12th International Symposium on Applications of Laser Techniques to Fluid Mechanics, 12-15 July 2004, Lisbon, Portugal.

Preliminary Investigations on Thermometry in Thermal Flows via Transient Grating Spectroscopy (TGS)

by

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ABSTRACT

The laser-based diagnostic method *Transient Grating Spectroscopy (TGS)* is investigated as a noninvasive, local and time-resolved temperature measurement technique with respect to its application in thermal flow environments. TGS determines in a probe volume comparable to the *Laser Doppler Anemometry (LDA)* in a period of a few hundred nanoseconds the local speed of sound and thus the temperature of the flow medium by using the contrast modulation of a pulsed laser induced refraction index grating. The contrast modulation is detected by a continuous-wave probe laser beam. Figure 1 shows a typical TGS-Signal trace recorded on a digital oscilloscope. Compared to other resonant laser-diagnostic applications like *Coherent Anti-Stokes Raman Spectroscopy (CARS)* the *Transient Grating Spectroscopy* is experimentally less complex and less extensive.

This work addresses the dependency of the signal strength and the signal-to-noise ratio on different parameters like ambient pressure, pulsed-laser energy and probe-laser power. The signal strength increases approximately quadratically with the ambient pressure and the pulsed-laser energy. The TGS signal amplitude is linearly related to the probe beam power.

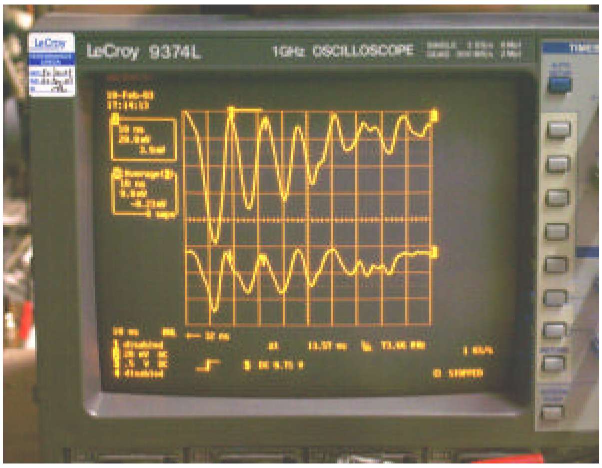

Fig. 1. Typical TGS-Signal trace on an oscilloscope.

Tests have been conducted and statistically analyzed at laboratory temperature. The resulting accuracy of up to 1.6 K seems to be very sufficient. Measurements in an electrically heated oven show a good agreement with simultaneously taken thermocouple readings. The influence of gaseous combustion products on the speed of sound was previously discussed in literature and will be investigated later on. The strong density or pressure dependence of the signal strength seems to be disadvantageous when measuring in hot environments as first tests in candle flames have shown. But this can be compensated by either increased pulsed-laser energy or higher ambient pressure in the medium, e.g. in high-pressure burners. Possible design relevant improvements concerning the pulsed laser like the usage of a seeded Nd:YAG laser are discussed. The application of the infrared wavelength of a Nd:YAG laser (1064nm) for the grating generation could also be favorable.

These investigations are implemented within the framework of project no.5 "Investigation of the Correlation of Entropy Waves and Acoustic Emission in Combustion Chambers" of the DFG Research Unit 486 "Combustion Noise" supported by the German Research Foundation (DFG). In this project the main interests are correlation measurements between temperature, velocity and pressure fluctuations in combustion flows.

1. INTRODUCTION

In thermal flow environments the temperature field is one of the very important basic quantities for diagnostic research. Especially in unsteady reacting flows the time-resolved measurement of temperature is of great interest in order to understand the complex interaction of the local chemistry, fluid dynamics, heat transfer and sound generation of combustion gases. Conventional measurement techniques with thermocouples acquire mainly time-averaged values, may show severe bias errors due to thermal radiation and due to fluctuating heat transfer in turbulent flows and are additionally highly intrusive. Other methods like *Coherent Anti-Stokes Raman Spectroscopy (CARS)* are highly developed, although they are still very demanding and require two lasers, typically a tunable pulsed dye laser and a pulsed YAG laser, and the means to spectrally resolve and evaluate the signal. Therefore, *Transient Grating Spectroscopy (TGS)* as a nonintrusive nonresonant laser-based technique has been investigated with respect to its application for local and time-resolved temperature measurements in thermal flows.

