Preliminary experimental results of heat flux surface field registration at the hypersonic aerodynamic shock tube using temperature sensitive paint

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Abstract. The temperature gradient fields of a wedge with double ramp were explored by using applied method temperature sensitive paint [1-4]. The model was studied experimentally in the HAST facility [5-8] at incoming airflow Mach numbers of $M = 5..7$. With the technique, perturbations of luminescent elements on the model surface during stationary hypersonic flow were recorded. The results of experimental data processing of surface temperature gradient fields are presented.

1. Introduction

Temperature sensitive paint (TSP) is a luminescent paint that provides the measurement of global temperature distribution. TSP consists of polymer binder and organic luminophore molecules and can be thin enough for measurements in short duration wind tunnels. Temperature Sensitive Paint application techniques for heat flux measurements in Ludwieg wind tunnel were described in [1−4]. In present tests the binary (two color) temperature sensitive paint was used. Binary paint contains two types of organic luminophore molecules. One luminophore (europium complex) is temperature sensitive. It’s luminescence decreases with temperature growth. Other luminophore (Coumarin) is temperature insensitive. Its luminescence is used as a reference for pixel-by-pixel correction of excitation light variation from flash to flash. Both luminophores are excited simultaneously by UV flash lamp (280−390 nm), but emit light in different spectral ranges. Temperature sensitive luminescence is red (580−630 nm) and temperature insensitive luminescence is blue (420−500 nm) and thus they can be separated spectrally.

Intensity of emitted red light decreases at temperature increase with the rate of 3−5% °C and is absolutely insensitive to pressure. TSP is optimized for the temperature range of 10−80°C. TSP degrades at the temperature above 120°C.

TSP is applied on the model surfaces by airbrushing like an ordinary paint. The thickness of the dry TSP layer is about 3−5 micrometers. After TSP application a set of markers are placed on the model surface. Markers are contrasted (black) points on TSP surface and are used for correction of the model displacement in the flow in respect with the position without the flow.
Six images (three by each CCD camera) are acquired for each facility run: dark images (without excitation light), wind-off (at known constant temperature without air flow) and wind-on (with air flow) images.

Data processing included the next steps:
- Dark signal correction (dark image subtraction);
- Flat field correction;
- Alignment of wind-off and wind-on images using the markers on the model images;
- Pixel-by-pixel correction of excitation light intensity variation: temperature sensitive (red) images are divided on corresponding reference (blue) images;
- Image normalization: wind-on image is divided on corresponding wind-off image. The ratio of 'wind-on' to 'wind-off' images depends only on temperature. It does not depend on paint layer thickness;
- Temperature field calculation using TSP calibration characteristics. TSP calibration is performed in laboratory calibration setup on TSP sample prepared simultaneously with the model covering (a priori temperature calibration);
- Heat flux calculation;
- Distortion correction using an image of etalon body;
- Projection of resulting 2D Stanton number field on the 3D mesh describing the model geometry.

Global heat flux image is computed from temperature field using exact solution of one-dimensional heat transfer equation:

\[ \vartheta = 1 - \exp(\beta^2) \cdot \text{erfc}(\beta), \]
\[ \vartheta = \frac{T_m - T_m}{(T_r - T_m)}, \]

where \( T_m \) is initial model temperature before wind tunnel start, measured with thermocouple; \( T_m \) is the model surface temperature at the moment \( t \) after flow initialization, measured by TSP; \( T_r \) is recovery temperature and is assumed \( T_r \approx T_0 \);

\[ \beta = \frac{h \sqrt{T}}{\sqrt{\lambda c_p}} \]

is non-dimensional heat flux (\( h \) is heat output coefficient and \( \sqrt{\lambda c_p} \) is thermal product of model material);

\text{erfc} is a complementary error function. Results are presented as Stanton number fields \( (St=h/\rho_c V_c C_p) \). The relation to maximum intensity presented in figure 1.

Figure 1. The spectrum of excitation and emission characteristics.
These procedures were tested on experimental facilities in TsAGI corporation and first used in experiments in the HAST [5-8] at the Institute for Problems in Mechanics RAS.

2. Operation of the measuring technique in the HAST
The observation windows were modified to accommodate two cameras and flash lights as shown in figure 2.

![Figure 2. New observation windows in HAST for providing the measuring technique.](image1)

The model was made of acrylic and painted with TSP in black colour, as shown in figure 3. The experiments of temperature field visualization on the model surface in the HAST were made under Mach numbers \( M = 5.3 \) and \( M = 5.5 \) with estimated time delay of the flash and the photo frames.

![Figure 3. Investigated model.](image2)

3. The results of experiments on heat flux field visualisation
In experimental studies of temperature gradient on the model surface by using fluorescent temperature transducer method the measured quantity is the intensity of luminescence, which was chosen by the maximum range of the CCD camera VS–STT–285 charge-coupled in different spectral regions. Processing of the results was carried by analysing data received in two stages: before the experiment and during the experiment. The time of measurement was chosen so that the signal did not come from the selected range of time.
The results of the measurements obtained with the help of a luminescent coating were processed into the Stanton numbers (the Stanton number is proportional to the measured heat flow and inversely proportional to the density, gas velocity in the undisturbed flow and the increment of temperature). Maximum values were located at different distances from the sharp edge. Figure 4 shows the processed results of the measurement of increment of the model surface temperature.

![Figure 4](image_url)

**Figure 4.** The processed results of the measurement of increment of the model surface temperature in two runs of the HAST: \( M = 5.3 \) (top) and \( M = 5.5 \) (bottom).

After experiments to determine the temperature field on the model surface the visualisation of shock-wave structures was carried out with a shooting video speed of 2000 frames/s at the oncoming airflow at \( M = 5.3, 5.5 \). Figure 5 contains pictures of the received shock interaction.

![Figure 5](image_url)

**Figure 5.** Shadow pictures of airflow shock structure at \( M = 5.3 \) (left) and \( M = 5.5 \) (right).

4. **Conclusion**

Preliminary experiments have been prepared and carried out to visualize the temperature field on the surface of models at the GUAT. The temperature parameters of the model system were measured
during experiment. Preliminary thermal data on the temperature gradient of the model surface are obtained.

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