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Application of Visualization Techniques and Quantitative Optical Diagnostics for the Investigation of Supercritical Jet Atomization

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Abstract

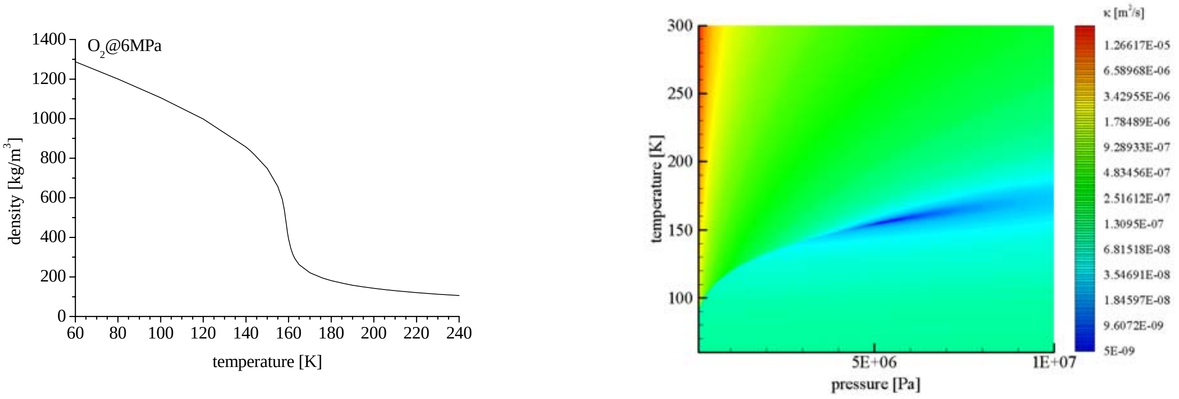
Oxidizer O_2 in high pressure cryogenic rocket engines is injected at pressures above the supercritical pressure of oxygen. At these conditions O_2 exhibits real gas behaviour and its thermo-physical properties reflect near critical point characteristics. Qualitative visualization techniques and quantitative optical diagnostics have been applied to investigate the atomization process and combustion in LOX/H_2-sprays under supercritical conditions at DLR Lampoldshausen. The diagnostic methods applied are presented and the specific adaptations of the methods to the high pressure conditions and there limitations are discussed. Exemplary results are given.

Keyword: *super critical flow, atomization, Schlieren photography, Raman scattering, CARS*

1. Introduction

The injectors for the propellants in rocket engines are the most critical components in respect to the performance of rocket combustors. Propellant injection, atomization and spray combustion are therefore high priority subjects of investigation. Nevertheless today the injection process is included in numerical simulations of rocket combustors as an empirical model. The physics of LOX-atomization is to complex to be simulated based on ab initio approaches. The situation is even worse for high pressure combustors where the combustion chamber pressure is above the critical pressure of oxygen (p_{cr}=5.04 MPa) and the injection temperature of cryogenic oxygen is below the critical point (T_{cr}=154.6K). Typical combustion chamber pressures for heavy thrust cryogenic liquid rocket engines are above 10 MPa. Concepts used to model spray combustion in sub-critical applications cannot be used at these supercritical conditions. The fluids have to be described by a real gas equation of state and their thermo-physical properties are showing a specific behaviour. For example surface tension is no longer controlling the disintegration of the dense cryogenic oxygen fluid. In the near critical temperature region the density becomes a very sensitive function of temperature (fig. 1a) and the thermal diffusivity exhibits a remarkable minimum (fig. 1b).

The request for experimental data on supercritical injection is challenging. Optical diagnostic methods proven at sub-critical conditions are suffering at supercritical pressure conditions. Imaging methods have to face high refractive index gradients resulting from the density gradients in these high pressure flows. Quantitative optical diagnostic methods like spontaneous Raman scattering or CARS have to take into account that spectroscopic properties may change at high molecular densities. During the last years at the Institute of Space Propulsion at DLR Lampoldshausen optical diagnostic methods have been applied for the investigation of supercritical injection in cold flow and hot fire conditions. This paper summarizes the experimental approaches and the results that have been obtained.



