



Noise reduction for temperature-sensitive paint measurement contaminated by strong background radiation in a high enthalpy hypersonic tunnel

Di Peng¹ · Xu Liu¹ · Lingrui Jiao¹ · Ziyang Li¹ · Xin Wen¹ · Chaokai Yuan² · Guilai Han² · Yunfeng Liu² · Yingzheng Liu¹ · Zonglin Jiang²

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Abstract

The strong background radiation in high enthalpy hypersonic shock tunnels has posed severe challenges for measurement using luminescent coatings. We proposed a solution for reducing background radiation from time-resolved temperature-sensitive paint (TSP) measurement in a hypersonic flow with $Ma=6.5$ and $T_0=3525$ K. The TSP was applied on an inlet ramp model, and the images were taken by a high-speed camera at 2 kHz under a modulated excitation. The strong background radiation led to a low signal-to-noise ratio and significant errors for the first half of the 130-ms test duration. Accordingly, three noise reduction methods were developed and evaluated based on temporal reconstruction, spatial reconstruction and robust principal component analysis (RPCA), respectively. The RPCA method showed the best performance that successfully recovered high-quality TSP data for a majority of test duration ($t \geq 40$ ms).

Keywords Temperature-sensitive paint · Time-resolved measurement · Hypersonic flow · Background radiation

1 Introduction

Hypersonic vehicles suffer from severe heating loads in operation and demands a proper design of the structure and thermal protection for flight safety. In high Mach number (Ma) flows, the real gas effect and the complex flow phenomenon (transition, shock-boundary layer interaction, etc.)

have generated barriers developing high-fidelity numerical simulation techniques. Thus, it is important to obtain high-accuracy data on the heat flux from ground testing [1]. Heat flux gauges have been widely applied to measurements in hypersonic wind tunnel; however, their discrete distribution and limited spatial resolution make it difficult to study complex fluid problems [2]. In contrast, temperature-sensitive paint (TSP) is an advanced measurement technique with low-intrusiveness and high spatial resolution for the capture of fine flow structures and full-field thermal loads [3–5].

Recently, the applications of TSP have been extended to high-enthalpy shock tunnels with extremely harsh environments [6, 7]. While the high enthalpy flow can reproduce the real gas effect during hypersonic flight and the gas contamination effect of supersonic combustion, it poses technical barriers for TSP measurement such as severe paint damage and strong background radiation (mostly spontaneous emission from the high enthalpy gas) [8]. The former issue may be alleviated by limiting flow exposure time and repainting after each run; however, the latter could lead to significant uncertainty in TSP results due to the spectral overlap between the radiation and TSP emission. As the strength of background radiation increases rapidly with total temperature and density, the TSP signal can be completely

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✉ Chaokai Yuan
yuanck@imech.ac.cn

✉ Yingzheng Liu
Xu Liu
yzliu@sjtu.edu.cn

¹ Gas Turbine Research Institute/School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

² Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

overwhelmed in certain test cases or over a specific period of time during one test. Thus, an effective method for removing the strong background radiation from the TSP signal has yet to be developed to improve the accuracy of the measurement of heat flux.

In this study, the TSP measurement was conducted on an inlet ramp model ($Ma = 6.5$, $T_0 = 3525$ K) in the JF12 long-test-duration shock tunnel at the State Key Laboratory of High-Temperature Gas Dynamics. The strong background radiation in the high enthalpy flow caused a significant error in the TSP data, which was particularly severe for the first half of the test duration (about 60 ms). Different methods for identifying and isolating the background radiation from the TSP signal have been proposed and compared.

