Probing of the reservoir, free stream and shock layers in HEG using spectroscopic techniques

W. H. Beck[1], O. Trinks[1], M. Wollenhaupt[1], A. Mohamed[2], C. Niederbäumer[3], P. Andresen[3], T. Kishimoto[4], H. Bito[5],

1. Institute for Fluid Mechanics, DLR, 37073 Göttingen Germany
2. ONERA, 92322 Châtillon France
3. Department of Physics, University of Bielefeld, 33615 Bielefeld Germany
4. Aerospace Group, Kawasaki Heavy Industries, Kakamigahara 504 Japan
5. Space Utilization Division, Science and Technology Agency, Tokyo 185 Japan

Abstract: Light emission from the HEG shock tube reservoir has been spectrally or temporally analysed. Diode laser absorption measurements on nitric oxide (NO) and rubidium atoms in the free stream flow are used to determine the change in kinetic temperature, gas velocity and NO concentration during the test time. Flash lamp absorption measurements, also in the free stream, lead to estimates of the rotational and vibrational temperatures of NO in the flow. Finally, an NO rotational temperature determination using laser induced fluorescence to probe the gas behind a weak shock in HEG is presented.

Key words: Shock tunnel, Diode laser absorption, Rubidium, Nitric oxide, Flow velocity and temperature, Planar laser-induced fluorescence

1. Introduction

In an ongoing effort to better understand and characterise high enthalpy gas flows, several spectroscopic techniques have been used on the high enthalpy shock tunnel HEG. So far one has had to rely on measurements of bulk properties (wall pressures and heat transfer rates), which are input into CFD calculations to determine the full gas and flow properties, a procedure which is only as good as the model and input data for the CFD calculations allow. In fact, a major purpose for using spectroscopic techniques is to validate the models and codes used in CFD. With the aid of these techniques, the following regions in HEG have been probed and the results are discussed here:- (i) The high pressure/high temperature reservoir region (∼40 MPa/9000 K for HEG condition I) at the nozzle inlet; (ii) the hypersonic free stream flow (∼900 K/6000 m s^{-1}, as calculated for condition I) in the test section; (iii) the shocked gas region in the vicinity of the wing tip fin of the Japanese space glider HOPE.

The application of four techniques will be described:- (i) Spectrally or temporally resolved emission spectra have been recorded in the HEG shock tube reservoir using a light sensitive diode or an optical multichannel analyser (OMA). The aim of these measurements is to understand the development of the flow in the reservoir and to probe its state (e.g. temperature). (ii) In order to characterise the HEG free stream flow, a diode laser is used to scan rapidly across the absorption line of a species present in this flow. Although this can be done at scan rates of well over 1 MHz, in this work rates of only 10 - 20 kHz (sawtooth function) were used. Nevertheless, several absorption line profiles can be measured during the 1 ms flow time in HEG. The laser beam also traverses the flow at an angle so that a measurement of line shape, spectral shift and area enables one to determine a kinetic temperature, flow velocity and species concentration spatially averaged along the line-of-sight. Two species have been probed here at two different wavelengths - naturally occurring nitric oxide (NO) at 5.4 μm, and seeded rubidium (Rb) atoms at ∼780 nm. This technique has been used already to examine NO absorption in a high enthalpy wind tunnel flow (Rosier et al. (1993)), and to measure O atom absorption in the heated gas behind the reflected shock in a small shock tube (Chang et al. (1992)). (iii) A further line-of-sight technique to measure rotational and vibrational temperatures in the HEG free stream flow is flash lamp absorption of NO. The lamp, with high UV output, is pulsed at a high repetition rate (50 kHz), and the light pulses are spectrally resolved by a spectrometer (at low and high resolution) and monitored by an OMA operating in the streak mode, enabling several time resolved spectra to be recorded during the HEG flow. This technique has already been used to carry out studies in an internal combustion engine. (Niederbäumer (1994)). (iv) Two line thermometry has been carried out in the vicinity of a model in the HEG flow (Wollenhaupt (1997)). Planar laser induced fluorescence images were recorded by laser excitation of NO at ∼193 nm at a location near the wing tip fin of a double delta model (a candidate shape for the future Japanese space glider HOPE), and suitably combined to yield a rotational temperature (relative to the free stream value). Where applicable and available, all measurements are compared with CFD calculations.

