Using Temperature Sensitive Paint (TSP) to map surface temperature

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UNSW Canberra has previously conducted considerable research into temperature surface-mapping techniques. The experimental mapping of surface temperature is a useful tool to verify the theoretical thermal behaviour calculated by generated simulations. The purpose of this research project was to trial the use of temperature sensitive paint (TSP) to achieve this task. The aims of this research were to assist in integrating this new capability into UNSW Canberra. This was achieved by calibrating the paint, then testing it on a nozzle test case to determine its accuracy, practicability, and suitability. This then aided in providing recommendations on future uses of the TSP. Another aim for this project was to develop an experimental method for using TSPs. TSPs are advantageous over other methods of temperature mapping as they provide a relatively non-intrusive, real-time approach with a relatively simple experimental setup. TSPs are made by embedding temperature sensitive luminescent molecules in an oxygen impermeable polymer binder. These molecules are excited by light of a certain wavelength, and when deactivating they may emit luminescent light. An effect known as thermal quenching leads to the decreasing in luminescent intensity with an increasing temperature. This is measured by capturing the intensity of the light using a DSLR camera and post-processing is used to give a measure of the intensity ratio. The relationship between the intensity ratio and temperature was plotted to find the calibration function of the paint. For this experimental research, TSP was applied to the surface of a test nozzle and its luminescent intensity was monitored throughout the use of the nozzle. The calibration function was then applied to the data to map the temperature distribution along the nozzle surface over time. The results were verified by an IR camera. It was found that with the method used the TSP data had a large variance, which contributed to an uncertainty of ±5°C. While the results from the TSP followed the same trend as the data from the IR camera it was found that the TSP was not very suitable to the test case chosen and would be more suited to applications that had higher operating temperature with a larger range. It was concluded that the TSP is more useful in providing a map of the distribution of the surface temperature, and not accurate in providing point temperatures.

Contents

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Nomenclature

TSP	=	thermal sensitive paint
I	=	luminescent intensity
I_{ref}	=	reference intensity
IR	=	infrared
T	=	temperature [K]
T_{ref}	=	reference temperature [K]
E	=	Arrhenius activation energy
R	=	universal gas constant
f	=	TSP calibration function
Q_{rad}	=	energy emitted by radiation [J]
ε	=	emissivity
σ	=	5.670373×10^{-8} = Stefan-Boltzmann constant[8] [W m^{-2} K^{-4}]

I. Introduction

UNSW Canberra has conducted considerable research into surface-temperature mapping techniques. Temperature mapping is needed in order to verify the thermal behaviour calculated by models of various engineering systems. Previous techniques employed by UNSW Canberra include infrared thermography, thermochromic liquid crystals (TLCs), and permanent-change thermal paints. This new research investigated the use of temperature sensitive paints (TSPs) to map surface temperature. TSPs offer real-time mapping of the surface temperature. Because the process is reversible it is required to be monitored at all times. To correctly perform, the TSPs must be illuminated by a UV light source and the surface captured using a filtered camera [1].

The aim of this project was to assist in integrating this new capability into UNSW Canberra. This was achieved by calibrating the paint, then testing it on a nozzle test case to determine its accuracy, practicability, and suitability. This then aided in providing recommendations on future uses of the TSP. Another aim for this project was to develop an experimental method for using TSPs.

A. TSPs

TSPs are made by embedding luminescent molecules, known as luminophores, into an oxygen impermeable polymer binder [2]. When the luminophores are at ground state no luminescence is released. However after they are brought to the excited state using light of a certain wavelength they will deactivate through either radiative or non-radiative means. It is the radiative process that causes the luminescence. As the temperature increases, the probability of deactivation by radiative processes decreases. This effect is known as thermal quenching. Comparing the intensity of the light emitted to a calibration plot will indicate the temperature [3].

The TSP used in this research uses an excitation light of 400nm. The wavelength emitted by the used TSP is longer than 600 nm with a peak at 610 nm [4, 5].

The main radiationless process that contributes to thermal quenching is external conversion. External conversion involves the energy transfer between excited molecules and their surrounds. At higher temperatures the frequency at which molecules collide increases which therefore increases the probability of deactivation occurring through external conversion [6]. This leads to the decrease in the light intensity emitted by the TSP. Over a certain temperature range the relation between intensity and temperature can be approximated into the Arrhenius form [1]

$$\ln\frac{I(T)}{I(T_{ref})} = \frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \tag{1}$$

Theoretically plotting $\ln\frac{I(T)}{I(T_{ref})}$ against $\left(\frac{1}{T}\right)$ will give a straight line with the gradient of $\frac{E}{R}$. However experiments have shown that some TSPs will not obey this approximation over a wide range of temperature. Therefore an alternative formula relating the intensity and temperature is

$$\frac{I(T)}{I(T_{ref})} = f\left(\frac{T}{T_{ref}}\right) \tag{2}$$

Where $f\left(\frac{T}{T_{ref}}\right)$ is a function that fits the experimental data. The temperature of a surface can be determined by comparing the intensity of the light emitted to the calibration plot [1].

The luminescent molecules used for TSPs are metal-organic and are effective between 273 K and 400 K. Higher temperatures can be measured using thermal phosphors which are made of inorganic luminophores [7, 8]. Research has also been conducted where the TSP formulation has been modified for cryogenic temperatures. These cryoTSPs are function between 90 and 200 K [9, 10].