2 Experiment setup

Figure 1a depicts the schematic of the JF12 shock tunnel, which includes six major components (from right to left): vacuum tank, test section, nozzle, driven section, detonation driver, and damping section. JF12 shock tunnel can reproduce pure air or nitrogen flow at a Mach number of 5–9 and altitude of 25–50 km with a test duration of over 100 ms [9]. The schematic of the TSP test system is shown in Fig. 1b. The test model is a 1.5 m by a 0.6 m inlet ramp made of stainless steel. A total of 12 heat-flux gauges were installed on the centerline of the model. The TSP was applied to two adjacent rectangular regions on the right side near the centerline. Considering the harsh test environment of the high

enthalpy flow and the relatively long test duration of JF12 shock tunnel, the paint thickness was deliberately increased to improve its robustness and signal strength. The resulting thickness was estimated to be between 50 and 100 μm . The luminophore used in TSP is Ru (dpp) with a lifetime around 5 μs , and the peak of its emission spectrum is around 600 nm. More details on the TSP formulation and spectral property can be found in the previous work of Peng et al. [10]. Illumination for the TSP was provided by a 405 nm LED (UHP-T-LED-405-EP, Prizmatix) through a glass window on top of the test section. The LED was triggered by a function generator (Tektronix, AFG1022) to produce a square wave output with a period of 4 ms and 50% duty cycle (See Fig. 1c). This modulation setup allowed the acquisition of a pure background radiation signal for 50% of the test time (2 ms in every 4 ms), providing the basis for reconstructing the entire history of background radiation. Images were recorded by a 12-bit high-speed camera (SA-4, Photron) at 2 kHz with maximum exposure time through a 50 mm/f1.2 lens. A 600 \pm 25 nm band-pass filter was selected to exclude the excitation light. Besides, a 700 nm short-pass filter was added to further reduce the strength of background radiation.

3 Noise reduction of background radiation

Figure 2a presents TSP images selected from different periods during the wind-tunnel operation to show the effect of background radiation. The radiation was particularly strong

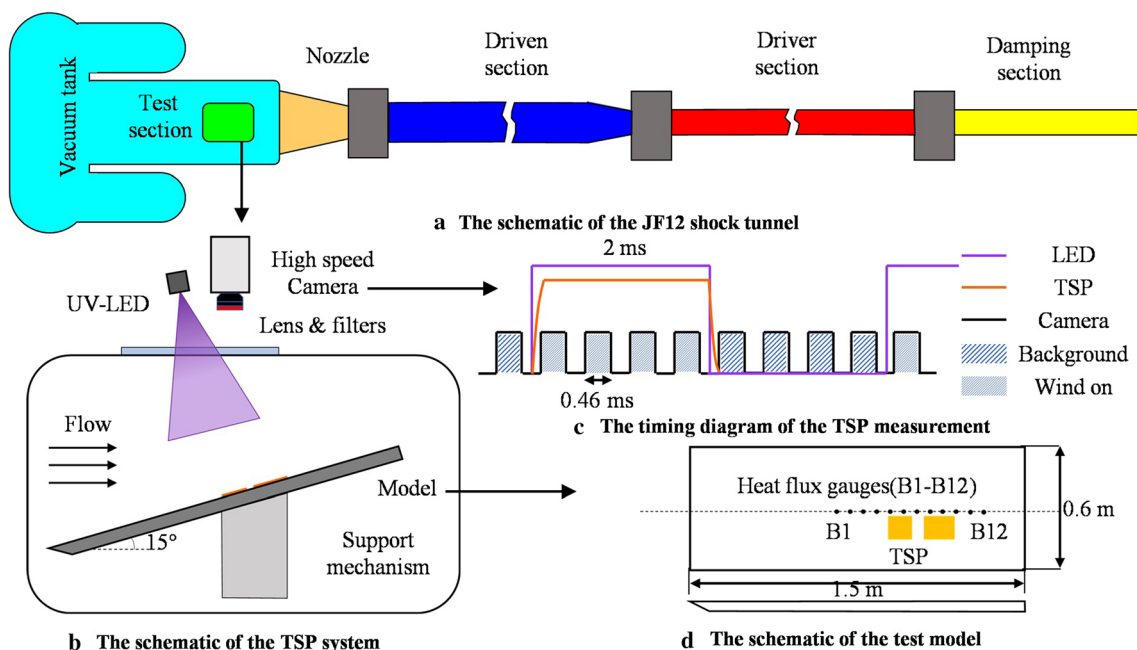


Fig. 1 Schematic of temperature-sensitive paint (TSP) measurement system in the JF12 shock tunnel