2. Experimental arrangement

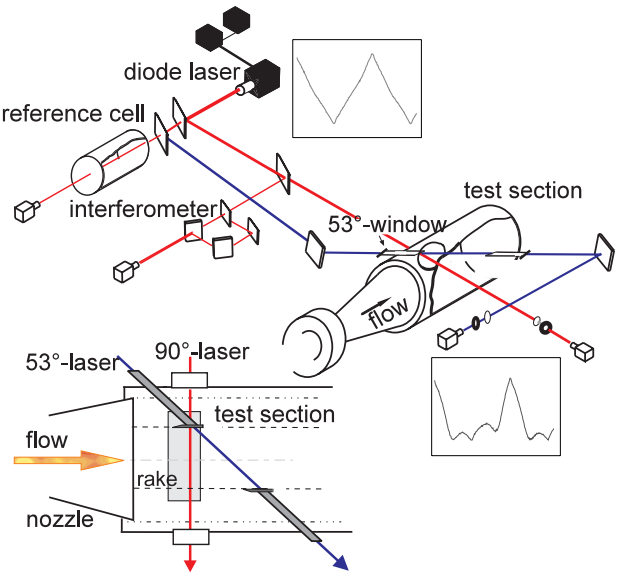

Figure 1. Experimental setup for both diode laser absorption measurements (using NO and Rb).

Emission measurements were carried out in the reservoir by installing a quartz window at the position of a pressure sensor in the shock tube end wall, and extracting the emitted radiation via a quartz optical fibre on to an OMA. This is described in detail elsewhere (Trinks et al. (1996)). Both experimental setups for diode laser absorption were similar (see Mohamed (1996) and Trinks (1997)), and are shown in Fig. 1. The laser beam, after decoupling a small percentage of the intensity into a calibration cell and into a Fabry-Perot interferometer, was sent at an angle of 53° through the HEG flow. A gas-tight, light guiding pipe with afixed wedges to reduce flow disturbance (see Fig. 1, lower schematic) was mounted at the laser windows and extended along the laser path into the flow through the outer stagnant gas region and the boundary layer; this was done to ensure that the laser beam itself passed through only the free stream core flow. The calibration and absorption signals were recorded on a transient recorder. The transitions and lasers used were:- for Rb, the D_2 transition $5^2P_{3/2} \leftarrow 5^2S_{1/2}$ at 780.245 nm, excited with a ROHM GaAlAs diode laser; and for NO, the (1,0) R(3.5) single line transition at 1863.6833 cm^{-1}, with a Laser Components DH4 (PbEu)Se diode laser. The flash lamp absorption apparatus (see Fig. 2 and Niederbäumer (1994)) consists of a Strobokin flashlamp with high UV output and high repetition rate, a Leeman Labs Echelle Spectrometer with high resolution or an Acton Research Spectrometer for low resolution, and a streak camera to record absorption spectra from the flash lamp pulses. Low (210 - 240 nm) and high (full range ~1 nm) resolution spectra were recorded, giving spectra with vibrational band envelopes and single rotational lines in order to determine a vibrational and rotational temperature, respectively. The PLIF apparatus has been described in detail elsewhere (Scheer et al. (1996), Wollenhaupt (1997)), and recent developments in the use of LIF on HEG are the subject of another paper presented here (Wollenhaupt et al. (1997)). The NO transitions $\varepsilon(0,1)$ $R_{22}(27.5)$ and $\varepsilon(0,1)$ $R_{21}(17.5)+P_{11}(35.5)$ ($\Delta E_{Rot} = 912$ cm^{-1}) are excited using two ArF excimer lasers (193 nm), and the fluorescence images are recorded using LaVision Flamestar image intensified CCD cameras (ICCD's). Since there is considerable interfering radiation from contamination in the gas flow, the 2D PLIF images were recorded through specially designed, image-quality filters with transmission in the range 215 ± 5 nm (see Wollenhaupt (1997)).

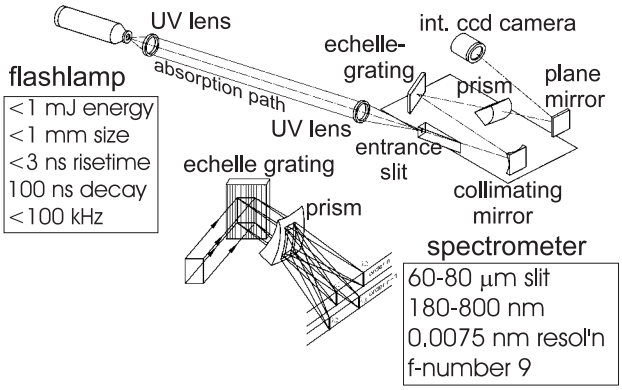

Figure 2. Experimental setup for flash lamp absorption measurements in HEG.

