SIMULTANEOUS TEMPERATURE AND CONCENTRATION CALIBRATION OF PRESSURE SENSITIVE PAINT WITH ATMOSPHERIC CALIBRATION SETUP FOR FILM COOLING EFFECTIVENESS MEASUREMENTS

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ABSTRACT

Pressure sensitive paints (PSP) are typically calibrated for discrete levels of oxygen partial pressure and temperature. This process can be time-consuming and result in higher levels of uncertainty when fitting calibration points. This study presents a new calibration setup and methodology for simultaneous observation of continuous temperature and concentration fields over a broad range of oxygen concentrations at atmospheric conditions. PSP calibration is conducted to determine the temperature and oxygen concentration dependency of the examined paint regarding the emitted intensity. The results indicate that intensity-temperature and oxygen concentrations relations can be extracted. The calibration data are validated with the manufacturer's data. The findings show an excellent agreement with the manufacturer's standards. A detailed uncertainty analysis showed that the typical uncertainty levels are less than 6%.

NOMENCLATURE

I	Intensity
P	Pressure
T	Temperature

Greeks

η	effectiveness

Subscript

air	air
blk	black
c	coolant
fg	foreign gas
g	gas
iu	intensity uncertainty
m	measurements
O	wind-off
ov	overall
ref	reference
sf	surface fit
sv	Stern Volmer
w	wall

Abbreviations

MW	Molecular Weight
N_2	Nitrogen
O_2	Oxygen
PSP	Pressure Sensitive Paint

INTRODUCTION

PSP is an organic substance with luminescent molecules sensitive to oxygen concentration which emits light when excited. The intensity of the emitted light is affected by the local partial pressure of oxygen as well as the surface temperature. The development of a calibration setup is required to investigate the dependence of PSP intensity on oxygen concentration and temperature. All previous research on the extraction of calibration data has been conducted with the same philosophy. The intensities are measured using experimental calibration setups that can test discrete temperature and oxygen concentration conditions in the painted surfaces. Cacioli et al. [1] developed a calibration chamber for various pressures and three different temperatures of an aluminum test plate, controlled by vacuum pumps and an adhesive electric heater, respectively. Ahn et al. [2] used a sealed vacuum chamber to perform a PSP calibration at various known pressures and temperatures ranging from 0 atm to 1.8 atm. The PSP intensity was obtained for each pressure and temperature setting. Suryanarayana et al. [3] calibrated PSP in a vacuum chamber using known discrete pressures and temperatures ranging from 0 atm to 1 atm and 22.2℃ to 60.1℃, respectively.

Shiau et al. [4] quantified the relation between partial pressure of oxygen - temperature and the

intensity of the PSP painted surface in a vacuum chamber with a transparent Plexiglass optical access. A copper plate was used as a painted surface and was placed inside the chamber. For temperature measurements, a T-type thermocouple was embedded in the copper, and a flexible heater mat was attached to heat the plate. For PSP calibration, Narzary et al. [5] used a small block of copper with a thin foil heater (0.05mm thick alloy 600) attached on one side and on the other side seven coats of PSP were applied. The block was placed in a tightly sealed vacuum chamber with optical access from the top. To record temperatures, two T-type thermocouples were embedded in the PSP coated side. The calibration was carried out for several pressures ranging from 0 atm to 1 atm and three temperatures (21°C, 40°C and 61°C).

Gurram et al. [6] performed an in-situ calibration for PSP in order to minimize bias errors. The calibration in this case was in-situ, no separate calibration set up was used, the calibration was conducted directly on the test piece, by pressurizing the test section (varying the partial pressure of oxygen).

All previous pressure-temperature PSP calibrations were accomplished by varying the pressure within the calibration chamber, whereas the only relevant parameter is the partial pressure of oxygen, which can also be varied in atmospheric conditions. Furthermore, temperature and pressure calibration are performed by changing one of the variables (P, T) at a time, making it a time-consuming process with high discretization in the acquisition of the paint's temperature sensitivity.