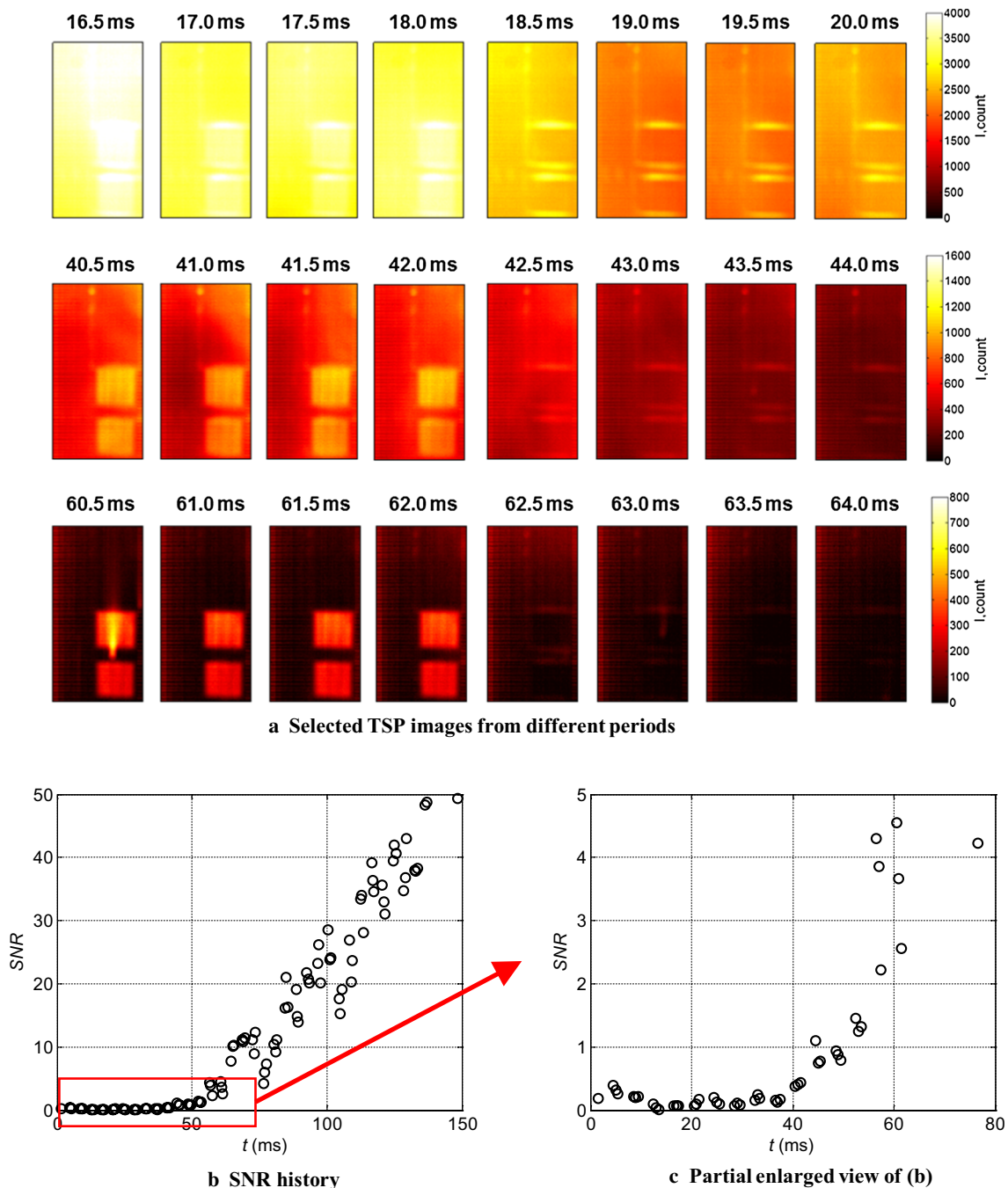


Fig. 2 Raw images captured and signal-to-noise ratio during the wind-tunnel operation

