TEMPERATURE MEASUREMENTS IN A SHOCK TUBE USING LASER-INDUCED THERMAL GRATING SPECTROSCOPY

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I. Introduction

Free-piston shock tunnels allow investigations of aerothermodynamic phenomena of high speed and high enthalpy flows and their interaction with probes and bodies. Such a facility named HELM (High Enthalpy Laboratory Munich) \cite{1} was designed and built at the University of the Armed Forces in Munich. The first operational tests have been completed successfully \cite{2}.

As a promising technique for the investigation of the flow properties during operation, laser-induced grating spectroscopy (LIGS) was chosen. In former work operating experience was gained by measurements in a test cell using LIGS. It was shown that the signal quality improves with high pressure and that single shot measurements are possible \cite{3}.

The next step was the transfer of this experience to single shot measurements in a conventional shock tube, where the exact synchronization of the test-bench with the optical setup is indispensable. The results of the first successful experiments on the shock tube are presented in this work.

II. Measuring Principle

The physical background of LIGS is described in detail in \cite{3, 4, 5, 6}. The optical grating is formed by the interference of two coherent laser beams (pump beams) with the wavelength $\lambda_{\text{pump}}$ and the crossing angle $\Theta$ (Figure 1).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Schematic of the crossing laser beams}
\end{figure}

The interference of the beams induces an optical grating in the cross-section of the beams whose grating constant $\Lambda$ can be expressed by:

$$\Lambda = \frac{\lambda_{\text{pump}}}{2 \sin \frac{\Theta}{2}} \quad (1)$$

The grating can be read out by a third laser beam (probe beam) with the wavelength $\lambda_{\text{probe}}$ intersecting under the Bragg angle $\varphi$.

$$\varphi = \arcsin \left( \frac{\lambda_{\text{probe}}}{2\Lambda} \right) \quad (2)$$
Two main techniques can be used for the measurements: The resonant thermal grating spectroscopy (LITGS) based on absorption, and the non-resonant electrostrictive grating spectroscopy (LIEGS) based on polarization. To generate a resonant grating, the wavelength of the pump beams needs to match an absorption line of a species in the test gas. For the generation of an electrostrictive grating a polarizable molecule has to be present in the test gas and the energy of the pump beam must be high enough for its polarization [3].

The oscillation frequency of the laser-induced grating $f_M$ can be written as

$$f_M = \frac{c a}{A}$$  \hspace{1cm} (3)

where $a$ is the sound velocity of the test gas and $c$ equals 2 for LIEGS and $c$ equals 1 for LITGS. The grating constant $A$ can be calculated from measurements at room temperature. With the sonic speed $a$:

$$a = \sqrt{\gamma R_s T}$$  \hspace{1cm} (4)

one obtains for the temperature $T$, assuming known isentropic coefficient $\gamma$ and specific gas constant $R_s$:

$$T = \frac{a^2}{\gamma R_s}$$  \hspace{1cm} (5)

III. Experimental Setup

The properties of both measurement techniques have been investigated for the application in more detail in former work [7]. For example the effect of the electrostrictive grating is applicable preferably at moderate temperatures and the thermal grating can be used best at elevated pressures, which is confirmed by literature [4], [8]. In Figure 2 the test setup for LIGS using a pulsed Nd:YAG laser (Innolas SpitLight High Power 2000, wavelength: 532 nm, maximum pulse energy: 1000 mJ, pulse duration: 7 ns) and a dye laser (Radiant Dyes Narrow Scan, Rhodamine B, efficiency: $\approx 30 \%$) as tunable source for the pump beams is shown.

The probe beam is provided by a continuous Argon ion laser (Coherent Innova 90-4A, wavelength: 514.5 nm, nominal power: 1.7 W). This setup was successfully used for stationary measurements at room temperature and different pressures in air [9], [10] and shall not be described in detail here. For the application of LIGS at a shock tube the exact synchronization of the optical setup with the passage of the shock was essential. In the presented work the shock tube was operated with a solid end, resulting in a reflected shock at the end of the shock tube where the measurement chamber was located.
In general either the shock tube or the pump laser can be used as master for synchronization. However, the varying fracture behavior of the used diaphragms causes different burst delays after triggering. This leads to an unknown time interval between trigger and shock incidence. Therefore, the shock tube cannot be triggered reliably by an external master. Additionally, a single shot triggering of the pump beams by an incidental event would lead to an unstable and unrepeatable output of the employed pulsed Nd:YAG laser. For this reason the Nd:YAG laser has to be operated at 10 Hz to ensure a stable operating point without the risk of a damage of the Nd:YAG rods e. g. by the generation of a thermal lens.

The functional principle of a Nd:YAG laser is shown in Figure 3. The Nd:YAG rod is pumped by a surrounding flash lamp causing the population inversion necessary for lasing. In order to increase the maximum pulse energy, the passive Pockels cell maintains the efficiency in the laser cavity low until a very high population inversion is developed. The Pockels cell is then gated and a high-energy laser pulse depopulating the upper laser energy level is formed and leaves the cavity through the output coupler.

The timing of flash lamp and Pockels cell can be realized by the internal laser control and can be used in combination with the adjustment of the flash lamp energy to variate the laser pulse energy. However, for the benefit of timing flexibility in this application the flash lamp was gated by an external pulse generator (BNC model 6040) with a constant frequency of 10 Hz. As the Pockels cell was not gated, no laser pulses were generated. The applied laser offers the possibility of emitting an
additional laser pulse between two regular 10 Hz pulses with a minimum delay of 10 ms to the next pulse.