TSPs are able to be used for surface-temperature mapping due to their ability to provide a high spatial resolution measurements compared to more traditional techniques such as thermocouples [11]. TSPs are also relatively non-intrusive, with a lower cost due to the ease of set up and small amount of instrumentation used [7]. They are also preferable over IR thermography in applications where the instrumentation must look through a window because the TSP can be captured through glass or Perspex while IR cameras need an expensive sapphire window to operate [3, 12].

The research conducted this year involved investigating the accuracy and suitability TSP using a Urethane TSP manufactured by Innovative Scientific Solutions, Inc. To conduct this research, two main experiments were performed. The first was a calibration experiment. The purpose of this experiment was to define the calibration function and to establish the type of accuracy expected for further experiments. The second experiment conducted was to investigate the thermal behaviour of the surface of a supersonic nozzle. This experiment utilised both the TSP and an IR camera. The nozzle that was tested is of interest to UNSW as studies are currently being undertaken on different nozzle profiles including this one. While computer models have been created to analyse the temperature distribution on these nozzles, it is advantageous for experimental data to validate these models.

There are a number of methods currently used to determine temperature using TSPs. Intensity-based methods are the most popular and are either accomplished using an intensity ratio CCD camera system or laser scanning system (Liu 1999). Life-time methods have also been effectively used to find the temperature. Multi-luminophore systems have also been proven (Liu 1999) [3, 11]. For this research the intensity ratio CCD camera system was chosen as the most appropriate for the research.

1. Intensity ratio CCD camera system

The intensity ratio CCD camera system is the most commonly used in aerodynamic testing [11] and is the method that will be used for this research. This method relies on having 'wind-off' and 'wind-on' images captured before and during the test run respectively. For this method the TSP is painted onto the surface of the material. A light source at the excitation wavelength is then used to excite the luminescence. The luminescence is captured using a CCD or DSLR camera with optical filtering to eliminate the excitation light. The wind-off image is captured at a known temperature while the wind-on image is captured at an unknown temperature. The relative luminescent intensity image is found by taking the ratio of the two images. The relative intensity is then compared to the calibration function to find the temperature [3, 11]. One of the main advantages of using this method is that the ratio process can reduce the effect of spatial variations in thickness of the TSP, luminophore concentration and illumination light [2]. A disadvantage of this method occurs when model deformation occurs when loads are applied. This results in the misalignment between the wind-on and wind-off images, which must be corrected in order to have the correct results. This therefore increases the difficulty in the image processing steps [2].

The intensity ratio CCD camera system has been chosen for this experiment for a number of reasons. The main reason is that there have been previous TSP experiments that have used this method, making it a proven method with literature on the correct procedure. Another appealing factor is that it has relatively simple experimental set-up using equipment already owned by UNSW Canberra. This method is also ideal for the supersonic nozzle rig at UNSW Canberra there is negligible movement by the nozzle during use, meaning that correction for misalignment in the wind-on and wind-off images is not necessary.

5. Uncertainty

The main identified sources of uncertainty are spatial variations such as illumination, paint thickness, and luminophore concentration. These spatial variations can be eliminated by the use of the reference wind-off image. Additionally camera shot-noise, photo-degradation and sedimentation, model movement and deformation, error in the reference temperature, and accuracy of the TSP calibration also contribute to the uncertainty of the measurement [3]. However it has been discussed that the accuracy of the TSP calibration is the greatest contributor to the uncertainty [3, 7, 11]. Therefore it is vital that the calibration test be carried out with care and accuracy to ensure the most correct calibration possible.

6. Previous applications

One of the first applications of TSPs was to detect the laminar/ turbulent boundary layer transition. The reason that TSPs are successful is because the heat transfer coefficient for a turbulent region in much larger than that of a laminar boundary layer. TSP was able to detect the transition point because of the large temperature difference between the regions [10].

There have been many experiments conducted utilising TSPs in hypersonic flow applications [1]. Surface temperature measurements of the aft-body of a capsule re-entry vehicle have been conducted to help visualise and quantifying of surface temperature interactions between the reaction control system jets on the aft body of re-entry capsules [12]. The experimentation shows that TSP is an effective tool for studying surface interactions in hypersonic testing environments. The standard intensity ratio CCD camera technique was used for the TSP measurements proving that this method is effective for hypersonic applications [12].

Mapping of heat transfer in transient supersonic and hypersonic flows using TSPs have also been successfully conducted [7, 11]. One of the advantages for such applications is that TSPs are relatively non-intrusive when compared to other measurement techniques such as thermocouples. This is relevant to the supersonic nozzle testing being conducted as part of this research as the TSP will not inhibit the flow of the gas [7]. This is important because the main purpose of the supersonic nozzle experiments is to validate the models and simulations of the flow.