(a) (b)

Fig. 1. (a) Density and (b) thermal diffusivity of O_2 in the near critical region.

2. Cold Flow Diagnostics

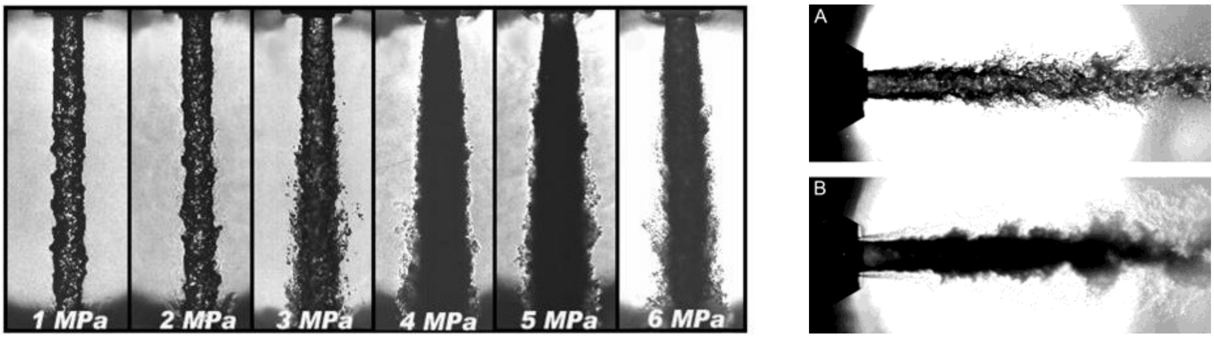
2.1 Cryo-Injector Test Facility

In cold flow tests at the cryo-test facility M51 in Lampoldshausen both free jet injection as well as co-axial jet atomization has been investigated at supercritical pressures, using N_2 as a substitute for O_2. The critical pressure of N_2 is p_{cr}=3.4MPa, thus reducing the pressure requirements to reach thermodynamic states similar to that for O_2 in rocket combustors. The test bench is designed for background pressures up to 6MPa. With N_2 as a model fluid, this pressure corresponds to a reduced pressure of P_r=1.76. Furthermore the chemical inactivity of N_2 is advantageous, especially when investigating coaxial injection and atomization, where the propellants O_2/H_2 are substituted by the non reactive fluid pairs N_2/He or N_2/H_2. Quartz windows allow the application of qualitative visualization as well as quantitative optical diagnostic techniques [1-3].

2.2 Shadowgraphy

Although a qualitative line-of-sight method, shadowgraphy has been shown to be an effective diagnostic tool to investigate single and coaxial jet injection. Shadowgraphy images the gradients of the refractive index, thus density gradients in a one component system as well as species gradients in multi-component systems. Due to the huge density gradients of the cryogenic sub- and supercritical fluids relative to the background gas the injected jet is clearly seen as shown in the examples in fig. 2. In the subcritical case the well defined boundary between the dark jet and the bright background gas can be identified with the liquid surface of the jet. At supercritical pressures the density varies continuously and no surface with dense supercritical fluid on one side and subcritical background gas on the other side exists. The images at P_r>1 show indeed smooth and not sharp interfaces between jet and background gas, however this interface is still clearly visible. In fig. 1a it can be seen that supercritical O_2 shows a very strong gradient $\partial\rho/\partial T$ in a small interval around 155K. Thus the boundary in the shadowgraphs for P_r>1 may correspond to the temperature iso-line where heat transfer from the warm surrounding gas to the cryogenic jet has heated the jet to the temperature where $\partial\rho/\partial T$ is maximum. In this region a small change in temperature is associated with a huge change in density. Therefore geometrical properties such as the spreading angle and the intact core length are accessible with shadowgraphy regardless of whether the jet is subcritical or supercritical. Using a short time-exposure light source, more detailed information on features reflecting the interaction of the jet with its environment can be obtained. For instance, geometric properties of the jet surface area and characteristic length scales of the density variations in the mixing layer of the supercritical jet can be revealed.

