Improvement of Temperature-Sensitive Paint Formulation for Heating with Infrared Laser

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ABSTRACT : *Temperature-Sensitive Paint (TSP) is a useful optical measurement technique for visualizing the boundary-layer transition on a model surface It is important to generate a relatively rapid change between the flow and the model surface temperature, and TSP surface heating with an Infrared (IR) diode laser is one of the useful methods. In this study, the influence of additive IR absorption molecules to the TSP coating that improve the temperature change and homogeneous heating was investigated. First, the influence of the IR absorber to the TSP properties was investigated in the laboratory using the paint calibration system. Subsequently, the efficiency of the TSP surface heating was demonstrated in the ambient low-speed wind tunnel with different formulations of TSP layers. The selected formulation of the TSP coating with IR absorber was afterwards applied on a large wind tunnel model and tested in ETW.*

Keywords: Temperature-Sensitive Paint, laminar-turbulent transition, infrared laser heating

1 Introduction

Measurements on the laminar-to-turbulent boundary-layer transition in the European Transonic Windtunnel (ETW) are of great interest for aircraft design to reduce the flight-related carbon dioxide emissions through the use of natural laminar flow technology. Temperature-Sensitive Paint (TSP) is a useful optical measurement technique for visualizing the boundary-layer transition on a model surface and has therefore been used quite extensively in ETW in the last decades [1]. Conventionally, the visualization of the laminar-to-turbulent transition in ETW has been performed using the "temperature-step" method, which generates a relatively rapid change in flow temperature. The response of the surface temperature to this change depends on the surface boundary-layer conditions, with the response time being faster in turbulent than in laminar flow. This temperature-step method has proven to be a reliable method in ETW, but also has some disadvantages, e.g., changing flow parameters and time-consuming measurements.

It was demonstrated in previous research that the TSP surface could also be heated using an Infrared (IR) diode laser instead of the temperature-step method [2]. To obtain an effective heat adsorption, a carbon nanotube (CNT) coating was additionally placed between the white screen layer and the TSP active layer. This CNT layer was effective in enhancing the increase of surface temperature. However, the obtained heat distribution over the CNT layer was not homogeneous, as it was difficult to produce a uniform CNT concentration and layer thickness.

In this study, the influence of additive IR absorption molecules (IR absorber) to the TSP coating has been investigated. Since this IR absorber can be dissolved in the TSP paint solution, it can be distributed homogeneously in the TSP coating. First, the influence of the IR absorber to the TSP properties was investigated in the laboratory using the paint calibration system. Subsequently, the efficiency of the TSP surface heating was demonstrated in the ambient low-speed wind tunnel with different formulations of TSP layers and compared with the coating with CNT. The selected formulation of the TSP coating with IR absorber was afterwards applied on a large wind tunnel model and tested in ETW. The results show that the applied TSP coating performs well at cryogenic flow temperatures in ETW.

2 Temperature-Sensitive Paint Formulation and Properties

2.1 Paint Formulations

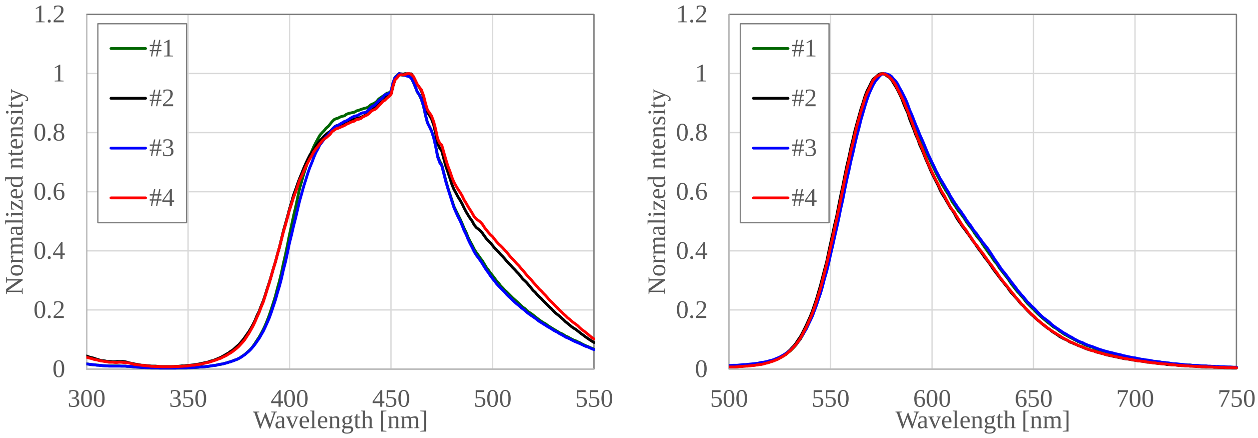
The TSP coating consists of three layers, a primary layer on the metal substrate (approx. 10 µm), a white screen layer (approx. 30 µm), and an active layer (approx. 40 µm) with the TSP luminophore. The TSP luminophore and polymer used in this study were Dichlorotris(1,10-phenanthroline) ruthenium(II) chloride and polyurethane, respectively. The IR absorber used in this study is Epolight 1178 (Epolin, Inc.). The peak wavelength of adsorption is 1073 nm. The IR absorber can be dissolved in Thinner, which is also used for solvent for TSP coatings. The IR absorber was added to the white screen layer and/or the active layer. Four different combinations of the TSP layer were prepared (Table 1). The sample #1 is the standard TSP formulation without the IR absorber.