3. Results

All results presented here were carried out at HEG condition I ($p_0 = \sim$37 MPa; $h_0 = \sim$22 MJ kg^{-1}). Results in the free stream are compared with values calculated from STUB, a 1D Euler code (including chemistry) which predicts the nozzle exit flow (see Vardavas (1984)).

3.1. Shock tube reservoir - emission

Fig. 3 shows spectrally resolved emission from the shock tube reservoir (upper trace), and, for comparison, a spectrum measured behind the bow shock of a cylinder in the test section at similarly high temperatures but much lower pressures (40 cf. 0.05 MPa). (The dip in the upper trace at 510 nm is an artefact due to an imperfection in the ICCD.) Also shown in the upper trace is the spectrum from a Hg vapour lamp used for calibration purposes, and recorded with the same setup as in the reservoir; the broadening of these lines is largely an apparatus function, and hence gives a measure of the spectral resolution of the measurement in the reservoir. The reservoir result shows no discrete emission, but clearly cannot originate from pressure broadening of a spectrum similar

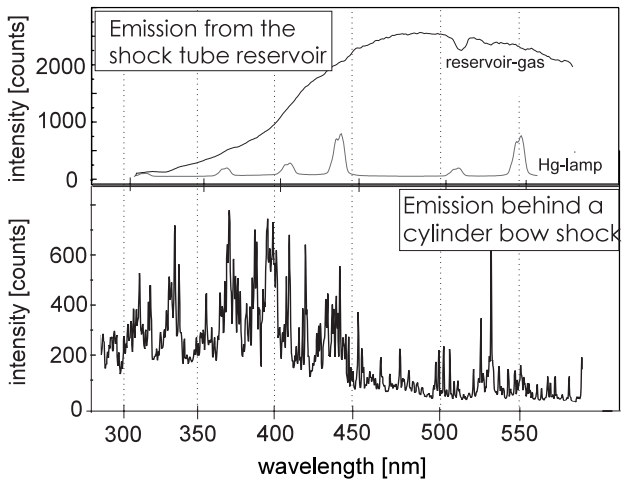

Figure 3. Comparison between emission spectra obtained in reservoir and behind a strong shock in front of a cylinder in HEG.

to that in front of the cylinder. The mechanism leading to the spectrum in the reservoir is not understood, although there seems to be a similarity to a blackbody radiation curve; measurements over a wider wavelength range, and with proper intensity calibration of the OMA are needed to answer this question.

3.2. Free stream - diode laser absorption

The measured Doppler shift in the position of the absorption lines is used to evaluate the gas flow velocity. It can be shown for Rb (Trinks (1997)) that the main mechanism leading to line broadening under HEG free stream conditions is Doppler broadening, so that measurement of the absorption line shape gives a value for the kinetic temperature T_{kin}. A similar assumption is made for NO in the free stream (Mohamed (1996)). Furthermore, the encompassed line area gives a measure of the species concentration (here for NO). Results are presented using two probed species, Rb and NO, and for two experimental arrangements in HEG - with and without the presence of a model (e.g. measurement rake) in the test section. Temperature results at early times (< 5 ms, see Fig. 4 and Fig. 5) show large fluctuations; at these times the nozzle flow starting processes are still occurring, and concentrations of the probed species are still quite low, leading to low absorption signals and hence less accurate temperature determinations.

3.2.1. Test species Rb

The time development of temperature and velocity in the free stream, as measured using Rb absorption lines, is shown in Fig. 4, middle and lower traces, respectively. Typical error bars (±20 % temperature and ±5 % velocity) are also shown. A comparison with STUB values, plotted at the time (∼6.0 - 6.2 ms) where the test window is taken to be, shows good agreement. Measurements with the rake lead to higher temperatures and lower (and noisier) velocities; this is as expected, since the rake decelarates a small portion of the flow, leading to gas at higher temperatures and lower velocities.