In the following the influence of various parameters on the signal-to-noise ratio are discussed in order to evaluate the applicability of the TGS technique in the combustion flows of interest.

The physical concept of the TGS method is described among others in Eichler et al. (1986). Successful tests in combustion flows have been conducted by Brown and Roberts (1999), and Stampanoni-Panariello et al. (1998).

2. PHYSICAL PRINCIPLE

The scheme of the TGS underlying physics is drafted in figure 2. By means of two crossed coherent pulse-laser beams (green) with a pulse length of about 5 ns a refraction index grating is locally induced into the flow medium. The grating induced by eletrostrictive effects remains for a duration up to a few hundred nanoseconds (q.v. Brown and Roberts (1999)).

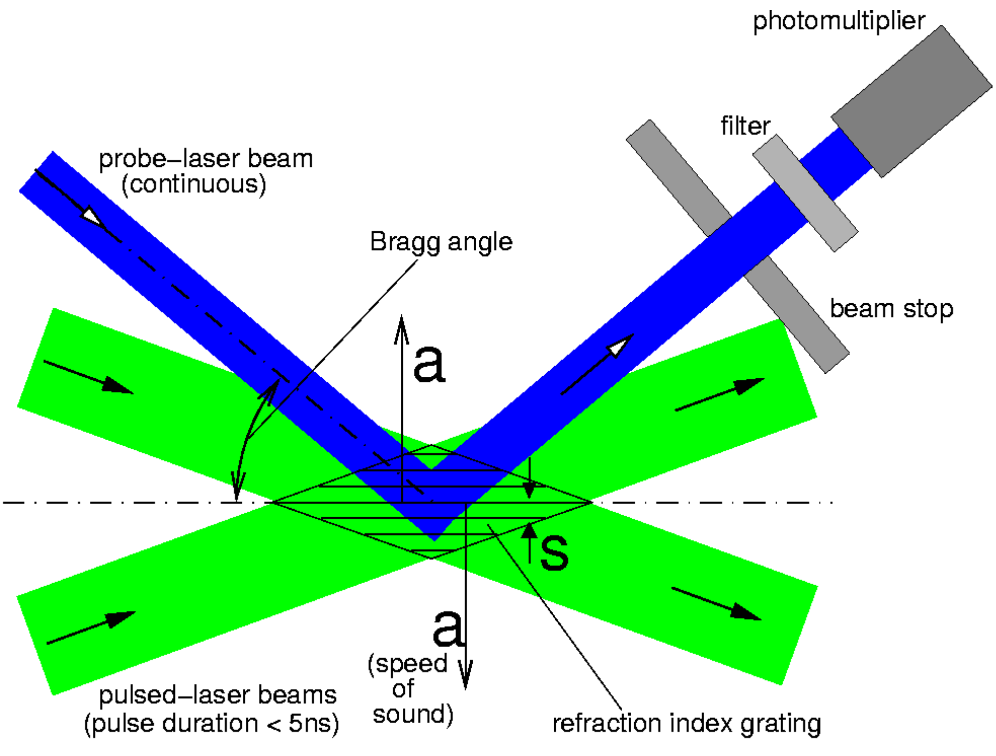

Fig. 2. Sketch of the physical principle of Transient Grating Spectroscopy.

During this time period the grating propagates with the local speed of sound in all directions. Due to the propagation in perpendicular direction of the grating fringes its contrast (visibility) is modulated in time. The modulation frequency f_M is calculated from local speed of sound a and grating fringe spacing s:

$$f_M = 2 \cdot \frac{a}{s}. \qquad (1)$$

The modulation frequency is detected by a third continuous-wave laser beam (blue). This so called probe beam is introduced under Bragg-angle conditions to the grating. The Bragg reflection of the probe light beam oscillates with the modulation frequency f_M of the grating contrast. A photomultiplier collects the intensity fluctuations of the probe light at frequencies up to 200 MHz. The local and time-resolved temperature follows from the expression for the speed of sound (ideal gas law):

$$T = \frac{a^2}{k \cdot R}, \qquad (2)$$

where T is the absolute temperature, R the gas constant and 6 the isentropic exponent. R is inverse proportional to the averaged molar mass of the gas.