In this work a new calibration setup will be presented for simultaneous observations of continuous temperature field (21 °C to 36 °C) and a broad range of oxygen concentration levels (0% to 31.5%) in atmospheric conditions. A single camera shot can be used to measure the temperature sensitivity of the paint over a wide range of oxygen levels. The calibration data will then be validated against the manufacturer's calibration data, and the differences will be noted. Finally, a detailed uncertainty propagation analysis will be performed to identify the uncertainty of the calibration system to film cooling effectiveness measurements.

PRESSURE SENSITIVE PAINT

The PSP technique is a fluorescent based measurement method. PSP is comprised of photoluminescent molecules and an oxygen permeable polymer binder, both dissolved in a solvent. By utilizing the luminescence behavior of these molecules, PSP can be used to measure the oxygen concentration in the atmosphere surrounding the paint, which can then be linked to the partial pressure of oxygen.

An incident light around 400-nm excites electrons in oxygen sensitive molecules to higher energy levels. When the sensitive molecules return to their original state, they emit light at a lower frequency around 650-nm, referred as pressure intensity signal, Figure 1; the excitation and the pressure signal (fluorescent signal) emit different wavelengths. The intensity of the light increases as the oxygen concentration in the binder around the sensitive molecules decreases.
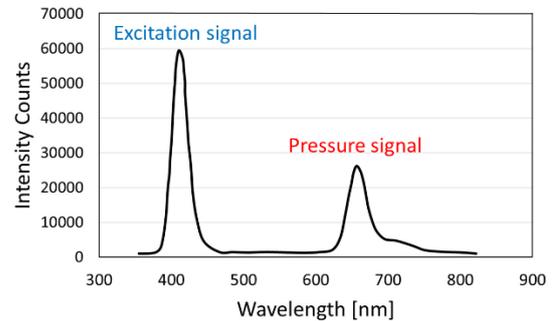

Figure 1. Spectral response of the ISSI UniFiB PSP signal.

This well-known phenomenon is referred to as "oxygen quenching," Liu and Sullivan [7] provided a detailed analysis of this process, including a mathematical formulation based on the Stern-Volmer's relation (Equation 1), which correlates the intensity of the PSP emitted to the oxygen concentration.

$$\frac{I_O}{I} = 1 + K_{sv}[O_2] \tag{1}$$

INSTRUMENTATION

Innovative Scientific Solutions, Inc. (ISSI) provided the PSP used in this study, which was a blend of Fluoro -Isopropyl -Butyl polymer (FIB) and Platinum Tetra Porphin (PtTFPP) [8]. A 400-nm UV lamp was used to excite the luminescent molecules and then emit photons around 650-nm as a relaxation from the excited state to ground state. The emission intensity of the painted surface is recorded through a Nikon D300S camera, with 4288 x 2848-pixel resolution and 16- bit dynamic range. A typical PSP system is show in Figure 2.
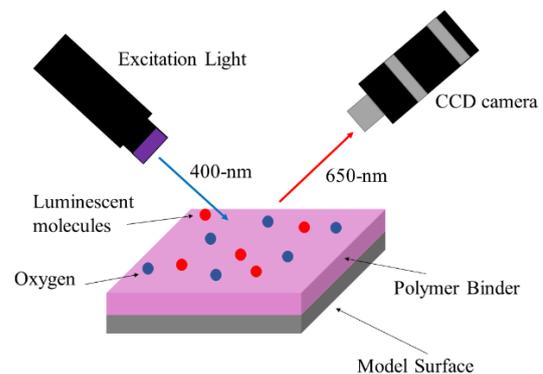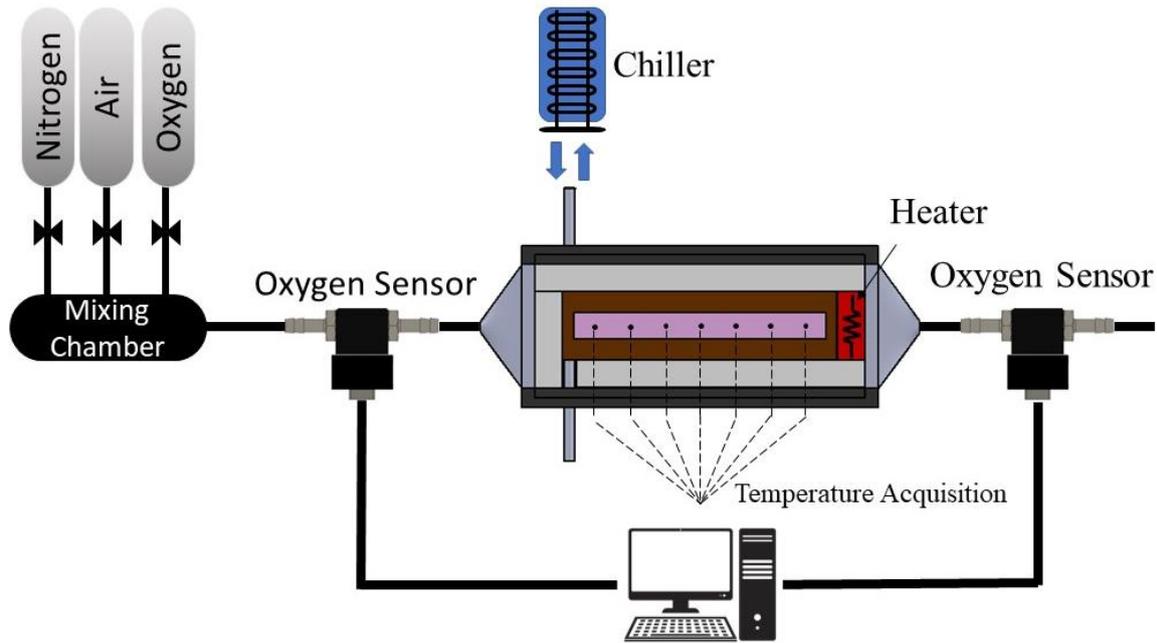