Table 1 TSP formulations with IR absorber

Sample number	White screen layer (30 µm)	Active layer (40 µm)
#1	w/o IR absorber	w/o IR absorber
#2	w/o IR absorber	w/ IR absorber
#3	w/ IR absorber	w/o IR absorber
#4	w/ IR absorber	w/ IR absorber

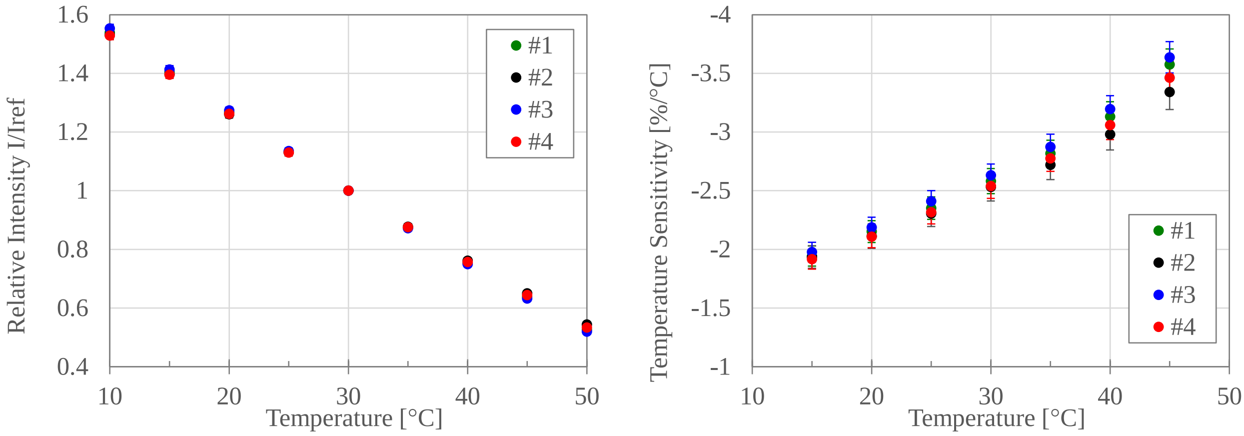
2.2 Paint Properties

The excitation spectra of the TSP coatings are shown in Fig. 1(a). The peak wavelength of the TSP coatings was around 460 nm and was not changed by the IR absorber A slight increase in the excitation wavelength of 470 to 550 nm was observed for the coatings with the IR absorber in the active layer. Figure 1(b) shows the emission spectra of the TSP coatings. No change in the emission spectra was observed with the IR absorber. The relative intensity changes and temperature sensitivities are shown in Fig. 2. A slight decrease in temperature sensitivity was observed for the coatings with the IR absorber. However, the influence of the IR absorber does not have a major impact on the TSP properties in general.