B. IR camera

For all experiments conducted with the TSP, an IR camera was also used. For the calibration experiment the purpose of the IR camera was to give the temperatures at the recorded intensities in order to find the calibration function. For the other experiments conducted, the purpose of the IR camera was to validate the TSP results. The IR camera was chosen as it provides surface temperature mapping, which is what the TSP measures. Other options such as thermocouples would not have been as effective as they only provide point temperatures [13, 14]. IR cameras convert infrared radiation released from an object to a calibrated display temperature. All bodies above absolute zero emit IR, and as the temperature increases so does the amount of IR. The total radiated energy from a body is known as the Stefan-Boltzmann law and takes the form,

$$Q_{rad} = \varepsilon\sigma T^4 \ \ (Wm^{-2}) \tag{3}$$

Where the energy emitted from the body is proportional to the emissivity and temperature. The emissivity of an object describes how well it emits IR. A black body is a perfect emitter and has an emissivity of one. All other bodies will have an emissivity of less than one [13]. To calculate the temperature of an object, the IR camera must know what the emissivity of the object being measured is. Therefore it was important to identify the emissivity of the TSP [15]. This is discussed in the results section of the calibration experiment.

Advantages of using the IR camera are that it does not need to interact with the object it is measuring and it is non-destructive. However it unlike the TSP it cannot be used through glass as the glass blocks the infrared radiation emitted by the object [13]. The accuracy of the IR camera used is ±2°C at ambient temperatures of 23±5°C with a frame rate of 120Hz [15].

C. Nozzle flow

To test the accuracy, practicability, and suitability the TSP was applied to a nozzle that is currently being trialled at UNSW. The nozzle tested was a linear expansion-deflection (ED) nozzle developed by Kyll Schomberg, an UNSW PHD student who is hoping to improve the thrust efficiency for rocket launches. Currently the thrust efficiency of conventional converging-diverging (CD) nozzles used in rocket engines is affected by the changing altitude. This is because the greatest efficiency is achieved when the pressure of the nozzle's exhaust flow is equal to the ambient pressure. This ambient pressure obviously changes with changing altitude resulting in nozzles that are not efficient throughout the flight [16-18]. The purpose of the ED nozzles being trialled at UNSW is to try to limit the expansion of the flow at all operating conditions in order to try to improve the efficiency at all altitudes [19]. This is achieved by deflecting the flow using a pintle as seen in Fig 1. As with conventional CD nozzles, the pressure is controlled by the area ratio. By deflecting the flow a viscous wake region is created in the nozzle, this theoretically will vary the area ratio to retain high efficiency at low altitudes. The area ratio should increase as the altitude increase, so as to maintain the high efficiency [18].

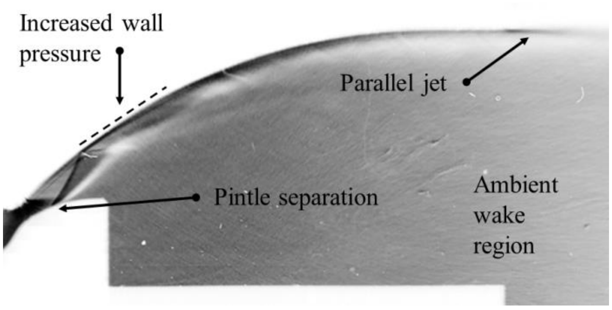

Figure 1. A schlieren image of the flow field of the tested nozzle at a pressure ratio of 10 [18].

For isentropic supersonic flow relations demonstrate that as the Mach number increases, the pressure and temperature decrease. This can be applied to the tested ED nozzle. Therefore in the nozzles that UNSW Canberra are testing, the temperature measured with the TSP should decrease along the length of the divergent portion of the nozzle [20]. However because

compressed gas bottles are used as the source of the air, the decrease in air temperature from the expansion out of these bottles will add to the decrease in temperature due to the expansion of the flow through the nozzle.

Due to time and personnel constraints, only one run of one of the prototype ED nozzle configurations was able to be tested with the TSP. For increased accuracy and certainty to confirm the results of the TSP, more runs of the experiment need to be carried out.

II. Results

A. Calibration

The purpose of this experiment was to calibrate the TSP, this is achieved by plotting intensity ratios at known temperatures to get a calibration function. The calibration was completed over the temperatures range that the paint is designed for.

1. *Experimental Setup*

The test piece for the calibrations was a 150 x 150 x 3mm steel plate. A square in the centre was initially airbrushed with a white undercoat to allow for maximum luminescent light to be captured by the camera. The TSP was then airbrushed over the top. The test piece was then placed on a hotplate. The 400 nm UV light, DSLR camera with red filter and the IR camera were then set up and focused on the plate as seen in Fig 2. The emissivity was set to 0.90 on the IR camera to ensure correct temperature recording. The UV light was turned on and all other lights providing ambient lighting were turned off. An image was captured using the DSLR camera at room temperature, 20°C. This was used as the 'wind-off' image. The hotplate was then turned on and photos were taken as the temperature rose in 5°C increments. These were the wind-on images. When the temperature reached above upper limit of the TSP, 100°C, the hotplate was turned off. The hotplate was removed from underneath the sample piece to facilitate a quicker cooling time. Once again photos were taken with the DSLR camera as the temperature of the piece decreased in 5°C increments.