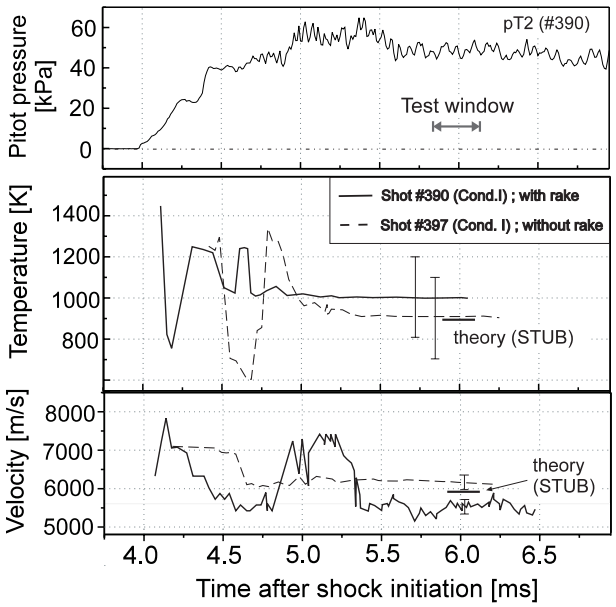

Figure 4. Time development of Pitot pressure, temperature and flow velocity, as determined from diode laser absorption measurements with Rb.

3.2.2. Test species NO

Temperature, velocity and concentration time plots for NO are shown in Fig. 5 and again compared with STUB in the test window, as before. The Pitot pressure trace is also shown (upper trace), and compared with values calculated by STUB and ESTC (a computer code using the standard shock relations, see McIntosh (1968)) for the assumption of frozen and equilibrium flow. STUB temperatures lie somewhat lower and velocities somewhat higher here, but after allowance for the error bars, they agree quite well with measured results for the case where the rake was removed. The measured NO concentrations lie well above and below the STUB value; however, due to the complex kinetic processes leading to this minority species, it is not surprising that both the measured and calculated values do not agree well. Here there is a negligible effect of the rake for temperature and velocity, but not so for NO concentration.

3.3. Free stream - flash lamp absorption

The high resolution apparatus used here enables one to resolve the rotational structure of NO in the HEG free stream. Fig. 6 shows the measured flash lamp absorp-

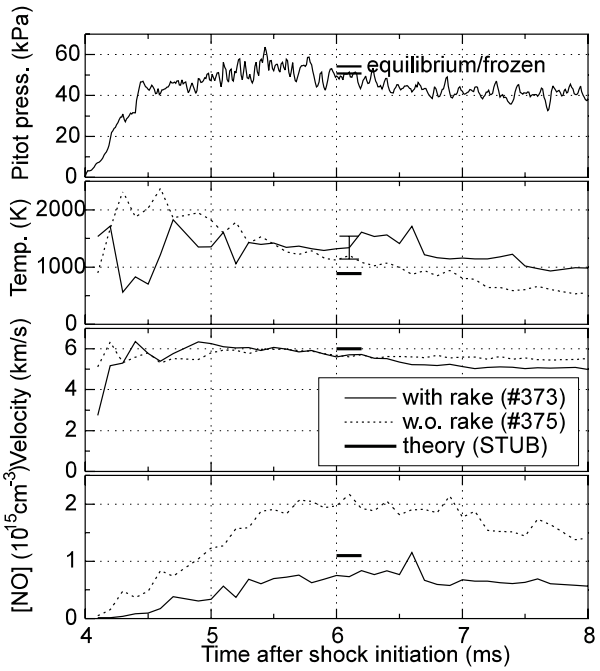

Figure 5. Change of Pitot pressure, T_{kin}, velocity and NO concentration in the HEG free stream.

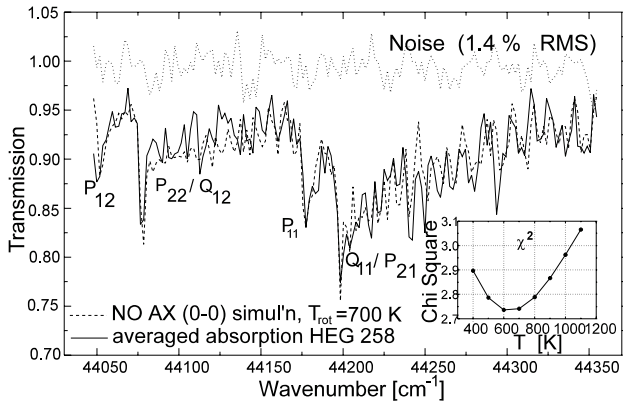

Figure 6. Comparison between measured and simulated NO absorption spectra, including a χ^2 plot to judge the goodness of fit for T_{rot}.