(a) Excitation spectra (Emission at 575 nm) (b) Emission spectra (Excitation at 470 nm)

Fig. 1 Excitation and emission spectra of TSP coatings with and without IR absorber



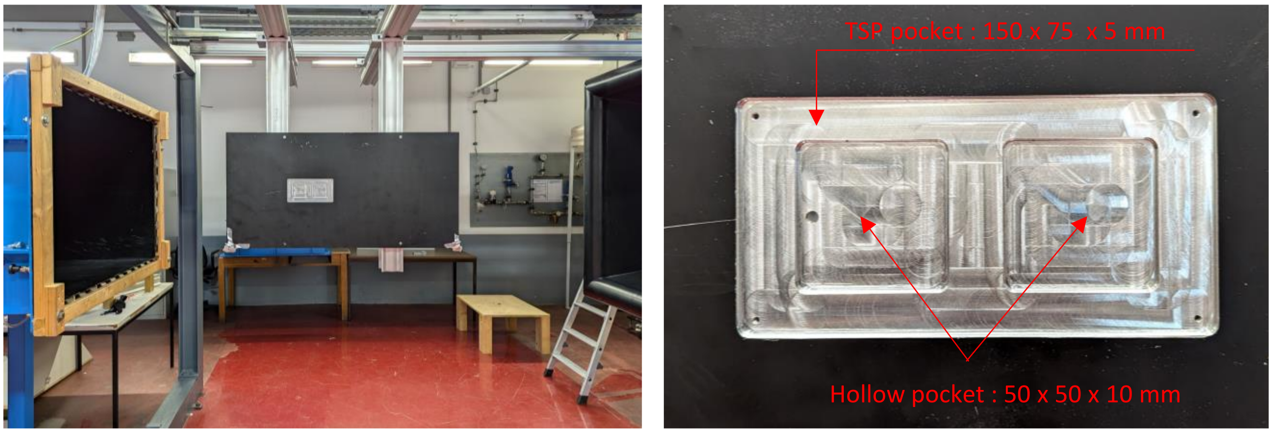
(a) Relative intensity (T_{ref} = 30 ˚C)   (b) Temperature sensitivity

Fig. 2 Intensity change and sensitivity to temperature of TSP coatings

3 Infrared Laser Heating Test

3.1 Measurement Setup

The investigation of the efficiency of the temperature increase by IR heating was carried out in the low-speed wind tunnel at DLR Göttingen. A flat aluminum plate with a thickness of 15 mm was installed vertically in the test section, as shown in Fig. 3(a). The flat plate has a large pocket with a depth of 5 mm for inserting the TSP-coated sample plate, as shown in Fig. 3(b). Within the large pocket, two small 5 mm depth (total 10 mm from the flat plate surface) pockets were prepared to simulate the hollow structure of the typical wind tunnel model.



(a) Flat aluminum plate   (b) TSP sample pocket and hollow pocket

Fig. 3 Setup in wind tunnel

The TSP coatings were applied to the 5 mm thickness aluminum plates (Figure 4). The TSP formulations were the same as Table 1, and two sets of TSP formulations (e.g., #1 & #2, #3 & #4) were applied to one aluminum plate. However, IR heating was performed only on one side of the TSP coating surface because the area of the emitting laser light was limited.

The IR laser used for the heating test was JENOPTIK JOLD-1250-CABN-25A high-power diode laser. It has a rectangular beam profile and emits IR light with a wavelength of λ = 938 nm. The IR laser was placed at a distance of 4 m from the TSP sample plates. The emitted area was about 165 mm in height and 82 mm in width, as shown in Fig. 4. The output power of the IR laser was 250 W.

The TSP was excited by two in-house developed blue-LEDs with 525 nm low-pass filter. The Photron MiniAX 200 high-speed camera was used to monitor the change in TSP intensity during and after IR laser heating. Two optical filters, a bandpass filter at 615±30 nm and low-pass filter at 850 nm, were used to block the LED and IR laser light. It was confirmed that there was no leakage light from the LED and IR laser in the camera images.

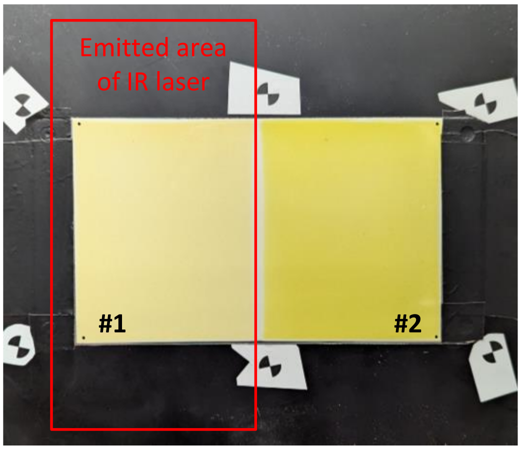


Fig. 4 TSP sample plate inserted into the flat plate. TSP formulation #1 (left), #2 (right).