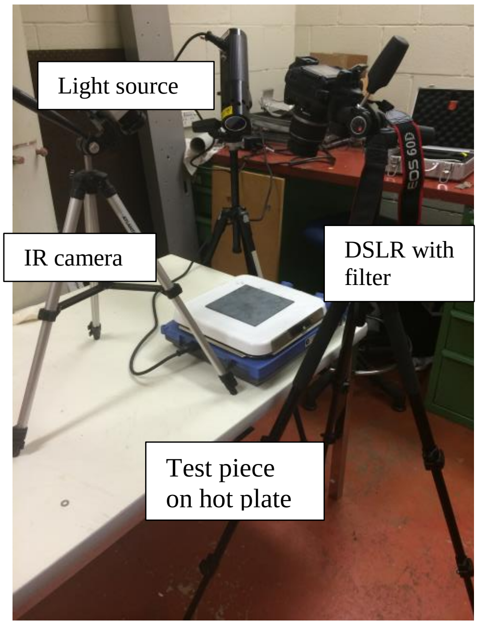

Figure 2. Set up of the calibration test

2. *Analysis Process*

To obtain a useful relationship the images are subjected to post-processing in Matlab. Firstly the wind-off image is established, taking only the red channel. This ensures that only the emitted luminescent light is evaluated. The wind-on images are also established, again taking only the red channel. The matrix for each wind-on image was then divided by the matrix of the wind-off image and cropped to only evaluate the area covered by the TSP. This process gives the intensity ratio between the images. An average of the intensity ratio given by the TSP was calculated and plotted against its corresponding temperature given by the IR camera.

3. *Results*

The above process was used to plot the relation seen in figure 3. This plot is called the 'calibration plot' and can be used to convert calculated intensities to temperatures.

As was expected, the intensity of the emitted light decreases as the temperature increases due to the thermal quenching process. Both sets of data, one with the temperature increasing and the other decreasing, show the same calibration function. This indicates that there was no significant hysteresis.

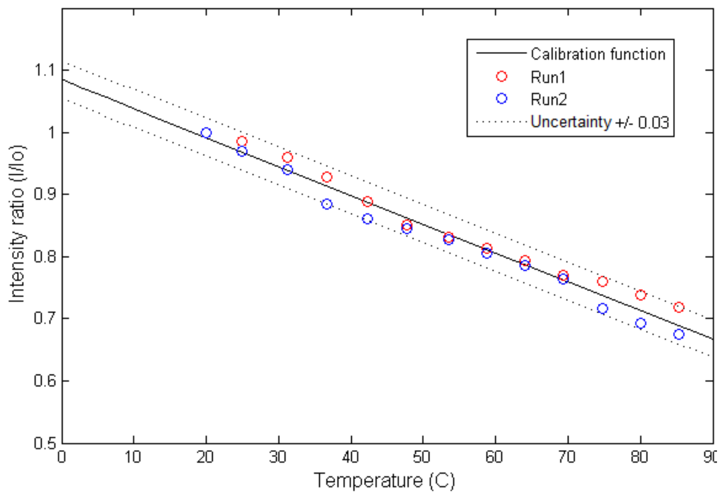

Figure 3. The calibration plot for the Urethane TSP tested at a reference temperature of 20°C. *Run 1 is increasing temperature, run 2 is decreasing temperature.*

From the plot, the relationship between intensity ratio and temperature, at a reference temperature of 20°C was found to be:

$$\frac{I(T)}{I(T_{ref})} = -0.0046\,T + 1.08 \pm 0.03 \quad (4)$$

This can be converted in terms of reference temperature to be:

$$\frac{I(T)}{I(T_{ref})} = -0.0927\left(\frac{T}{T_{ref}}\right) + 1.08 \pm 0.03 \quad (5)$$

This form of the equation can be used when analysing data at a different reference temperature. The found calibration function was found to have an uncertainty of ±0.03. When this is converted to a temperature it gives an uncertainty of ±5°C. This is seen to be a fairly large uncertainty when compared to other methods, for example the used IR camera gives an uncertainty of ±2°C [15]. Potential contributing factors to this uncertainty are human error, temperature sensitivity of the TSP, the response time of both the TSP and IR camera, incorrect emissivity set on IR camera or the IR camera's error.

The greatest contributing factor to the uncertainty in the results is most likely the human error. This is due to the methodology used. For this experiment the wind-on images were manually taken, with the photos taken when the person conducting the experiment saw that the IR camera showed that the temperature had increased by 5°C. The delay in information processing, would have meant that the images may not have been taken at exactly the shown temperature.

The temperature sensitivity is quoted to be 0.9% per °C [15]. However when analysing the data it was found that the pixel to pixel variance was large for the intensity ratio. This variance may have also contributed quite heavily to the uncertainty.

The other main contribution to the error may have been the uncertainty of the IR camera. This includes, response time, setting of the emissivity and uncertainty of the IR camera, ±2°C [15]. I is seen that the contribution from the uncertainty is relatively large is therefore most likely the main contributor to the IR uncertainty of the experiment.

4. Importance of the base layer

When this experiment was initially performed, no base layer was used. This resulted in the signal strength of the TSP being very weak. Therefore it was decided that a white base layer should be applied to the metal before the TSP. The importance of this base layer can be seen in Fig 4. It is seen that with the white base layer it is easy to determine where the paint on the test begins and ends by the large change in signal strength. However the signal from the TSP without the base layer cannot be distinguished from the background signal. This was determined to be due to the dark colour of the steel absorbing approximately half of the luminescent light emitted. By adding the white background, the luminescent light was reflected off the white, and could then be detected by the camera.