3. EXPERIMENTAL SETUP

The pulse-laser beams are generated using a Nd:YAG laser from Spectra-Physics (DCR-11) with a maximum pulse energy of 135 mJ/pulse at a wavelength of 532 nm. Figure 3 shows a schematic top view on the installed setup. The pulse-laser beam is divided by a beam splitter plate into two beams of 50 % each. These are aligned parallel via adjustable mirrors onto a convex lens. Three different focal lengths, 400, 700, and 900 mm, are in use. The probe beam of an Argon-Ion laser at a wavelength of 488 nm is adjusted by mirror under Bragg angle conditions onto the interference grating of the two pulse beams.

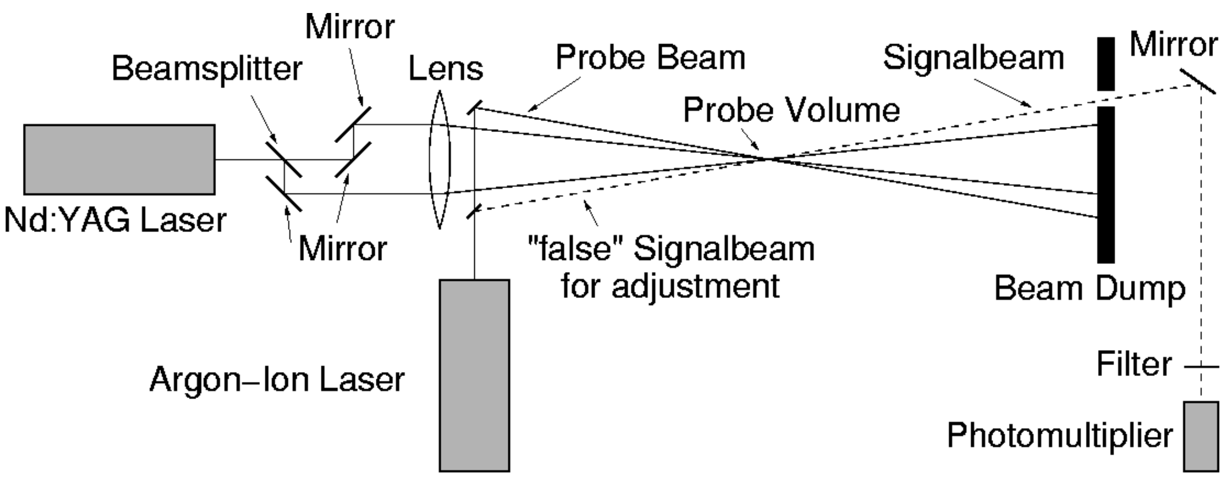

Fig. 3. Schematic drawing of experimental apparatus used for Transient Grating Spectroscopy (top view).

A so called false signal beam is used for the adjustment of the receiving unit consisting of beam dump, a 488 nm line filter and a photomultiplier. This false signal beam is aligned symmetrical to the probe beam and generates an interference pattern with the probe beam with same fringe spacing as the pump beams. If this condition is satisfied, also called phase matching, the false signal beam runs parallel to the reflected signal beam.

For the data acquisition a digital oscilloscope is primarily used. It is triggered by a photodiode on the laser pulse. The signal time traces are then transferred via a GPIB-interface onto a computer (PC). Further signal processing is done by a standard FFT or wavelet analysis (q.v. Torrence and Compo (1998))[1].

4. PARAMETRIC STUDY

In order to evaluate the applicability of the TGS method in thermal flows, the dependency of the signal-to-noise ratio on various parameters has been investigated. The system pressure, the pulse laser energy and the probe beam power were changed. To obtain a good reproducibility the measurements have been carried out in air at room temperature.

4.1 Pressure Dependency

For these tests at different pressure conditions a pressure tank with optical access passed a glass window of 10 mm thickness was used. Overpressures up to 3.5 bar using compressed air could be achieved.