First, the blue LED was turned on and waited for 5 s to stabilize. Next, the high-speed camera acquisition was started and the first 3 s of the camera acquisition was used for the TSP reference image without IR laser heating. Then, continuous IR laser heating was emitted to the TSP sample plate for 20 s. After switching off the IR laser heating, the temperature change was monitored for 5 s. Here, the time of the IR laser start is t = 0 s. The frame rate of the camera was set to 50 fps.

3.2 Measurement Results

Figure 5 shows the snapshots of temperature distribution on the TSP sample plate #2 during and after IR laser heating. The flow came from the left and the flow velocity was 25 m/s. The distribution of the surface temperature during IR laser heating was not uniform, and vertical stripes of hot spots appeared. As these patterns quickly disappeared after the IR laser was switched off, this could be due to the emission pattern of the IR laser.

The time series of temperature changes during and after IR laser heating are shown in Fig. 6. This also shows the result of the conventional TSP with CNT heating layer (only 10 s heating to avoid overheating). There was a rapid rise and fall in temperature when the IR laser was switched on and off. After these rapid temperature changes, the temperature of the TSP sample plate was gradually increased or decreased. The degree of temperature change was three times higher for the TSPs with the IR absorber in the active layer than for the TSP without the IR absorber. The efficiency of the temperature change is not higher than that of conventional TSPs with CNT heating layer, but the performance was sufficiently high. Based on these results, it was decided that TSP formulation #2 is used for the following TSP test campaign at ETW.

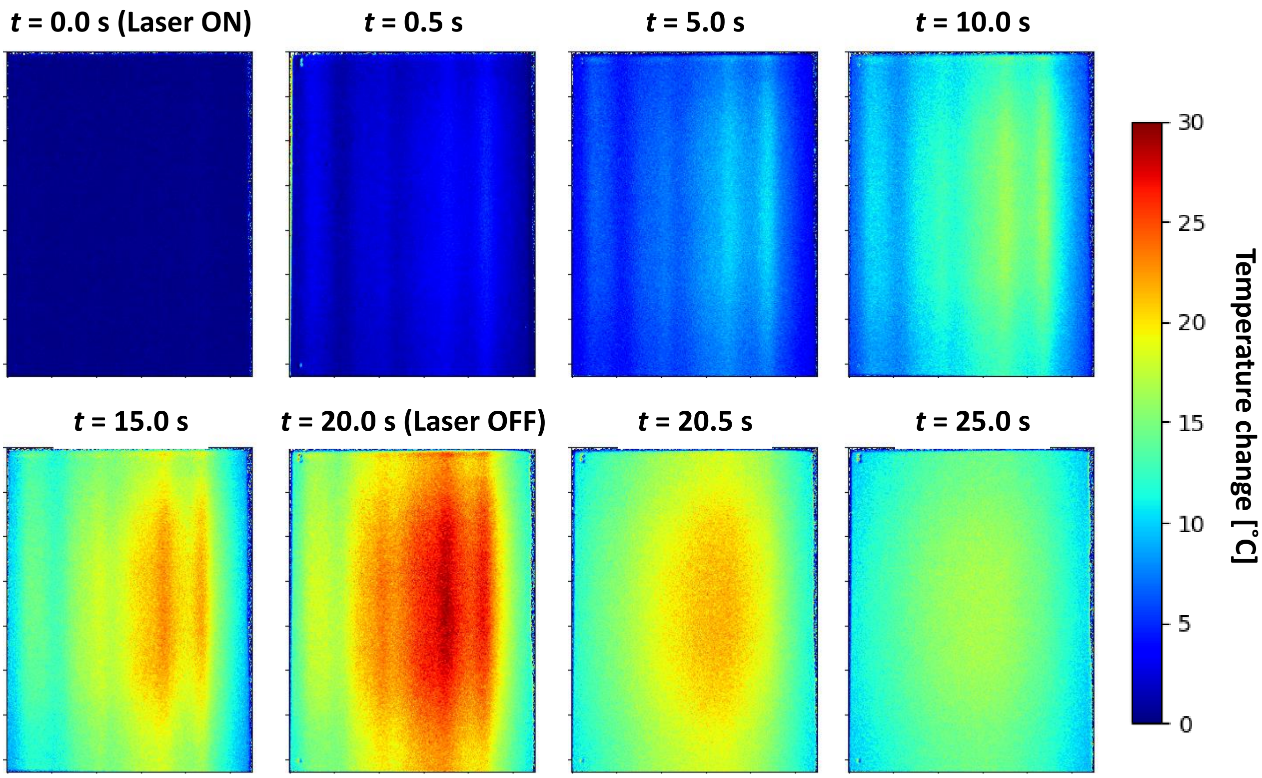


Fig. 5 Snapshots of temperature distribution on the TSP plate #2 during and after IR laser heating.