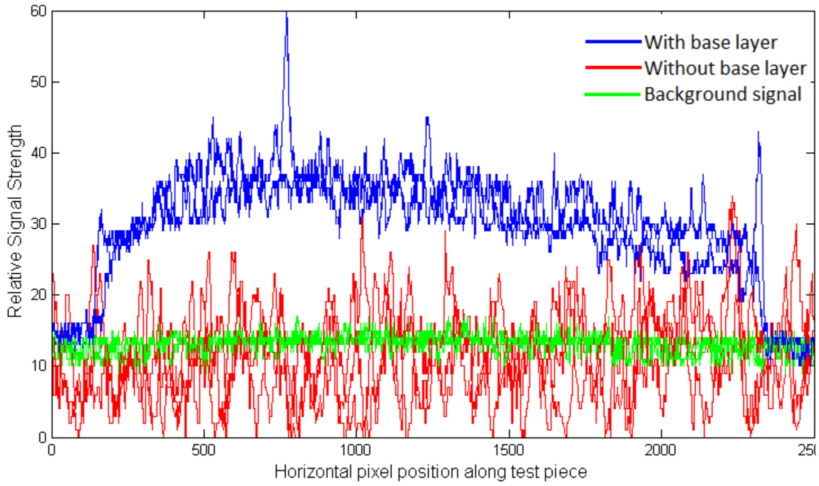

Figure 4. Signal Strength of the TSP with a white base layer compared to no base layer and the background signal.

5. Determining the emissivity

To ensure that the correct temperature was recorded by the IR camera, the emissivity of the TSP had to be determined. The initial step was to paint a matte black square next to the TSP and white base layer square on the test piece. The reason that matte black was chosen as it has a high, known emissivity of 0.94 [15]. The method chosen can be found in the FLIR manual [13].The test piece was then heated with the hot plate with the assumption of uniform temperature distribution. Both squares of paint were analysed, setting the emissivity on the software at 0.94 for the black square. The emissivity of the TSP square was then adjusted until both squares were reading the same temperature. This was found to be 0.90 and was checked at multiple different temperatures. The reason that high temperatures were used as the reference temperature is because of the T^4 relationship. At higher temperatures, different emissivities will record a much larger deviation in recorded temperature by the IR camera [13].

B. Thermal behaviour of the supersonic nozzle surface

The purpose of this experiment was to map the surface temperature and investigate the thermal behaviour of a test supersonic nozzle profile over time during a 15-30 second period. For the experiment conducted, the flow pressure was set at 10 bar.

Figure 5. KS-10 the tested nozzle profile. *Note that it was only the right side that TSP data was collected for.*

1. Experimental Setup

The nozzle profile tested (see Fig 5) was initially divided into three strips along the length. The left strip was painted with pressure sensitive paint, the centre was left as bare metal, and the right strip was coated with the white base layer followed by the TSP. All paints were applied with the airbrush to ensure an even spread of the paint

The nozzle was then placed into the supersonic nozzle rig. The TSP measurement system for this was nearly identical to the calibration test. The 400 nm UV light was aimed at the surface to be mapped. The DSLR camera with a red filter attached was set up to ensure that it viewed the whole of the nozzle surface. As the IR camera cannot give temperature readings through glass/ Perspex, it was mounted above the nozzle, looking onto the surface through the gap at the top. Before the airflow was started, a wind-off image was taken as the reference intensity and temperature. The reference temperature was recorded to be 15°C. During the run, the IR camera video recorded the temperature of the surface and the DSLR took continuous photos.

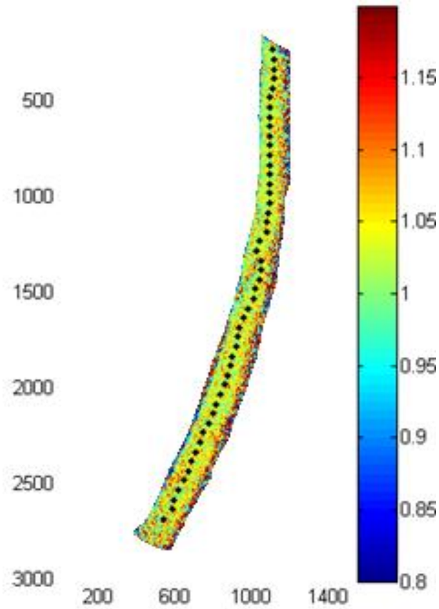

Figure 6. Example of intensity ratio image with data points shown. *The axes shown are pixel position and the colour bar shows intensity ratio. Only the TSP is shown, the background has been removed.*

2. Analysis Process

The analysis of the thermal behaviour of the nozzle surface was conducted with the TSP, with these results being verified by IR data and computational analysis. Two main pieces of information extracted from the data were the temperature distribution along the length of the nozzle at select times and the average surface temperature of the nozzle over time.

For the TSP data the initial step was to find the intensity ratios between the wind-on and wind-off images as detailed in the calibration section. Data points were then selected along the images (see Fig 6) and the average intensity of the surrounding 15 pixels was found.

To plot the temperature along the length of the nozzle, the intensity ratio of each data point was plotted against the length. The images chosen for this corresponded to the chosen times during the run length. The calibration function, for a reference temperature of 15°C, was then applied to the given intensities to give the temperature in degrees Celsius. Because of the curved nature of the nozzle and the angle of the DSLR camera, the pixel position also was converted into a metric length from the

throat of the nozzle. Due to illumination issues, the data from the throat to 15mm along the length was not recorded. The results of this are discussed in the next section.