Figure 4 shows a characteristic single shot TGS signal trace at room temperature and ambient pressure. The signal trace is very clearly oscillating with the modulation frequency $f_{M.}$. The signal amplitude is declining in time due to the decay of the grating contrast.

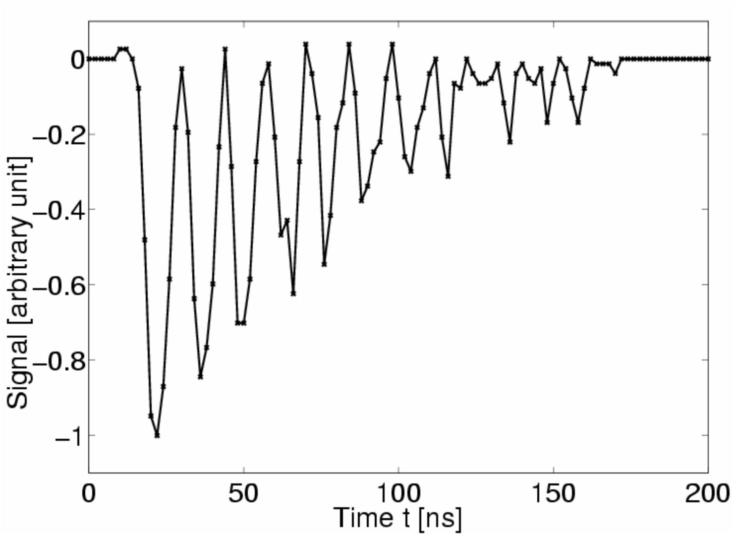

Fig. 4. Example of a typical TGS signal trace at room temperature and ambient pressure.

Typical signal traces at different pressure states are displayed in figure 5. All the other parameters, in particular the pulse laser energy (about 15 mJ/pulse per beam) remained constant. The signals are averaged over 2000 single shots each. The amplitudes are normalized with the maximum at 3.5 bar overpressure. The augmentation of the signal strength with increasing system pressure is very distinct.

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[1] **Wavelet software was provided by C. Torrence and G. Compo, and is available at**
URL: http://paos.colorado.edu/research/wavelets/

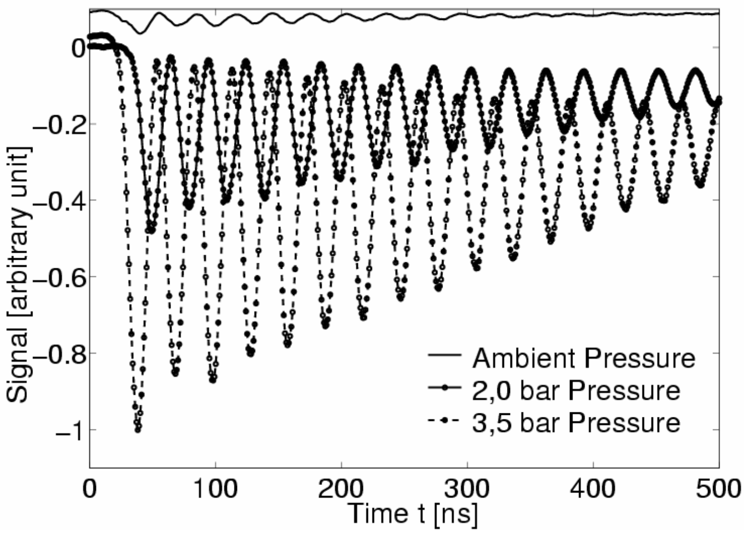

Fig. 5. Comparison of signal strength at different pressure states.

According to Brown and Roberts (1999) the signal strength gains quadratically with the density or the pressure of the flow medium. This behavior also appears in figure 6. Here the maximum modulation amplitude of the signal is plotted versus the overpressure in the pressure tank. The signal strength is again normalized to its value at 3.5 bar overpressure.

