive speed of sound database for binary jet mixing zones at high pressure. It contains quantitative data for five different configurations with well-defined experimental conditions and comprises three different injectants to assure representative trends in the data. The injectant was always preheated to supercritical temperature prior to injection and discharged into cold chamber gas at supercritical pressure (with respect to the injectant). Quantitative speed of sound values were acquired along the jet centerline and in radial direction to allow for an assessment of both the axial decay and transversal mixing characteristics. The consistency of the data trends are assessed in light of the expected speed of sound characteristics for the five injection cases. Here, we used an adiabatic mixing model based on non-ideal thermodynamic mixture properties to qualitatively predict the speed of sound behavior for the individual binary systems in combination with the corresponding injection conditions.

Results of this study give further insight into the underlying physics of high-pressure jet mixing phenomena. The quantitative speed of sound measurements, furthermore, serve as an important reference to elaborate the quality of numerical tools for the simulation of mixture preparation processes, which is as an essential task in the development of future liquid rocket motors and internal combustion engines.

2. Experimental facility and measurement technique

2.1. High-pressure chamber and injection system

The experiments have been carried out in a cylindrical constant-volume chamber ($V \approx 4 \cdot 10^{-3}\,\mathrm{m}^3$) that is designed for injections into non–heated ambient gas with a maximum pressure of up to 6 MPa. The chamber pressure p_{ch} was measured with a piezoresistive sensor (Keller PA-21Y, 0.015 MPa uncertainty), while two thermocouples (type K) provided the chamber temperature T_{ch} within ± 1 K. In context of this study, we regularly exchanged the chamber gas to avoid accumulation of the injectant within the chamber atmosphere. Furthermore, we took care that T_{ch} adapted to ambient temperature prior to the start of an experiment series and did not vary across the experimental set. Two quartz windows enabled the optical access for the measurements. A magnetic-valve common-rail injector (commercially distributed by Robert Bosch GmbH) is mounted to the chamber such that the center axis of the injector nozzle and the cylinder coincide. The custom-made injector nozzle features a single straight-hole of diameter $D = 0.236$ mm and length $l = 0.8$ mm (i.e. $l/D \approx 3.4$). The injectant is stored in a fluid reservoir that is pressurized with a driver gas to establish the injection pressure p_{inj}, which was also measured with a piezoresistive sensor (Keller PA-23, 0.02 MPa uncertainty). As the fluid reservoir is directly connected to the fuel supply port of the injector, p_{inj} also represents the reservoir pressure for the injection. Two heater cartridges are mounted to the injector body and tip to control the injection temperature T_{inj} (i.e. the temperature of the fluid in the reservoir close to the nozzle exit) with an uncertainty of ± 2 K. The calibration of