As previously indicated, the IR camera was mounted above the nozzle opening looking down onto the surface. The IR camera was set to record throughout the length of the run. A run is defined as from when the airflow is started, to when the airflow is stopped. In post-processing the recorded temperature along the length of the nozzle was extracted. Similar to the TSP data, the IR camera data had to be converted from pixel position to a metric length, accounting for the curvature of the nozzle. The main problem with the IR data was because it was looking directly down onto the nozzle, the last 10mm was not able to be measured the section is vertical. The pintle of the nozzle also mildly impinged on the viewing.

As one of the reasons for using TSP is to validate experimental data, it was decided that doing a transient-thermal simulation of the nozzle profile would be beneficial to the project. The experimental data could then be compared to the analytical data. For this analysis ANSYS-Workbench was used, with an imported CAD model. Research on the flow properties of this nozzle profile have shown that both the heat transfer coefficient and the working fluid temperature vary considerably along the nozzle length as the fluid is expanded (see Fig 7). These distributions were incorporated into the nozzle model by splitting the model into sections and applying the average values over the area to the corresponding section. Figure 8 shows the model used with the sections shown. More divisions were made in areas where there is a large change in values. Figure 7 also displays the division lines. The simulation was then run for 26 seconds, the run length of the nozzle experiment.

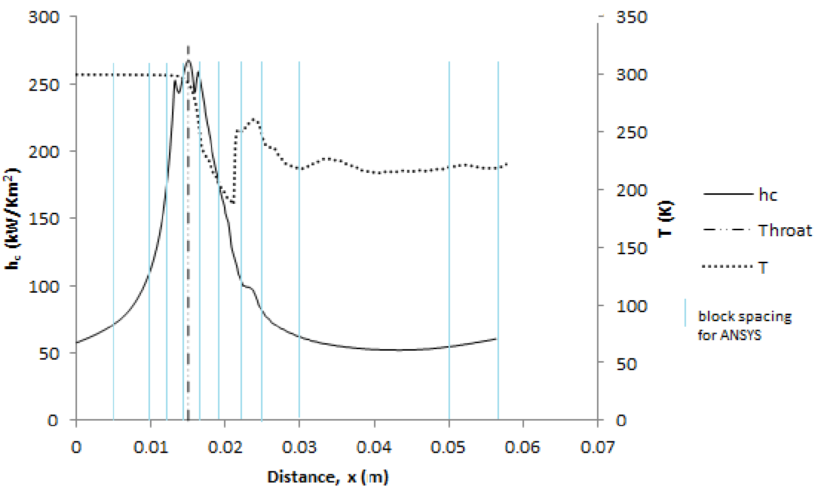

Figure 7. Heat transfer coefficient and working fluid temperature along the KS-10 nozzle for a pressure ratio of 5 [21].

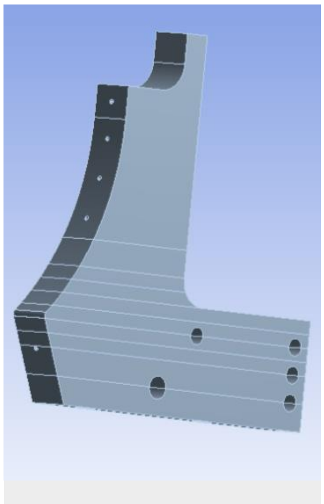

Figure 8. KS-10 model analysed. *The sections are identified by the light blue lines*

3. Results

The first data analysed was to compare the temperature distribution along the nozzle at selected times. The data compared was from the IR camera and the TSP. This can be seen in figure 9 where the continuous line represents the data collected by the IR camera. The dotted line represents the data gathered by the TSP. It is seen that both sets of data indicate that the surface temperature along the nozzle decreases with time. Both the IR camera data and the TSP data indicate that the initial surface temperature of the nozzle is approximately 15°C, indicating that the calibration of the TSP is correct. However it is seen that the TSP offers a much larger variation in temperatures for each run time along the length of the nozzle while the IR data indicates a fairly constant surface temperature. The reason that the initial temperature data for the TSP indicates a constant temperature is because the intensity ratio calculated is one. This is due to the image being divided by itself. When the calibration function is used to transform the intensity to a temperature, it gives a constant temperature.

A potential reason for the IR data indicating a much more constant surface temperature than the TSP is due to the positioning of the IR camera. In order to ensure that the IR camera was not damaged by particulates such as dust and paint flakes coming out of the nozzle at high velocity, the IR camera had to be mounted approximately 1m above the nozzle exit. This meant that the resolution of the IR data for the nozzle surface was decreased. This led to each pixel being responsible for a much larger area than each pixel of the TSP data, and therefore the data may have appeared more constant. In future, the IR camera should be mounted much closer to the opening of the nozzle and a sapphire window used to protect the camera lens. This would increase the resolution and therefore the amount of data that the IR camera could collect for the experiment.