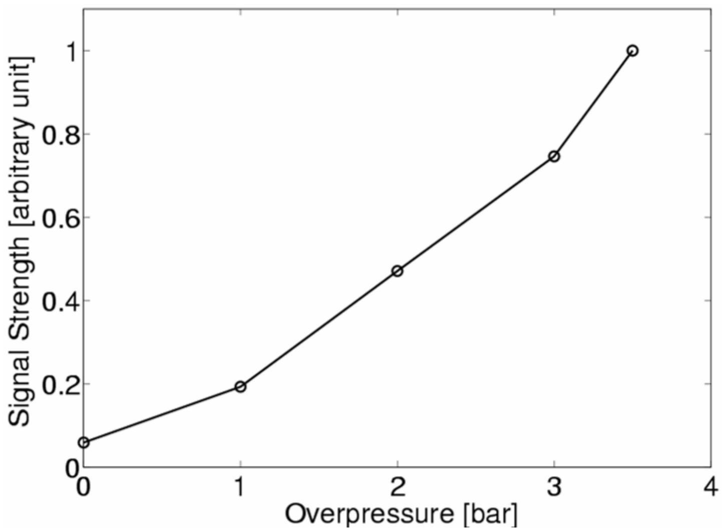

Fig. 6. Dependency of signal strength on system pressure.

4.2 Pulse Energy Dependency

With regard to the application of the TGS technique in thermal or combustion flows at ambient pressure the relation between signal strength and pulse laser energy has been investigated. The pulse energy per beam varied between 7 mJ and 47 mJ. The results in figure 7 show again an approximately quadratic growth of the signal strength with the pulse laser energy similar to the pressure dependency.

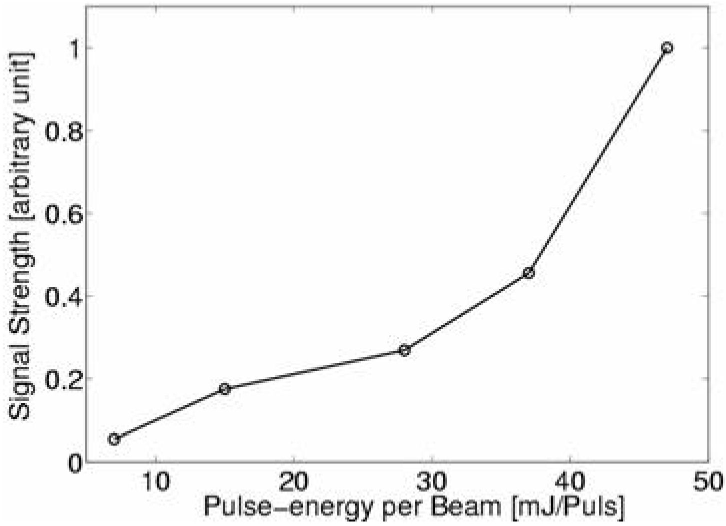

Fig. 7. Dependency of signal strength on pulse-beam energy.

4.3 Probe Power Dependency

As a last parameter the influence of the probe beam power on the signal modulation amplitude was determined. The probe beam laser power was changed from 39 mW to 152 mW. Figure 8 shows an almost linear dependency of the signal strength on the probe power.

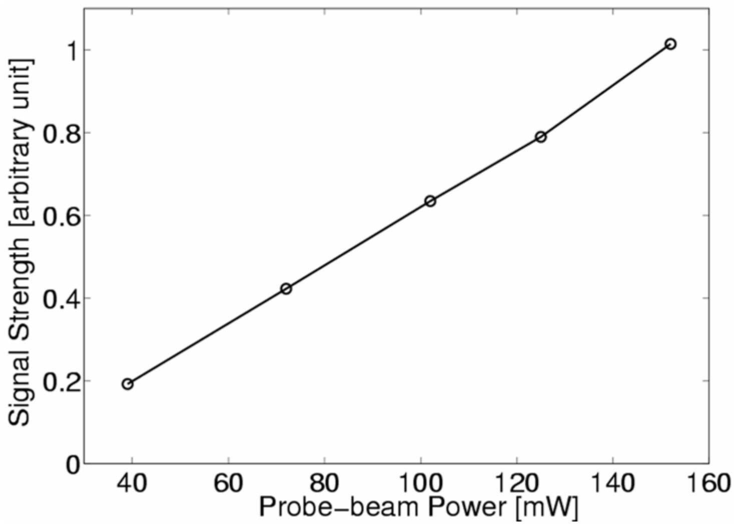

Fig. 8. Dependency of signal strength on probe-beam power.