tion spectrum (full line) in the range 44050 - 44350 cm^{-1}, compared to a simulation (dotted line) calculated for NO absorption with an assumed rotational temperature T_{rot} of 700 K. Even though the agreement is not perfect, one can see that the essential features have been captured. An estimate of the accuracy of the measured T_{rot} is given by the inset plot, where the goodness of fit, represented by values of χ^2, is given for different values of T_{rot} - it can be seen that the best-fit T_{rot} = 650 K has an uncertainty of about ±10%. A value for an NO vibrational temperature T_{vib} could be inferred from further measurements (not shown here) carried out at lower resolution, where one could measure simultaneously several vibrational bands. A value for T_{vib} = 2500 ± 300 K was obtained, which agrees reasonably well with a calculation for the HEG flow, but is different from a measurement using LIF (both described in Wollenhaupt et al. (1997)).

3.4. Comparison of free stream results

Temperatures and velocities obtained with the three aforementioned techniques are compared with STUB calculations in Fig. 7. T_{kin} from laser diode absorption of Rb and NO (measurement without the rake) and T_{rot} from flash lamp absorption all lie quite close to the STUB values. However, when the error bars shown in the figure are considered, the flash lamp result T_{rot} seems to lie below STUB and experimental T_{kin}. Too few results are available on HEG to determine whether this is a systematic trend. Both diode laser techniques give quite good agreement in the gas velocity, and lie (just) within experimental error of the STUB value. Since the measured velocity is a good guide to the enthalpy of the flow, this agreement is encouraging and confirms that the HEG flow enthalpy, as calculated by STUB, is close to the experimentally determined value.

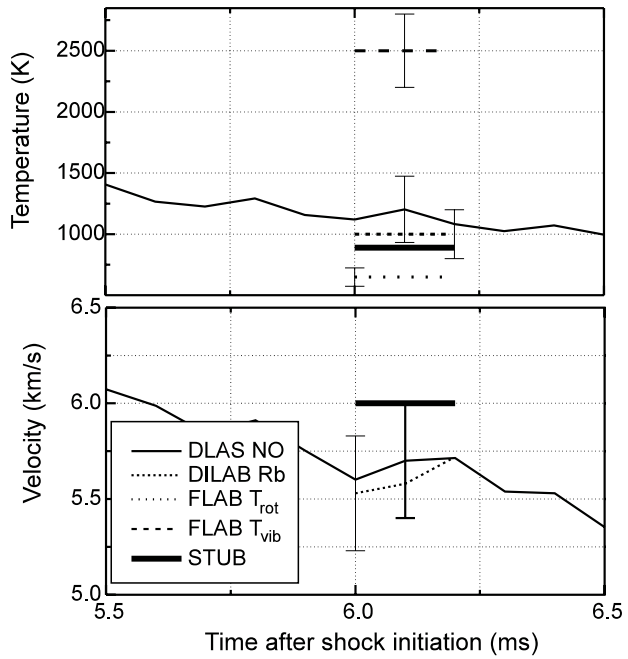

Figure 7. Comparison between measured diode laser (DLAS and DILAB) and flash lamp absorption (FLAB) and calculated (STUB) temperatures and flow velocity.

3.5. Shock layer - planar laser induced fluorescence

A plot of temperature across the oblique bow shock near the wing tip fin of the HOPE model, measured using PLIF, is shown in Fig. 8. Interference arises from un-

known saturation effects in the contribution of the NO $\varepsilon(0,1)$ $P_{11}(35.5)$ line (these saturation effects are discussed in Wollenhaupt et al. (1997)), so that this contribution needs to be estimated and allowed for; this leads to a considerable uncertainty in the measured T_{rot}. It is compared with a laminar Navier Stokes calculation assuming equilibrium flow, and also with two calculations using the standard shock relations (ESTC, see McIntosh (1968)) for an oblique 20° shock in the HEG free stream flow, where both equilibrium and frozen flow have been assumed. In HEG the equilibrium temperature for this oblique shock lies higher than frozen because the free stream flow is not in chemical equilibrium, so that the "stored" chemical energy is released for forced equilibrium behind the shock. All measured and calculated plots have assumed the value for free stream temperature calculated by STUB, T_{fs} = 700 K. The apparent mismatch in temperature T_{fs} at 0 mm (location of shock) is due to the poor numerical and experimental spatial resolution. As expected for this quite weak oblique shock, the frozen calculation agrees much better with the measured result - the flow is not strongly turned behind the shock, so that the temperature jump across the shock is not large, and the flow velocity is still quite high, both effects making attainment of equilibrium unlikely.