Figure 2. PSP system schematic

Figure 3. PSP calibration system schematic

CALIBRATION SETUP

PSP calibration is critical for obtaining accurate film cooling effectiveness measurements. In the current study, the calibration setup is shown in Figure 3, and it includes: an atmospheric calibration cell with a copper test block inside, two oxygen sensors, a chiller, three gas cylinders (air, nitrogen and oxygen), a mixing chamber, seven thermocouples and a data acquisition computer.

The copper block is inserted into the calibration cell and is insulated with styrofoam from all sides except the top, which is painted with PSP and the heater's side, where the heater is placed. Water from the chiller is circulated through implanted cooling tubes to cool one side of the copper block. The other end was heated by attaching a 100W resistor and controlling its heat release with the current of the electricity passing through. In addition, seven K-type thermocouples were implanted evenly spaced at 25 mm intervals to record the temperature. With this configuration a temperature gradient was achieved upon the block surface. On the top of the calibration cell a sapphire optical window was placed for PSP illumination and image capturing. The air/nitrogen or air/oxygen mixture is introduced into the calibration cell via a nozzle and continues to progress in a 3mm gap between the copper block and the sapphire glass window (Figure 4).

The partial pressure of oxygen in the mixture was controlled by adjusting the mass flow rate of oxygen and air or nitrogen and air through valves while simultaneously measuring the concentration at the calibration setup's inlet and outlet with oxygen sensors. When the two oxygen sensor readings matched, the concentration inside the calibration cell

has reached a steady state and the concentration field above the copper surface was assumed uniform.

In film cooling effectiveness experiments, the effectiveness can reach unity using a foreign gas (with zero O_2 concentration). By passing pure nitrogen through the calibration cell, this calibration setup can achieve zero oxygen concentration. The calibration cell was designed to maintain pressure balance with the surrounding environment. Experiments in atmospheric conditions simplify the setup and make the experimental procedure more convenient.
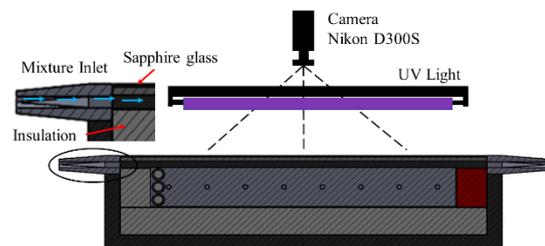