4.4 Temperature Resolution and Accuracy

In order to analyse the accuracy of the TGS method test measurements were carried out at room temperature and were statistically evaluated. The signal processing was done via wavelet analysis as mentioned before. The usage of wavelet functions enables a much higher frequency resolution than conventional Fast-Fourier-Transformation algorithms (FFT). The frequency resolution using fft methods is limited due to the shortness of the signal bursts of a few hundred nanoseconds. At a signal length of about 500 ns the FFT analysis provides a frequency resolution of only 2 MHz. Using wavelet functions a frequency resolution of 5 kHz and lower can be achieved. Wavelets are mathematical functions that decompose a time signal into various frequencies with a resolution according to its scale (see Graps (1995)). The result is a two dimensional time-frequency distribution which show the dominant frequencies and how these are changing in time

(Torrence and Compo (1998). The advantage for analysing short time signal traces is based on the finite character of the wavelet functions in contrast to the FFT decomposition into infinite long sine and cosine functions.

Test measurements at room temperature show a decline of the statistical error with increasing system pressure. The histograms of measurements at two different pressure states are presented in figure 9. The distributions consist of 2000 single shot measurements. The test at ambient pressure, shown on the left hand side, gives a standard deviation of 1.22 % or 3.6 K while at 3.5 bar overpressure (right histogram) this standard deviation reduces to 0.54 % or 1.6 K.

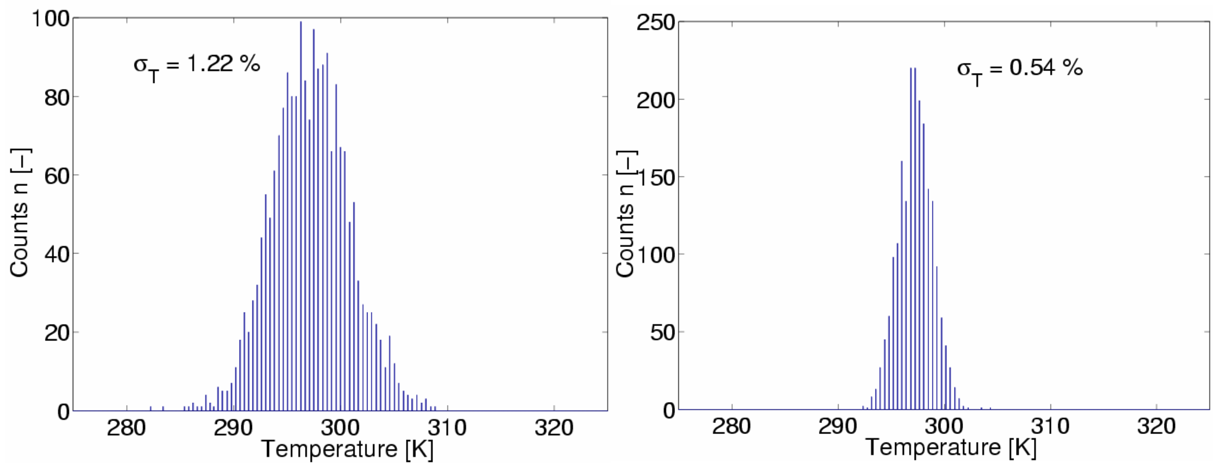

Fig. 9. Distribution and standard deviation of 2000 single-shot readings at ambient pressure (left) and 3.5 bar overpressure (right). Both measurements were taken in air and at room temperature.

Further test were conducted using an electrically heated oven. For comparison mean temperature measurements were taken with a thermocouple setup. Figure 10 shows the results with the standard deviation of each measurement point. The comparison to the thermocouple readings displays a good agreement, however, with increasing temperature a higher discrepancy and a larger statistical spread can be observed. This discrepancy is supposedly caused by the decreasing signal-to-noise ratio due to the lower density of the medium.