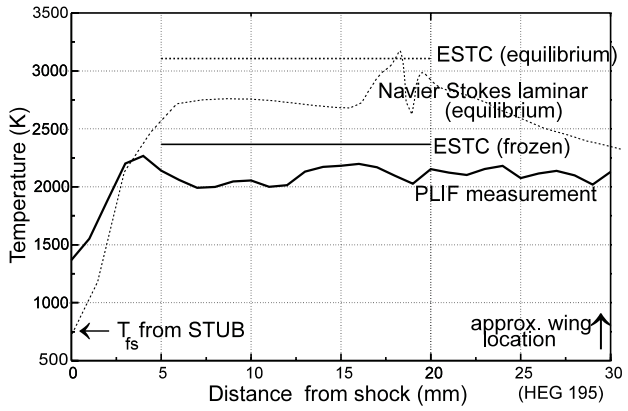

Figure 8. Comparison between measured (laser induced fluorescence) and calculated (Navier stokes and ESTC) temperatures near the HOPE wing tip fin in HEG.

4. Conclusions

It has been shown, with the help of four different optical spectroscopic techniques, that these techniques have matured sufficiently to help in characterising the HEG free stream and to examine the gas flow around quite complex model shapes in HEG. Further work and refinement is needed to improve the accuracy of the methods, and to account for or remove disturbances which may influence the measurements.

Acknowledgement. The authors would like to thank D.Bize and D. Henry (both ONERA) for contributing to the NO diode laser work, and J. Lenz, D. Garbe and U. Frenzel (all from HEG) for their support on the tunnel. The financial support of ESA is also gratefully acknowledged.

References

Chang HA, Baer DS, Hanson RK (1992) Semiconductor laser diagnostics of atomic oxygen for hypersonic flowfield measurements. AIAA Paper 92-0628.

McIntosh MK (1968) Computer program for the numerical calculation of frozen and equilibrium conditions in shock tunnels. Internal report, Department of Physics, ANU, Canberra.

Mohamed AK (1996) Infrared diode laser absorption spectroscopy in wind tunnels. I. Experimental setup. ONERA Technical Report 8/7301 PY.

Niederbäumer C (1994) Rotationsaufgelöste Absorptionsspektroskopie an NO- und OH-Molekülen zur Untersuchung von Verbrennungsprozessen. Diplom thesis, University of Bielefeld, Germany.

Rosier B, Mohamed AK, Henry D, Juville S (1993) Mesures par spectroscopie d'absorption diode laser a la soufflerie F4. ONERA Final Report 8/4383 PY.

Scheer M, Wollenhaupt M, Rosenhauer M, Beck WH (1996) Temperature and density measurements on hypersonic wind tunnels using laser induced fluorescence of NO, including a study of NO spectroscopy using a novel heated cell. DLR-IB 223-96 A 32 (Diplom thesis, University of Göttingen, Germany).

Trinks O (1997) Diodenlaser Absorptions Spektroskopie am atomaren Rubidium im Hochenthalpiekanal HEG zur Bestimmung der Strömungsgeschwindigkeit und Gastemperatur. Diplom thesis, University of Göttingen, Germany. In preparation.

Trinks O, Wollenhaupt M, Beck WH (1996) Messungen des Gasleuchtens, der Ionisation und der Temperatur am Stossrohrende des Hochenthalpiekanals HEG. DLR Report DLR-IB 223-96 A 34.

Vardavas IM (1984) Modelling reactive gas flows within shock tunnels. Aust J Chem 37:157–177.

Wollenhaupt M (1997) Einzelpuls Zwei-Linien-Thermometrie mit planarer laserinduzierter Fluoreszenz an NO-Molekülen in Hochenthalpieströmungen. Dissertation, University of Bielefeld, Germany.

Wollenhaupt M, Rosenhauer M, Müller T, Jourdan J, Scholz J, Hartung S, Beck WH (1997) NO laser-induced fluorescence studies for the application of single-shot two-line thermometry to HEG. Paper 8360 presented at ISSW21, Great Keppel Island, Australia.