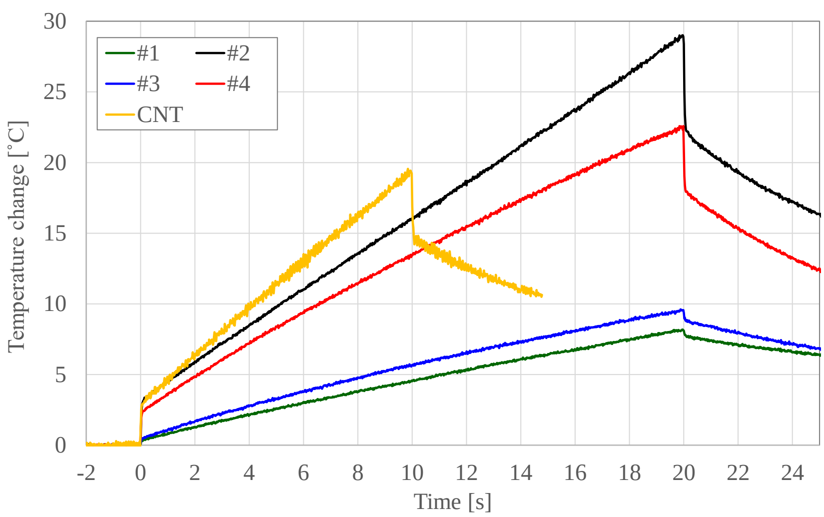
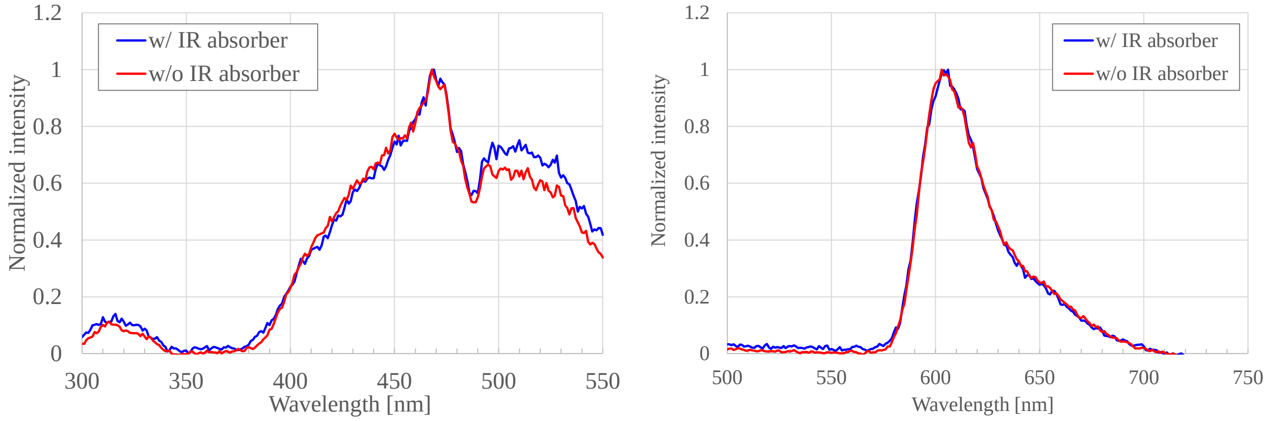


Fig. 6 Time series temperature changes of TSP plates during and after IR laser heating.