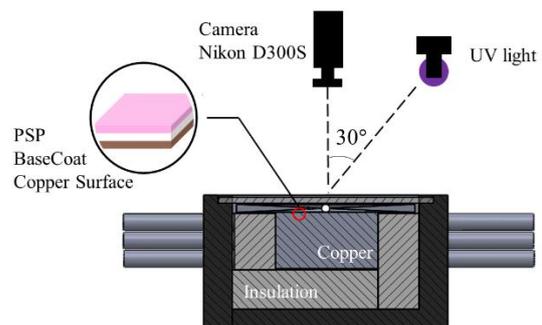**Figure 4. PSP calibration system side view schematic**

Figure 5. PSP calibration system front view schematic

As shown in Figure 5, the camera is positioned perpendicular to the optical access of the calibration cell, and the UV light is positioned in 30 degrees angle from the perpendicular plane. The painting procedure of the copper block began with applying 5 basecoat layers, followed by 12 PSP layers. The basecoat was used to eliminate surface uniformities, provide an opaque background (to aid image acquisition) and improve adhesion to the model surface.

CALIBRATION PROCEDURE

Each PSP data point in the calibration curve necessitates three intensity measurements. The reference image (I_{ref}) at reference partial pressure of oxygen (0.21 atm) and reference temperature. In the current setup, the reference temperature is achieved by turning off the chiller and the heater. As a result, the copper remains at room temperature (24 °C) and there is no temperature gradient. The black image (I_{blk}) was captured under reference conditions with the UV light turned off and no mixture flow passing through. To account for camera noise and ambient disturbances, this image must be subtracted from the acquired images. The test image (I) was acquired with the heater and chiller turned on, resulting in a temperature gradient on the PSP painted surface. In parallel, flow of different oxygen concentrations is introduced into the calibration cell.

The PSP calibration was performed in two steps. For $P_{O_2}/P_{O_2,air} < 1$ and fixed temperature gradient, mixture of nitrogen/air permeates the calibration cell. The concentration of oxygen in the mixture is controlled by valves located upstream of the mixing chamber and measured by oxygen sensors located upstream and downstream of the calibration cell. The temperature gradient remains unchanged when $P_{O_2}/P_{O_2,air} > 1$. The difference in this case, lies in the fact that an enriched oxygen mixture is used, to increase the concentration of oxygen above the atmospheric value.

Table 1. Calibration procedure

Case	Mixture	Temp. Gradient
Black	Air	OFF
Reference	Air	OFF
$P_{O_2}/P_{ref} < 1$	N_2/Air	ON
$P_{O_2}/P_{ref} > 1$	O_2/Air	ON

Instead of matching the pressure of air with the partial pressure of oxygen, we are matching the patrial pressure of oxygen in atmospheric condition by changing the oxygen levels of the mixture. The calibration was performed for seven partial pressure of oxygen readings with $P_{O_2}/P_{O_2,air}$ ranging from 0 to 1.5 and a temperature gradient ranging from 21 to 36℃. The reference image was taken at the end of the calibration process. The dark image was taken at the beginning of the experiment. For each reading,

20 intensity images were captured by the Nikon D300S camera, which were then averaged to give a mean intensity image. The calibration procedure is summarized in Table 1.

The relation between the intensity of the emitted PSP and the partial pressure of oxygen and temperature for the specific calibration setup is described by a function of two variables.

$$\frac{I_{ref} - I_{blk}}{I - I_{blk}} = f\left(\frac{P_{O_2}}{P_{O_2,ref}}, T\right) \qquad (2)$$

where P_{O_2} is the partial pressure of oxygen measured by the oxygen sensors for different mixture concentrations. $P_{O_2,ref}$ is the partial pressure of oxygen in air for atmospheric pressure. It is clear from Equation 2 each pair of pressure -temperature values give a unique intensity value. In film cooling effectiveness measurements using PSP, the key component is the knowing of the partial pressure of oxygen, a more convenient form of Equation 2 is:

$$\frac{P_{O_2}}{P_{O_2,ref}} = f\left(\frac{I_{ref} - I_{blk}}{I - I_{blk}}, T\right) \qquad (3)$$