for the first 40 ms after the tunnel initiation, and the maximum radiation level was reached between $t=10\text{--}20$ ms, causing intensity saturation in a few images. For $t=40\text{--}60$ ms, the radiation level quickly reduced although the spatial and temporal variations were still significant. For $t>60$ ms, the overall radiation signal became small compared to the TSP signal. However, a few random bright spots were observed, which could still lead to significant error if they overlapped with TSP regions, as shown in the

image on the bottom left corner ($t=60.5$ ms). Those bright spots were likely due to the burning particles in the high-enthalpy flow, which were scraped off the rust on the wind-tunnel wall. Meanwhile, the signal-to-noise ratio (SNR) was calculated based on the bottom TSP region over the entire tunnel operation to provide a quantitative evaluation of this issue. As shown in Fig. 2b, the SNR was below 0.5 for the first 40 ms, and then showed a ten-fold increase for $t=40\text{--}60$ ms. Afterwards, the SNR increased almost linearly

over time to the end. The issue of background radiation was severe for the first half of the wind-tunnel operation, which would cause a large error in TSP measurement. Accordingly, three noise reduction methods have been proposed, which are based on (1) temporal reconstruction of radiation signal using the images without LED illumination, (2) spatial reconstruction of radiation signal using the data adjacent to the TSP regions, and (3) a combination of image processing with robust principal component analysis (RPCA) and spatial radiation signal reconstruction. These methods are referred to as the temporal method, spatial method, and RPCA method for the rest of this paper.

As mentioned earlier, the pure background radiation signal acquired for 50% of the test time was used to reconstruct the entire history of background radiation for the temporal method. For each set of four LED-on frames, a linear interpolation was performed based on four background-only frames (as shown in Fig. 1a of the supplementary material (linking to the electronic supplementary material)). For the spatial method, the radiation intensity distribution within the TSP region was obtained by applying two-dimensional interpolation using the intensity data of two adjacent areas on both sides of the TSP region. The background radiation was then removed by subtracting the radiation intensity from the overall intensity for each pixel of the TSP region. The schematics of the two method can be found in supplemental

materials. However, due to the fast-changing nature of the background radiation and its randomness in spatial and temporal distributions, the above two methods had fairly limited success as shown, as discussed in the results. Therefore, the third method based on RPCA was developed. The purpose of using RPCA is to identify and separate only the non-uniform part of background radiation instead of the whole radiation signal. According to the principle of RPCA [11, 12] (more details can be found in the supplemental materials), the original data can be separated into a low-rank component and a sparse component. If the low-rank component has a low frequency in time and space (compared to the sparse component), it can be extracted from the original data. Here, the low-dimensional data included the TSP signal and the uniform part of the background radiation, whereas the remaining data was a fast-changing, non-uniform pattern in the background radiation. As shown in Fig. 3a, the RPCA algorithm was able to identify and separate the non-uniform pattern in each image, and the spatial variation was effectively reduced in the processed images. The remaining large-scale gradients in the processed images could be accounted for using the spatial method (see more details in the supplemental materials). In this way, the accuracy of radiation reconstruction in the TSP regions could be greatly improved, and the measurement errors were reduced, as shown later in the results. Meanwhile, the RPCA algorithm effectively