The phenomenology of liquid N_2-jet disintegration have been investigated at the cryo-test facility by Mayer et al. [8]. Shadowgraphs of liquid N_2-jet at a temperature of 100K injected into background gas of ambient temperature nitrogen are shown. For subcritical pressure conditions the jet surface appears as a sharp boundary in free jet injection (Fig. 2a) as well as in the binary LN_2/H_2 system. With increasing pressure the typical length scales of surface irregularities become smaller. Slightly below the critical pressure small droplets can be observed in the free jet case. Also in the co-axial injection case at subcritical pressure the classical atomization phenomenology is observed: ligaments and droplets are separated from the liquid core due the shear forces of the annular He-flow (fig. 2b, A). Above the critical pressure significant changes occur. The interface between the dense cryogenic nitrogen and the gaseous environment becomes smooth, drops are no longer detected (fig. 2b). This clearly reflects the disappearance of the surface tension for $P_r>1$.



$P_r=0.3$ 0.59 0.85 1.18 1.47 1.77 A: $P_r=0.3$, B: $P_r=1.77$

(a) (b)

Fig. 2: LN_2 injection into N_2 at 293K. (a) free jet injection ($d_{LN2}=1.9mm$, $v_{LN2}=5m/s$, $T_{LN2}=100K$), (b) co-axial LN_2/He-injection ($d_{LN2}=1.9mm$, $v_{LN2}=5m/s$, $v_{He}=100m/s$, $T_{LN2}=97K$, $T_{He}=280K$) [8].

2.3 Raman scattering

Raman scattering known to suffer from its low scattering efficiency at ambient pressure benefits from the high number densities of the probe molecules at high pressure. Each molecule has its specific Raman shift, Raman scattering is therefore selective for the molecule of choice and individual species can be analysed in a multi-component system.

Limitations at high pressure appear in our applications due to the strong refractive index variation at the boundary between cryogenic N_2 and ambient temperature background gas. This results is severe beam steering and strong elastic scattering at the interface. The strong refractive index gradients require an efficient blocking of the elastically scattered light from the exciting laser beam.

At ambient pressure conditions it is a proven assumption that the Raman scattering cross section is independent of density and the Raman signal intensity is proportional to the number density of the probe molecule. However at high densities this cross section becomes a function of density [9]. There is indication form the experiments that due to internal field effects for N_2 the Raman scattering cross section is increasing at supercritical densities. Fortunately the density on the jet axis is decreasing downstream due to mixing with the surrounding gas and heat transfer. Thus the problems associated with the refractive index gradients and the internal field effects are only prominent in the very near injector region.

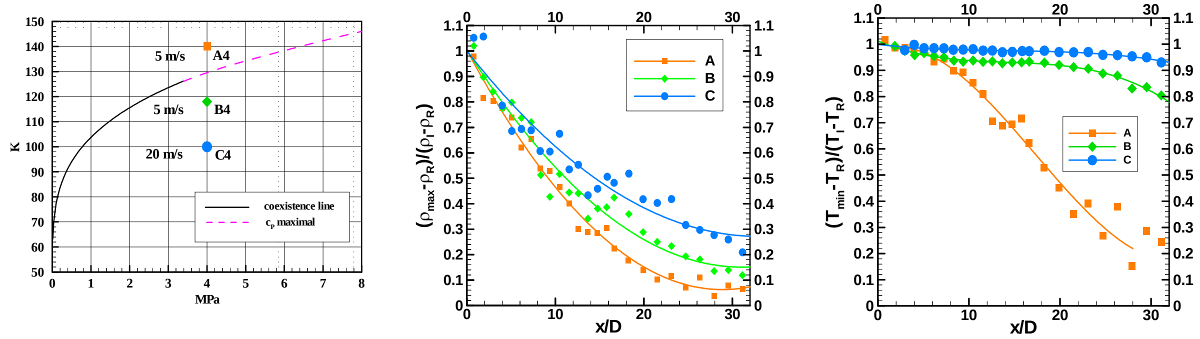
Using a continuous wave Ar-Ion laser operating at 488nm a data acquisition time of 1s was necessary to achieve a sufficient signal-to-noise ratio. The use of a CW-laser practically prevents the formation of signal due to stimulated Raman scattering that may interfere with the spontaneous Raman signal.