Figure 4 shows the chronological signal sequence of the synchronization of test bench and optical setup. When the shock passes the pressure gauge in the shock tube the first time, the pressure jump that may appear at any delay \(X\) to the 10 Hz gating of the flash lamp releases a trigger signal, which is transmitted to a second delay generator (Stanford Research Systems DG645). This four channel delay generator is the time master for the following sequence of TTL pulses. The flash lamp of the Nd:YAG laser is delayed to this pressure signal by 1 ms in order to synchronize the light pulse with the passage of the reflected shock through the test gas. The delay between the flash lamp and the Q-switch pulse determines the pulse energy and was set to 235 µs.

\[\text{Fig. 4. Chronological signal sequence of the timing.}\]

**IV. Results**

The aim of this work was the application of LIGS under single shot conditions of a shock tube on the basis of measurements in a stationary test cell [7], [10]. Therefore the shock tube was operated under different initial conditions leading to different temperatures and pressures in the test gas at the end of the shock tube. In Table 1 the two investigated conditions are listed.

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>(Ma) ([-])</th>
<th>(p_1) [MPa]</th>
<th>(p_{refl}) [MPa]</th>
<th>(T_{refl}) [K]</th>
<th>(T_{LITGS}) [K]</th>
<th>(p_{meas}) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>1.48</td>
<td>0.09</td>
<td>0.46</td>
<td>482</td>
<td>500</td>
<td>0.49</td>
</tr>
<tr>
<td>Condition 2</td>
<td>1.71</td>
<td>0.09</td>
<td>0.80</td>
<td>589</td>
<td>627</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Under the predicted temperatures of both conditions it was expected that the thermal grating would be the better developed grating in comparison to the electrostrictive one. Therefore, LITGS
was chosen for these temperature measurements. As the NO concentration behind the reflected shock was too low for the formation of a thermal grating, the test gas was seeded to a NO concentration of 180 ppm. \( \text{Ma} \) denotes the Mach number of the incident shock. It is calculated by the time interval between the pressure jumps of the incoming shock measured by two pressure gauges at known positions in the shock tube close to the location of measurement. The pressure \( p_1 \) is the filling pressure of the shock tube before experiment and \( p_{\text{refl}} \) the calculated pressure behind the reflected shock. \( T_{\text{refl}} \) is the corresponding temperature. Both are calculated from the Mach number of the incident shock using the shock relations for ideal gas. The temperature \( T_{\text{LITGS}} \) is the temperature derived from the LITGS single shot measurement and \( p_{\text{meas}} \) the pressure measured at the location and at the time of the optical measurement. In both cases the shock tube was filled with air to a pressure of 0.09 MPa. Due to an incomplete opening behavior of the diaphragm in case 1, the Mach number was lower than in case 2, resulting in lower values for pressure and temperature, respectively.

Figure 5 shows the signal from the single shot measurements for both conditions (upper graph: condition 1, lower graph: condition 2).

![Fig. 5. Measurement signals from LITGS for condition 1 (upper graph) and condition 2 (lower graph).](image)

It can be seen that the signal strength is higher for condition 2, most likely due to the higher pressure in the test gas. A discrete fast Fourier transform was carried out to obtain the frequency of the oscillation. Using equations 3, 4 and 5 the temperature can be calculated. For condition 1 the measured temperature is 500 K, which means a deviation from the predicted temperature of 18 K. For condition 2 the difference between measured temperature (627 K) and calculated temperature (589 K) is 38 K. Obviously LITGS in both cases delivers higher temperatures than the gasdynamic calcu-
lations. It has to be mentioned that in both cases the measured reflected pressure $p_{\text{meas}}$ is higher than the calculated value. It is assumed that the difference between $p_{\text{meas}}$ and $p_{\text{refl}}$ is caused by an underestimation of the Mach number and therefore an underestimation of $T_{\text{refl}}$. If the Mach number of the shock is calculated from the pressure ratio $p_{\text{meas}}/p_1$, one obtains for condition 1 a Mach number of 1.5 and for condition 2 a Mach number of 1.73. The corresponding temperatures behind the reflected shock $T_{\text{refl}}$ are 493 K and 598 K for condition 1 and 2, respectively. The deviation of calculated and measured temperature would decrease to 7 K and 29 K, respectively.

V. Conclusion and Outlook

In the presented work it was shown that the developed system for temperature measurements by laser-induced thermal gratings is applicable to single shot experiments under severe conditions. The first results are gained in a NO-seeded test gas to ensure a strong thermal signal. The realization of the next experiments at the shock tube under different conditions and also with LIEGS will focus on the identification of the measured temperature deviations and their elimination.

The future work will be the transfer of the measurement experience to the piston-driven shock tunnel, which is operated at the institute for thermodynamics. The main challenge will be the higher temperature level decreasing signal quality and the movement of the test bench during experiment, which has to be compensated by the optical setup.

REFERENCES

2. Ch. Mundt, P. Altenhöfer Initial results of HELM in initial operation as a shock-tube, 11th Australian Hypersonics Workshop, Brisbane (AUS), 2011.