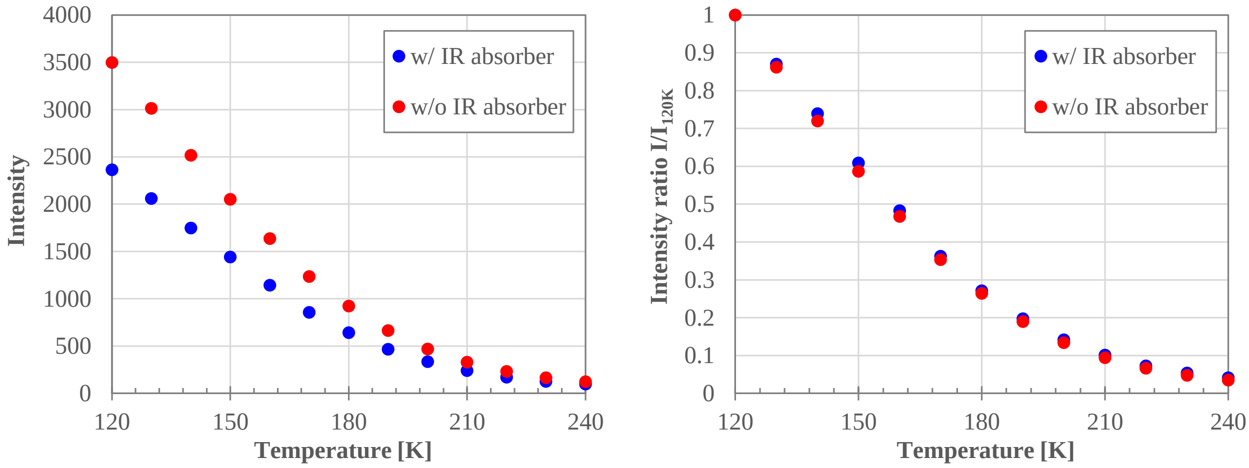
4 Application to Cryogenic Wind Tunnel Test in ETW

The TSP luminophore used for the cryogenic conditions is Bis-(2,2´:6´,2´´-terpyridine)ruthenium(II) chloride. The IR absorber was added to the active layer. The excitation and emission spectra at 120 K are shown in Fig. 7. The spectra only change slightly in the wavelength range from 470 nm to 550 nm in excitation. Figure 8 shows the absolute intensity, relative intensity and the temperature sensitivity of the TSP coatings. Although the absolute intensity of TSP with IR absorber is about half that of TSP without IR absorber, the temperature sensitivity of the two coatings is comparable.

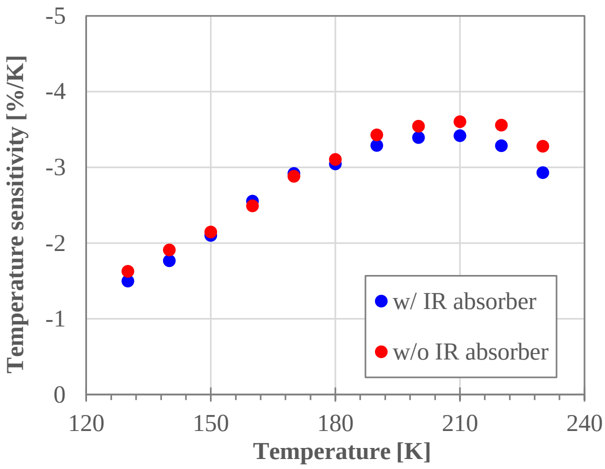


(a) Excitation spectra (Emission at 610 nm) (b) Emission spectra (Excitation at 470 nm)

Fig. 7 Excitation and emission spectra of TSP coatings for cryogenic condition



(a) Absolute intensity (b) Relative intensity



(c) Temperature sensitivity

Fig. 8 E Intensity change and sensitivity to temperature of TSP coatings for cryogenic condition

The applied TSP coating on the large-scale wind tunnel model showed good adhesion, even after several temperature cycles between ambient and cryogenic temperatures. The TSP works well with IR laser heating at cryogenic flow temperatures in the ETW. The homogeneity of the TSP surface heating showed a great improvement compared to the previous CNT heating layer.

5 Conclusions

In this study, the influence of additive IR absorption molecules to the TSP coating that improve the temperature change and homogeneous heating was investigated.

(1) The IR absorber does not have a major impact to the TSP coating properties, e.g., excitation and emission spectra, and temperature sensitivity.
(2) With the IR laser heating, the degree of temperature change was three times higher for the TSPs with the IR absorber in the active layer than for the TSP without the IR absorber
(3) The TSP works well with IR laser heating at cryogenic flow temperatures in the ETW.

References

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