Raman scattering has been successful applied to obtain quantitative data on the N_2-density in the case of LN_2 free jet as well N_2- and H_2-density in the case of coaxial LN_2/H_2 injection [1,10]

LN_2 free jet decay has been analysed for three injection conditions at 4MPa, i.e. $P_r=1.18$. The supercritical pressure region in the P/T-diagram near the critical point is characterized by a line continuing the coexistence line, where the specific heat c_p exhibits a maximum (Fig. 3a). Injection temperatures have been chosen to be above (test case A) and below (test cases B and C) of this line. The evolution of the centreline density and temperature of the N_2-jet is shown in fig. 3b and fig. 3c. The units are normalized so that LN_2-injection conditions correspond to a value of 1 and background gas conditions to 0. The general behaviour of the density decay for all injection temperatures is similar. With increasing injection temperature the decay is more efficient and back ground conditions due to efficient mixing are reached earlier. Using the equation of state based on the measured densities temperatures have been determined in this one-component system. As seen in fig. 3c there is a significant difference between test case A and test cases B and C. The test cases B and C with cold injection temperatures show the phenomenon of pseudo-boiling due to the high values of the specific heat in the near critical region. Transfer of thermal energy of the surrounding gas to the cryogenic

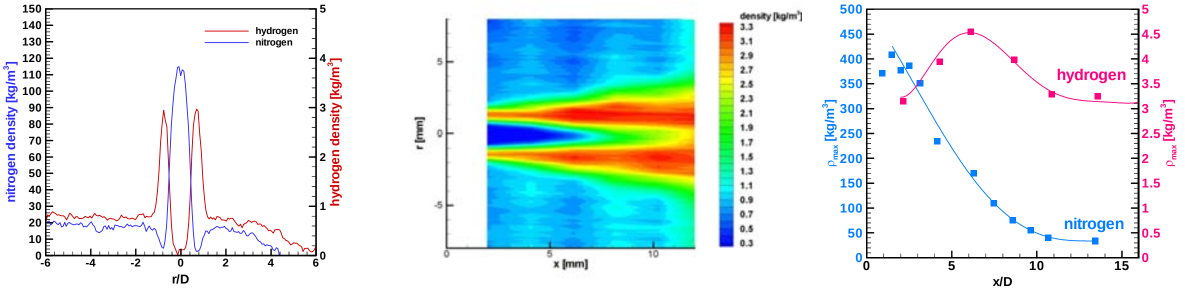
N_2-jet is not resulting primarily in an increase of temperature but in an expansion if the supercritical fluid at this conditions.

Radial density profiles for coaxial LN_2/H_2 injection are shown in fig. 4a. In this test case the ability of Raman scattering to measure specific molecules allows to separately determine N_2 and H_2 densities. In this near injector region the profiles clearly reflect the fluid distribution at the injector exit: cryogenic N_2 is injected through the central post with an annular slit for H_2 injection around it. The reason for the decrease of the density values for large r/D in fig. 4a is beam steering due refractive index gradients. The exciting laser beam traverses the LN_2/H_2-jet from left to right, after the laser beam has passed the jet it is strongly disturbed. In fig. 4b it can be seen how the H_2-density on the centreline is increasing downstream due to mixing into the nitrogen flow. One would expect that downstream the density of H_2 should decrease continuously due to this mixing process. However an increase of the maximum density of H_2 has been observed in the near injector region as seen in fig. 4c. The phenomenon is understood as a fingerprint of an efficient heat transfer from the central cryogenic LN_2-jet to the annular H_2-flow.