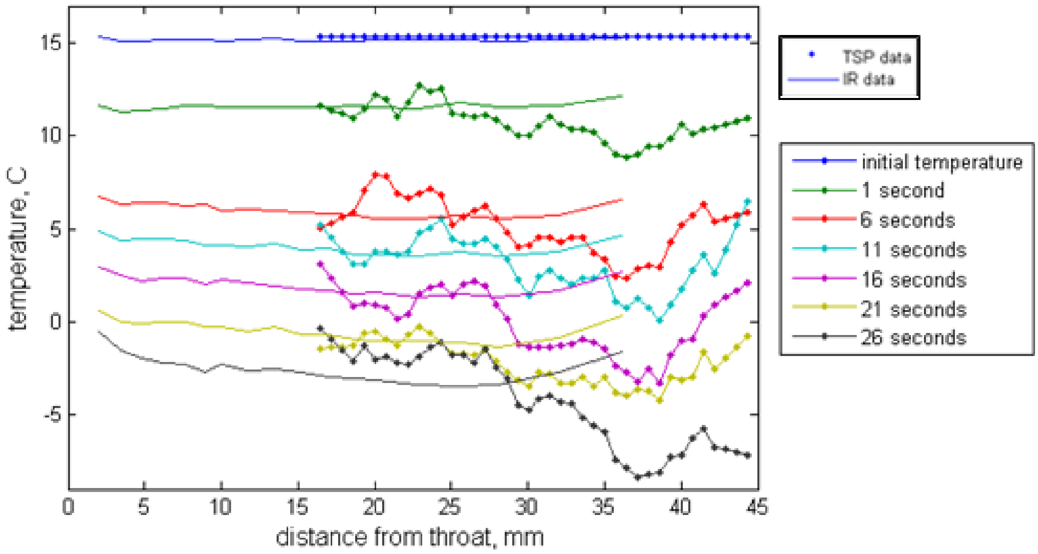

Figure 9. Surface temperature along the length of nozzle at selected times.

It was found that the TSP data demonstrated a large pixel-to-pixel variance (see Fig 4 for example of this). It is known that in reality, that due to the highly conductive material (stainless steel) of the nozzle, the variance of the actual temperature would not be this great. Although many pixels were averaged for each data point, the large amount of noise this variance created may be a cause of the variation in recorded surface temperature the TSP shows. Another potential cause for the large variation in the TSP data is due to the product's specified temperature range, 0-90°C [15]. It is seen that this experiment operates at and below the limit of this paint. It would then be reasonable to assume that the data for temperatures below 0°C cannot be relied upon, and potentially the temperatures leading to the limit, i.e. below 10°C may also be unreliable.

The intensity-based method that was used should reduce the effects of spatial non-uniformities such as the un-uniform distribution of luminophores. However it was found that throughout the experiment paint was flaking off. The method would not be able to account for lost luminophores. Therefore losing luminophores due to the throughout the run may account for the variation of the later seconds being greater than the variation in the initial few seconds.

It was decided that to further compare the data collected, the average surface temperature of the nozzle throughout the run should be analysed. The results are seen below in figure 10. In the above plot, the blue dots indicate the average intensity ratio for each wind-on image. The data has then been converted to degrees Celsius and plotted over the length of the run. The black line indicates the temperature of the nozzle surface as indicated

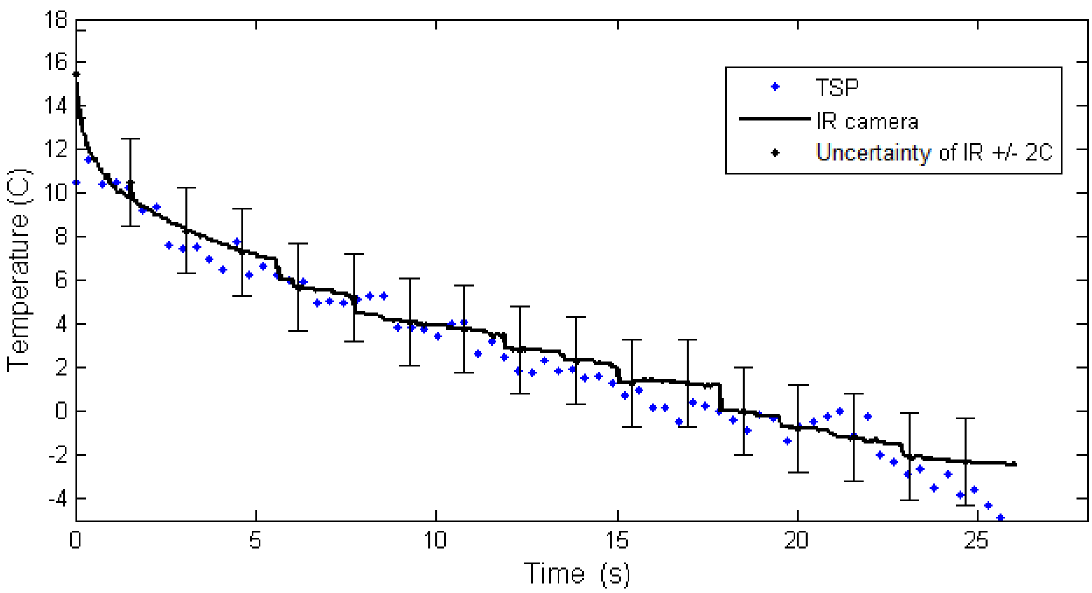

Figure 10. The average temperature of the nozzle surface throughout the duration of the run

by the IR camera. The error bars are the uncertainty of the IR camera. It can be seen that both the IR camera and TSP data show a large initial temperature drop followed by an almost linear decrease in temperature.