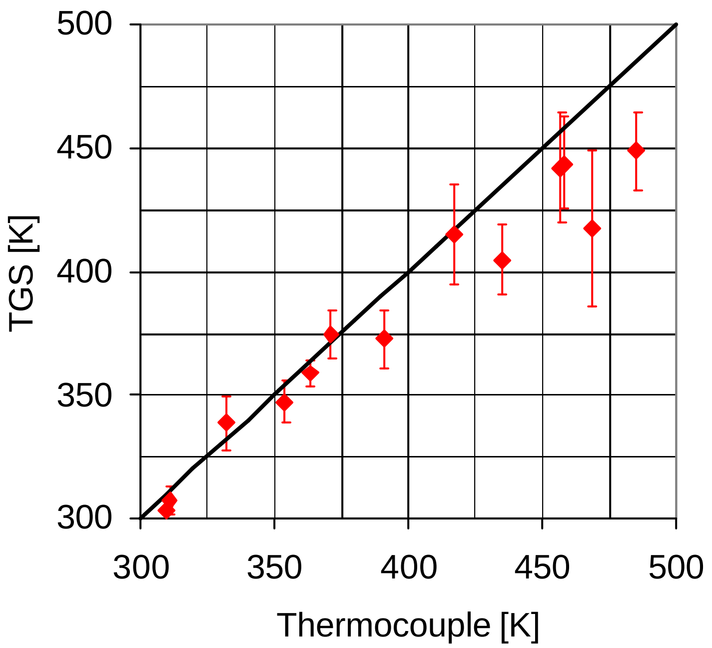

Fig. 10. Comparison of TGS measurements and thermocouple readings using an electrically heated oven. The error bar indicates the statistical spread of the measured data.

5. DISCUSSION AND OUTLOOK

An experimental setup for the *Transient Grating Spectroscopy* has been installed and successfully tested. A parametric study showed a quadratic increase of the TGS signal strength with both the pulse laser energy and the system pressure. The dependency of the signal-to-noise ratio on the probe beam power is linearly related as expected. The results show the favorable usability of this measurement technique in environments of elevated pressure as for example in high pressure combustion facilities. Statistical analysis of test series at room temperature and different pressure states provide a decreasing standard deviation with increasing system pressure. The statistical error of 3.6 K at ambient pressure already seems to be sufficient for various applications, e.g. in combustion processes, where temperature fluctuations of more than 400 K can be expected. Improvements of the signal processing methods will provide an even higher temperature resolution. First test in an electrical heated oven show a good agreement to thermocouple measurements.

In the discussed work the influence of the gas composition is not taken into account. Especially in combustion flows the gas composition is subject to changes due to the chemical reaction process. This affects the gas constant and the isentropic exponent (see equation (2)). However, Brown and Roberts (1999), showed that this influence on the temperature values is an order of magnitude lower than the temperature fluctuation itself. The quadratic dependency of the signal strength on the density of the flow medium acts unfavourably for measurements at higher temperatures due to the reduction of the signal-to-noise ratio. However, this phenomenon can be compensated using higher pulse laser energy as shown before. In this work the pulse energy was limited to 47 mJ/pulse per beam. A more powerful pulse laser would enhance this possibility. However, the upper limit is determined by the optical access of the test facility. High pulse laser energy beams can damage the used glass windows if they are focused through the windows.

Another improvement of the signal-to-noise ratio could be achieved using a seeded Nd:YAG laser. It was shown by Yuanyuan (2001) that the usage of a seeded Nd:YAG laser increases the signal strength by a ratio of 500%. Investigations of Stampanoni-Panariello et al. (1998) described the application of the infrared wavelength (1064 nm) of the pulse laser for the grating generation with a resulting increased signal-to-noise ratio. However, the difficulties of handling this non-visible laser light during the adjustment procedures have to be accomplished.

In result the *Transient Grating Spectroscopy* shows good potential as a non-invasive, local and time resolved method for temperature measurements. It is less extensive than other laser-based diagnostic systems. With sufficient pulse laser energy it is probably applicable in combustion flow environments. Other possible applications are compressor rigs, turbine test facilities and wind tunnel measurements.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the German Research Council (DFG) through the Research Unit FOR 486 ``Combustion Noise''.

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