(a) (b) (c)

Fig. 3: (a) test cases for LN_2 free jet tests, centerline decay of density (b) and temperature (c)



(a) (b) (c)

Fig. 4: Coaxial injection of LN_2/H_2 (T_{N2}=140K, T_{H2}=270K). (a) Radial density profiles for N_2 and H_2 for x/D= 1, (b) H_2 density distribution, (c) Evolution of maximum nitrogen and hydrogen density downstream of the injector for T_{N2}=118K, T_{H2}=270K.

3. Diagnostics of Hot Run Tests

3.1 High Pressure Combustion Research and Technology Test Facility P8

The European test bench P8 is a French/German high-pressure test facility for research and technology investigations at combustion chamber conditions representative of modern cryogenic rocket engines [4]. Propellant supply systems (LOX, LH_2 and GH_2) can provide pressures up to 360 bar at the test bench interface to the test specimen. The model combustor C has been used in the hot fire tests and under super-critical pressures. The modular combustor is equipped with a single coaxial injector head. At temperatures up to 3400K and pressures up to 10MPa only non-intrusive measurement techniques can be applied to get information about the thermal field in the flow. A module with optical access enables the application of optical diagnostic techniques at pressures as high as 9MPa [5-7] (see fig. 5).

3.2. Flow Visualization

At cold flow conditions cryogenic jet atomization has been shown to change significantly its phenomenology when going from sub- to supercritical pressures. At hot fire conditions heat release and change of the gas composition due to chemical reactions are participating processes in controlling the dynamics of jet atomization.

Mayer et al. [8, 12] have applied shadowgraphy at combustor C at the P8 test facility. When applying the shadowgraphy method in high pressure combustion, it is essential to gate the background light originating from the flame emission by short-exposure times. In the tests at the P8 bench, this has been accomplished by mechanical shutters.

As in the cold flow case at sub-critical pressure a sharp interface between cryogenic O_2 and surrounding gas is observed similar to the cold-flow results (fig. 7a). Significantly different as compared to the cold flow is the strongly reduced number of small droplets due to evaporation.

At supercritical pressure conditions no more droplets can be observed (fig. 7b), the interface between the central O_2-flow and the surrounding gas has a diffuse character. The phenomenology appears now less similar to atomisation but rather to the turbulent mixing of two gas-like fluids.

At supercritical conditions further downstream the jet as visible in the shadowgraphies remains compact showing oscillations with increasing amplitude. Whereas at subcritical pressures the jet is disintegrated into individual droplets (fig. 7a) at these positions the supercritical LOX-jet is disintegrated into O_2 clumps much larger than a typical liquid entity observed in the subcritical case.

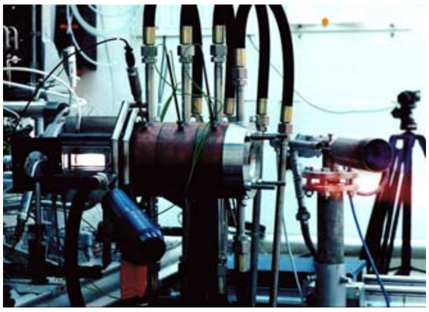
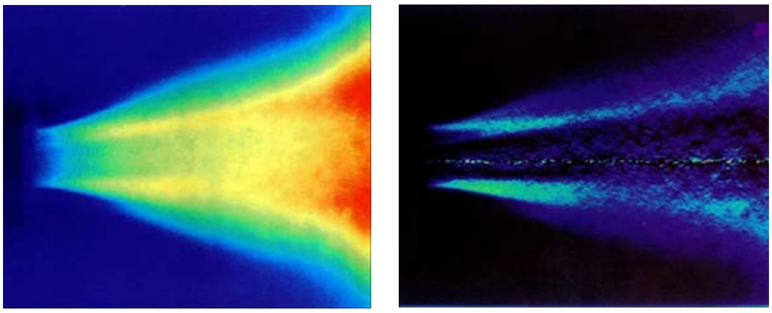
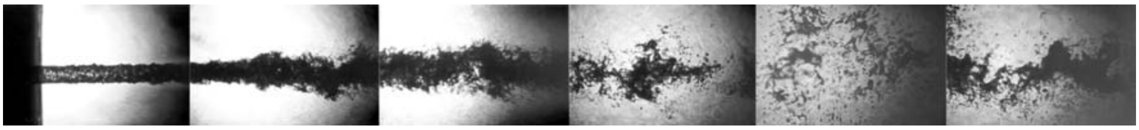