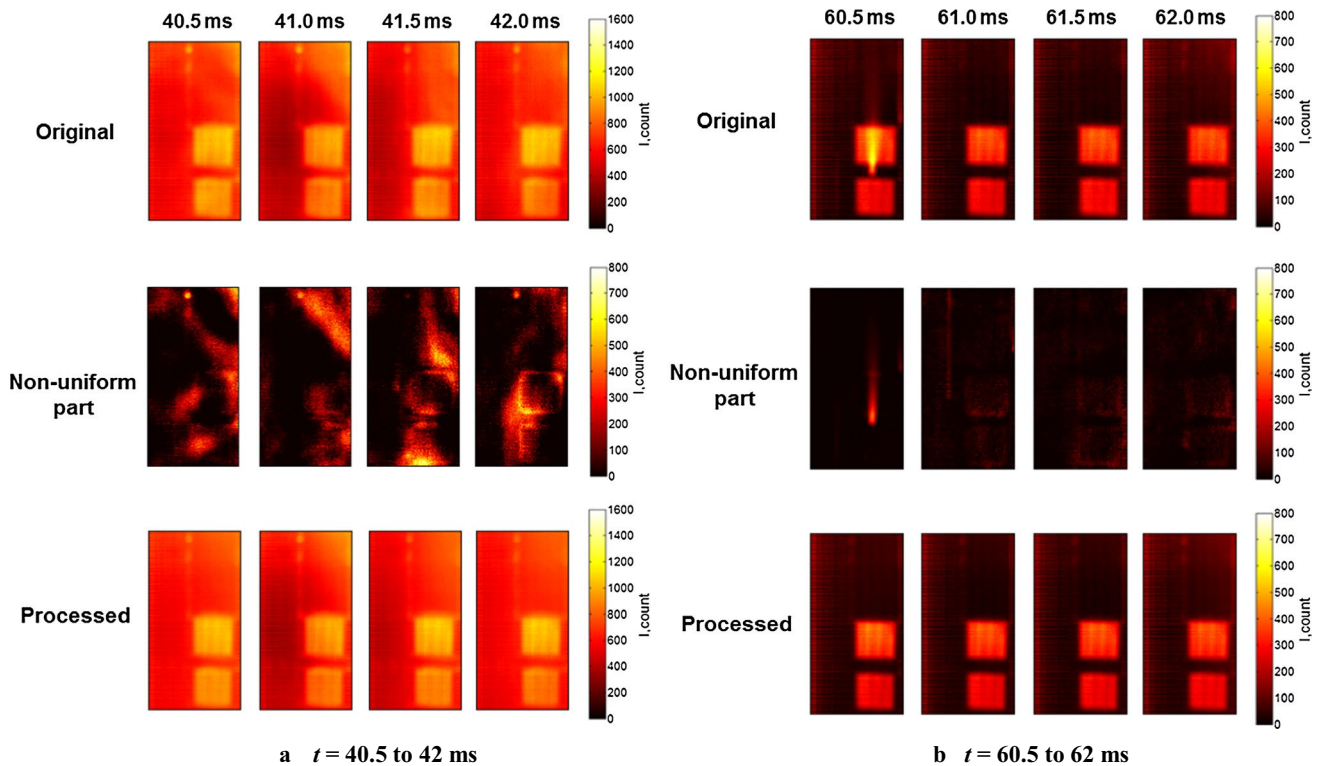


Fig. 3 Example of TSP images that are processed by RPCA

captured the occasional bright spots and eliminated the corresponding errors under low radiation conditions (see Fig. 3b). In principle, the separation should be effective if the temporal frequencies of the TSP signal are significantly less than the background radiation.