It can be seen that the trend from the TSP data is comparable to the trend shown by the IR camera. This reaffirms that the calibration plot is correct. It is also seen that the TSP results seem to be more accurate when taken as an average over the area, compared to the previous analysis where it there was a lot of variation. As with the previous analysis, it is seen that at temperatures below 0°C the TSP data has a larger deviation from the IR data. This could once again be attributed to the range of the paint.

The IR plot also appears to indicate camera lag, especially around the 18 second point. However as this sharp drop is approximately 1°C and the error bars cover 4°C, it can be said that this lag does not significantly affect the results. As mentioned in the previous analysis, possible causes of the TSP deviation could be the large raw data variance and lost luminophores from flaking or paint being worn off by particles in the flow.

When the ANSYS simulation result was compared to the results from both the IR camera and the TSP the temperatures received were exceptionally different. Because of this, the simulated results have been deemed inconclusive for a number of reasons. The first is that the properties of the gas that was simulated may not have been that of air. If the properties of the gas used varied significantly to that of air, the Reynold's number, and therefore the Nusselt number and heat transfer coefficient would also be different. This would greatly affect the simulated result. Another discrepancy between the data input into the ANSYS simulation and the experiment was the pressure ratio. The experiment used a ratio of 10 while the input data was 5. Because of the large discrepancy between the simulated and experimented data as well as the discussed issues with the simulation, it was decided not to include the ANSYS results into figures 9 and 10.

C. Practical aspects of using TSP

This next section will discuss the practicability, and suitability of using TSP as well as commenting on the recommended methodology of using the TSP.

For the application that the TSP was used for in this research, it was discovered that the TSP may not have been the best choice. The main reason for this was because the operating temperature of the nozzle rig was at the lower limit of the TSP's operating range. Also the large variance in intensity was not suitable for the small change in temperature that was experience by the nozzle surface, as the uncertainty of the paint was 25% of the total change in temperature.

It then can be concluded that TSP is more suitable at providing a map of the surface temperature distribution, than giving point temperature readings. It is also better suited for applications that will have a larger change in overall temperature, within the range of 0-90°C.

For the practical aspects of TSP it was discovered that both the base layer and the TSP are fragile once applied and have a tendency to flake off. Therefore the paint should be protected as much as possible to prevent this. This also indicates that the paint may not be suitable in environments that have the potential to corrode, such as in environments where particles may scrape along the paint.

Although the TSP is non-intrusive, the amount of equipment needed to record the measurements is significant. Therefore using TSP may not be the most effective in isolated or confined environments. Due to the method used, it is also ideal if the experiment does not move throughout the recording process as taking the intensity ratios become inaccurate.

III. Conclusions

The aim of this project was to assist in integrating the TSP capability into UNSW Canberra. Initially a method to use the paint had to be established. The paint could then be calibrated and tested on a nozzle test case.

When developing the methodology it was found that to ensure maximum signal, a white base layer needs to be applied before the TSP. It was also found that the paint is quite fragile and must be handled with care once applied. Performing the calibration experiment found the calibration function which could then be applied to later cases. The experiment also gave an uncertainty of ±5°C for the TSP. The emissivity of the paint was also found to be 0.9.

When applied to the test nozzle it was found that the TSP gave a much larger variance of temperature than the IR camera used. However it did follow the same trend as the IR data indicating that it is effective for larger areas of temperature. Whilst both sets of experimental data followed the same trend as the theoretical simulation, due to a number of problems with the simulation its results were deemed inconclusive. It was also found that the test case was not very suitable as its operating temperature was at the lower limit of the TSP's temperature range. It may also have been unsuitable as the overall temperature change was small.

It was concluded that the TSP is more useful in providing a map of the distribution of the surface temperature, as it is not accurate in giving point temperatures. It is also more suitable for applications that have a larger change in overall temperature within the operating range. It would also be difficult to correctly operate all the required supporting equipment in isolated or confined environments.

IV. Recommendations

A. Methodology

It is recommended that for all future uses of the TSP, a white base layer must be applied before the application of the TSP. It is also advantageous to set up the UV lights with the diffuser as close to the experiment as practicable to maximise excitation. If using the IR camera to determine the reference temperature, the emissivity of the paint should be subjected to a confirmatory test to ensure that the set emissivity is correct. It is also not recommended to be used in harsh environments where the paint has the potential for flaking off or wearing away. This will cause discrepancies in the amount of luminophores present during the wind-on and wind-off images.

B. Calibration

It is recommended that the calibration experiment be repeated and expanded to identify how the signal strength and the calibration plot of the TSP varies under different conditions. Potential testing could include; varying the light conditions, varying the thickness of the paint, repeating over a smaller range of temperatures, and varying the reference temperature. This would assist in finding the optimum experimental conditions for the experiment. If these extra calibration plots are consistent with the calibration function found during this research, they would verify the universal application of the function. However if the plots differ dramatically, one would have to conclude that experiment related calibrations must be performed for each new experimental configuration.

C. Application to test cases

In order to test the performance of the TSP further, it is recommended that more suitable test cases are found than the nozzle rig that this research was performed on. These test cases would preferable operate with a higher operating temperature within the TSP's performance range. Ideally the test cases would also have a bigger surface area for the TSP to be applied on, with more test runs to confirm the results.

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