Fig. 5: Combustor C with optical access for the investigation LOX/H_2-injection at pressures up to 10MPa.

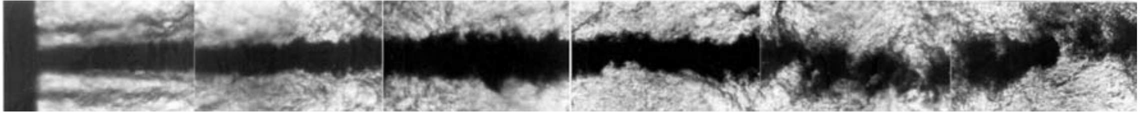


(a) (b)

Fig. 6: (a) OH emission of the LOX/H_2-spray flame, (b) cross sectional distribution of OH-emission reconstructed by the Abel deconvolution-method

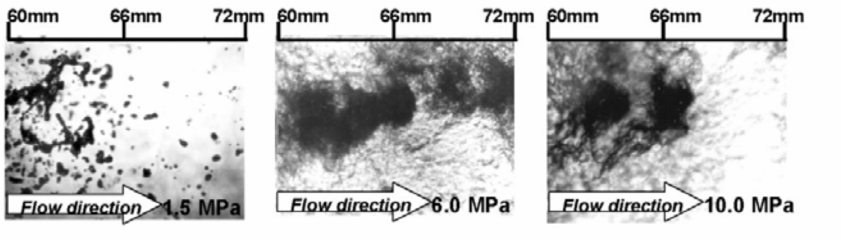


(a)1.5MPa, P_r=0.3



(b) 10MPa, P_r=2.0

Fig. 7: Combustion of coaxial injected LOX/H_2 at sub- and supercrtical pressure [11]



(a) P_r=0.3 (b) P_r=1.2 (c) P_r=2.0

Fig. 8: Visualization of the O_2-jet break up in hot fire tests up at sub- and supercritical pressures [8]

3.3. Flame Visualization

As a standard tool for detecting the regions of chemical activity in the reactive flow imaging of the chemiluminescence of the OH-radical has been used. The OH-emission is detected with an intensified CCD camera with an interference filter transmitting radiation in the range 300-310nm in front of the imaging system.

Although a line of sight method this visualization technique can contribute essential information on flame stabilisation and flame anchoring mechanisms. The draw back of the spatial integration of the light detection is limited because the cylindrical symmetry of the problem allows the deconvolution of the image to recover the OH-emission in a cross section through the cylinder axis by the Abel-method. Image raw data and the deconvoluted image are shown in fig. 6a and fig. 6b respectively. In the deconvoluted image it is clearly seen, that the flame is anchored in the recirculation at the lox-post between the O_2- and H_2-flows.

3.4. CARS Thermometry

For quantitative thermometry in combustor C CARS, a proven optical technique for thermometry at ambient pressure conditions, has been applied [5]. By fitting theoretical CARS-spectra to experimentally obtained spectra the temperature dependent population in the ro-vibrational states of the probe molecule is determined and thus the temperature evaluated. At high pressure collisional line broadening has to be taken into account for accurate data reduction. Especially H_2-H_2O collisions contribute the major part to the line width. In co-operation with V. Smirnov et al. from the IOFAN institute in Moscow these line broadening data have been determined in laboratory experiments in the temperature range of interest (fig. 9) [12]. However, for analysing experimental spectra also the density of H_2O in the probe volume has to be known to determine the line broadening due to H_2-H_2O collisions. Two approaches are possible to get the necessary information. In the measured H_2-CARS spectra probe molecules other than H_2 contribute with there non-resonant suszeptibility to specific spectral features that can be analysed. Another approach that requires more effort on the experimental side is to measure simultaneously to H_2- also H_2O-Cars spectra from which the H_2O-density can be estimated.