4 Results and discussions

TSP images were processed for background radiation noise reduction using the temporal method, the spatial method, and the RPCA method as previously discussed. The temperature fields in the lower TSP region are processed using these three methods for $t = 50$ ms, 75 ms, and 100 ms, as presented in Fig. 4. No filtering or averaging was applied to the data. The results of temporal and spatial methods clearly showed higher noise. In particular, Fig. 4b shows

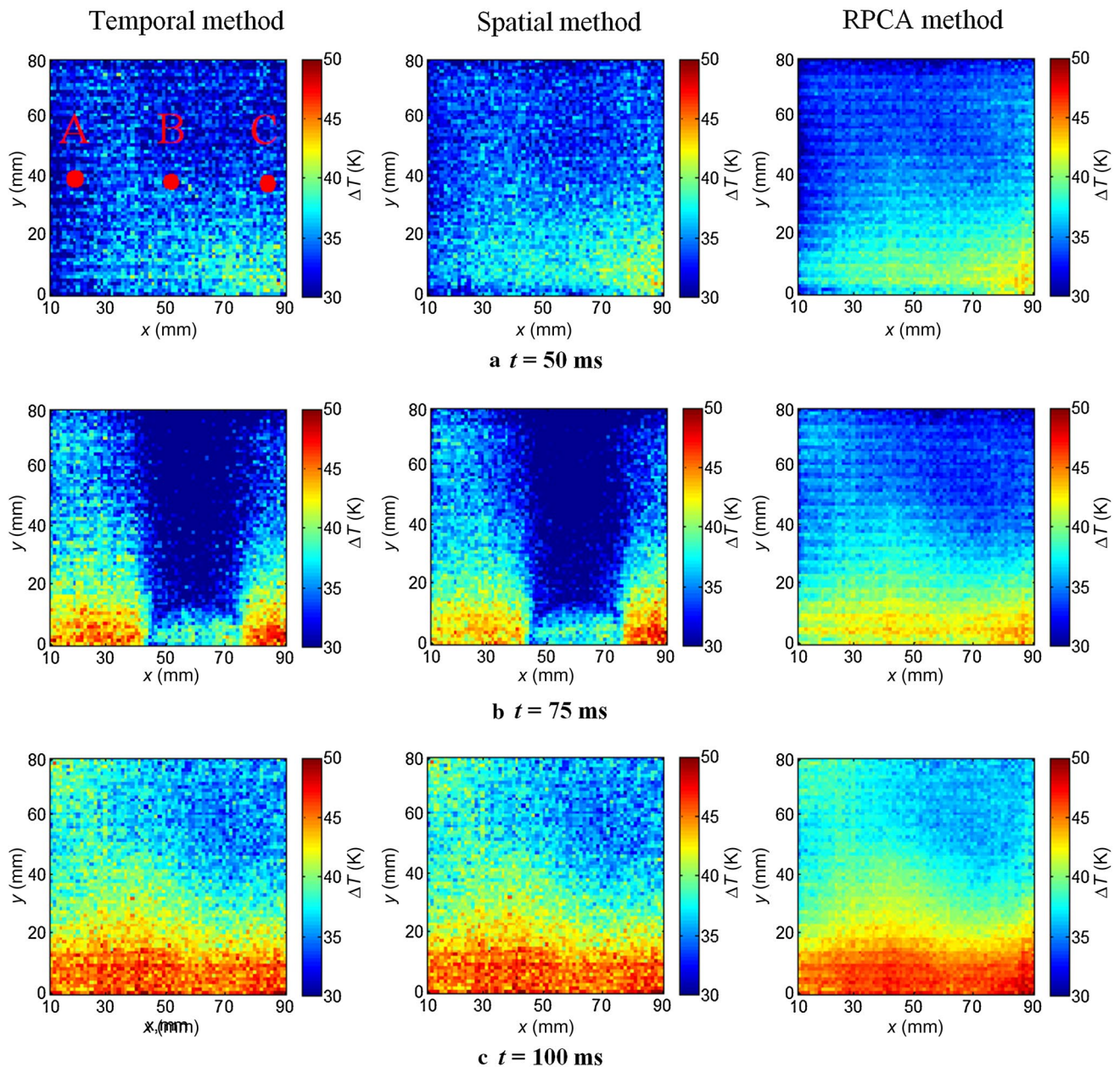


Fig. 4 Distributions of temperature rise at different moments in the lower TSP region obtained using temporal method, spatial method, and RPCA method for noise reduction. **a** $t = 50$ ms, **b** $t = 75$ ms, **c** $t = 100$ ms