Examples of temperature distributions determined with CARS for positions y=8mm off-axis in the turbulent reactive flow in combustor C are shown in fig. 10. Combustion chamber pressure was 6.3MPa. 50mm downstream the injector an unimodal temperature distribution is found with a mean temperature of 430K, indicating that hot reactions products are still not mixed into the injected H_2-flow. At 80mm downstream the injector bimodal temperature distributions are observed. The flow is still stratified due to incomplete mixing at this position and alternately hot gas pockets of reaction products and cold gas pockets are convected by the turbulent flow field into the measurement volume. This results show that CARS data not only deliver mean temperatures. Due to the temporal and spatial resolution of the method information on the state of mixing can be obtained as well.

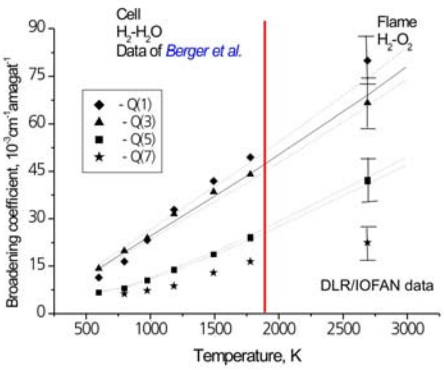


Fig. 9: Line broadenng coefficients for H_2-H_2O collisional broadening at high temperatures [12].

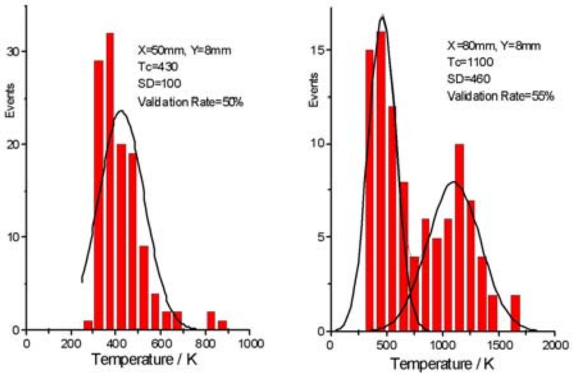


Fig. 10: Histograms of temperatures determined with CARS at 50mm and 80mm downstream the injector [6].

Conclusions

Optical diagnostics at high pressure has to face two major problems: beam steering of optical rays due to refractive index gradients and the interaction of the environment with the probe molecules when using spectroscopic methods. Although the density gradients may prohibit the application of optical diagnostic methods, especially in the near injector region, the experiments have shown that non-intrusive diagnostics can successfully be applied at supercritical pressure conditions.

Shadowgraphy benefits from the huge gradient $\partial\rho/\partial T$ which occurs in a small temperature interval at supercritical conditions and which allows discriminating the cryogenic jet against the background gas at ambient temperature. Shadowgraphy therefore can evaluate geometric features of the jet atomization phenomenology and thus gives access to basic jet atomization mechanisms as well as geometric properties like e.g. jet spreading angle.

Spectroscopic methods benefit from the high number density of the probe molecules: the more molecules interact the higher is the signal intenisty. For spontaneous Raman scattering this makes density measurements possible with acceptable S/N-ratio. On the other hand collisions of other molecules with the probe molecule can have significant influence on its spectroscopic properties. This requires more detailed modeling of the interaction process of light with matter and/or increased experimental effort to characterize the environment that influences this interaction process. With CARS it has been demonstrated at pressures up to 6MPa that this problems can be handled in high pressure combustion applications.

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