the results at $t = 75$ ms contained a region with large bias error. This was due to the accidental occurrence of a bright spot in the original image, similar to that shown in the bottom left corner of Fig. 2a. By considering the randomness of such incidents in space and time, the corresponding errors could not be effectively identified and removed using either the temporal or the spatial method. While it was possible to remove a bright spot from one image manually, the processing method in one image might not apply to another due to the randomness of these spots, causing difficulties in batch processing. In contrast, the RPCA method successfully

suppressed the overall noise level and precisely captured and excluded the random noise sources (bright spots). Thus, the RPCA method provides a robust solution for batch image processing, significantly reducing the processing time and workload.

Figure 5 presents the results of time-dependent temperature rise at selected points within the lower TSP region (point A, B, and C in Fig. 4) to evaluate the performance of noise reduction methods. Each data set was based on a single-pixel without averaging or filtering. The data from $t = 0$ to 150 ms were compared to fully evaluate the effectiveness

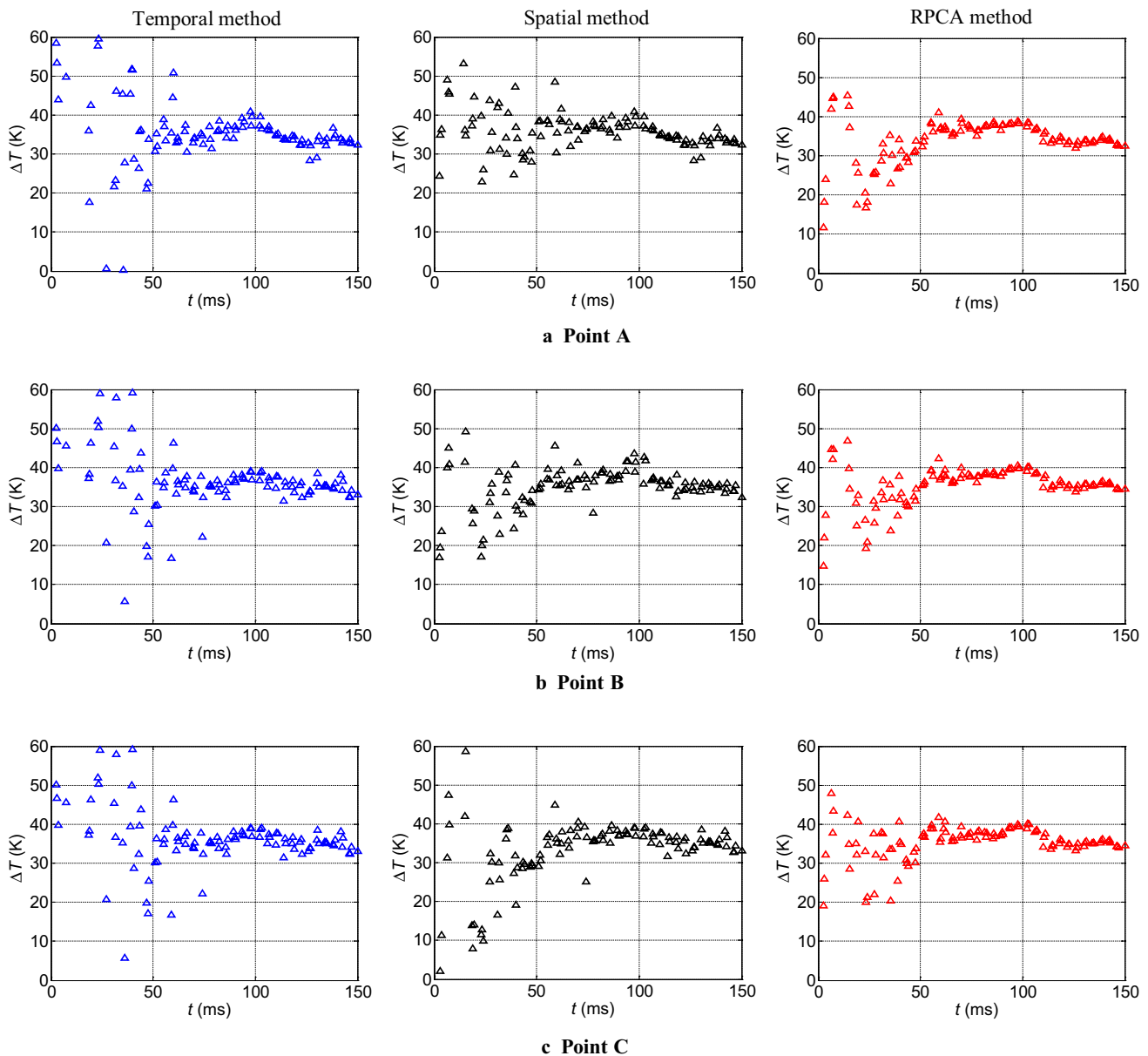


Fig. 5 Time histories of temperature rise at different points from TSP measurement using temporal method, spatial method and RPCA method for noise reduction

Table 1 Level of data scattering in the TSP results obtained by different noise reduction methods

Location	Temporal method	Spatial method	RPCA method
Point A	2.84 K	2.25 K	1.21 K
Point B	3.25 K	2.23 K	1.27 K
Point C	3.49 K	2.44 K	1.68 K

of the three methods in both low and high SNR conditions. In general, the temporal method produced results with the most scattered distributions, indicating that the background radiation signals were not accurately recovered, and the corresponding errors were not effectively removed. The remaining errors were over-whelming for the first half of the test duration ($t=0-60$ ms) with a low signal-to-noise ratio ($SNR < 2$). The data were comparatively less scattered for the latter half due to higher SNR, but the data quality was still poor. This unsatisfactory performance of the temporal method was mostly due to the limited sampling rate, which was unable to resolve the fast-changing radiation signal. For the spatial method, the results were similar but showed overall less scattering. The spatial interpolation based on adjacent regions also had difficulties in recovering random and non-uniform distribution of radiation in the TSP region. In contrast, the RPCA method clearly showed superior performance than the previous methods, as the data quality was significantly improved with little scattering for a majority of test duration ($t \geq 40$ ms). For the first 40 ms, the data scattering still existed due to extremely strong background radiation ($SNR < 0.5$ according to Fig. 2b). This method effectively reduced measurement uncertainty in high SNR conditions and recovered most data in low SNR conditions. For quantitative analysis, the temperature histories with $t=50-150$ ms were fitted from the TSP data obtained from all three methods. Then the root mean square of the difference between TSP data and fitted temperature history was calculated. The results of points A, B, and C are shown in Table 1. The RPCA method shows the least amount of data scattering, proving that it is the most effective background noise reduction method. Based on the TSP images processed by RPCA, time-resolved heat-flux fields can be determined, and the TSP results are in good agreement with those of heat-flux gauges (with an average difference of 9%). More detailed information about the heat flux calculation can be found in the supplemental materials.

5 Conclusions

The strong background radiation in high enthalpy hypersonic flows leads to significant errors in heat-flux measurement using TSP. This issue is addressed by developing a noise

reduction method and heat flux calculation scheme. The RPCA method could significantly reduce the spatial non-uniformity in the radiation signal and effectively remove the related noise from TSP images under $SNR \geq 0.5$. For a majority of test duration ($t=50-150$ ms), the level of TSP data scattering was less than 2 K after the images were processed by the RPCA method, and the error of heat flux (calculated from the TSP results) was around 9%. This noise reduction method paved the way for accurate surface heat-flux measurement using TSP in high enthalpy hypersonic flows.

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