FILM COOLING EFFECTIVENESS

Assuming the analogy between heat and mass transfer, the PSP film effectiveness can be defined in the same way that heat transfer is defined [9], [10].

$$\eta = \frac{T_g - T_w}{T_g - T_c} \approx \frac{(C_{O_2,g} - C_{O_2,fg})}{(C_{O_2,g} - C_{O_2,c})} \qquad (4)$$

The wall temperature is T_w, the coolant temperature is T_c and T_g is the mainstream gas temperatures. The concentration of oxygen in the mainstream flow is $C_{O_2,g}$, and the concentration of oxygen for the coolant and at the wall using foreign gas is $C_{O_2,c}$ and $C_{O_2,fg}$, respectively. The commonly used gas for PSP film testing is nitrogen, which leads to zero concentration in the coolant flow. The definition of film effectiveness can be further simplified as follows:

$$\eta = 1 - \frac{C_{O_2,fg}}{C_{O_2,g}} \qquad (5)$$

In the special case where the foreign gas's molecular weight is similar to that of air, the mass fraction ratio equals the mole fraction ratio, resulting in the simplified form of film effectiveness as:

$$\eta = 1 - \frac{P_{O_2,fg}}{P_{O_2,g}} \qquad (6)$$

However, if a different fluid is used for coolant, the relations between mass and mole fractions must be taken into account. Han et al. [11] showed the detailed derivation of film cooling effectiveness:

$$\eta = 1 - \cfrac{1}{\left[1 + \left(\cfrac{\frac{P_{O_2,air}}{P_{O_2,ref}}}{\frac{P_{O_2,fg}}{P_{O_2,ref}}} - 1\right)\left(\frac{MW_{fg}}{MW_{air}}\right)\right]} \quad (7)$$

The molecular weights of the foreign gas and the air are MW_{fg} and MW_{air}, respectively.

Four types of images are required for each tested flow condition to evaluate the adiabatic effectiveness distribution using the PSP technique. First, the dark image (I_{bg}) is acquired with the UV lamp off, to compensate for the background noise of the camera. Using nitrogen as a tracer gas for the coolant flow and air for the mainstream, the second image (I_{fg}) was acquired, allowing the desired flow conditions to be set. The third picture is the same as the previous case but using air as coolant flow instead of nitrogen (I_{air}). The last image is the reference image (I_{ref}), which is captured without mainstream and coolant flow in ambient conditions. Table 2 summarizes the test sequence used to obtain these four images, as well as the corresponding mainstream and coolant flow operating conditions.

Table 2. Experimental sequence

Index	Coolant	Mainstream	UV
blk	OFF	OFF	OFF
ref	OFF	OFF	ON
fg	0% O_2	21% O_2	ON
air	21% O_2	21% O_2	ON

From the ratio of the reference image and foreign gas image I_{ref}/I_{fg} and the ratio of reference image and air image I_{ref}/I_{air}, both corrected with the black image, the two dimensional calibration map can be used to estimate pixel by pixel the normalized partial pressure of oxygen in case of a foreign gas injection $P_{O_2,fg}/P_{O_2,ref}$. The ratio $P_{O_2,air}/P_{O_2,ref}$ was calculated using the same procedure, with intensity input for the calibration map the images obtained for the air injection case. Finally, as suggested by Equation 7, both pressure fields are combined to calculate the bidimensional map of adiabatic film cooling effectiveness. A flowchart description of the PSP experimental procedure is depicted in Figure 6.

RESULTS AND DISCUSSION

CALIBRATION RESULTS

The extraction of the calibration map is possible after capturing the necessary images and applying the correct image post-processing based on the described calibration procedure. The calibration map of the ISSI UniFIB PSP is shown in Figure 7. The calibration was carried out for a continuous temperature range of 21℃ to 36℃. The temperature gradient's resolution is determined by the camera's resolution. The pixel size of the camera in this experiment is 30μm x 30μm, which results in knowing the temperature value for 30μm intervals. To simulate this temperature gradient upon the copper plate, the temperature difference between two pixels is 0.07 ℃. The small temperature gradient between the pixels can confirm the assumption that the temperature field is continuous.
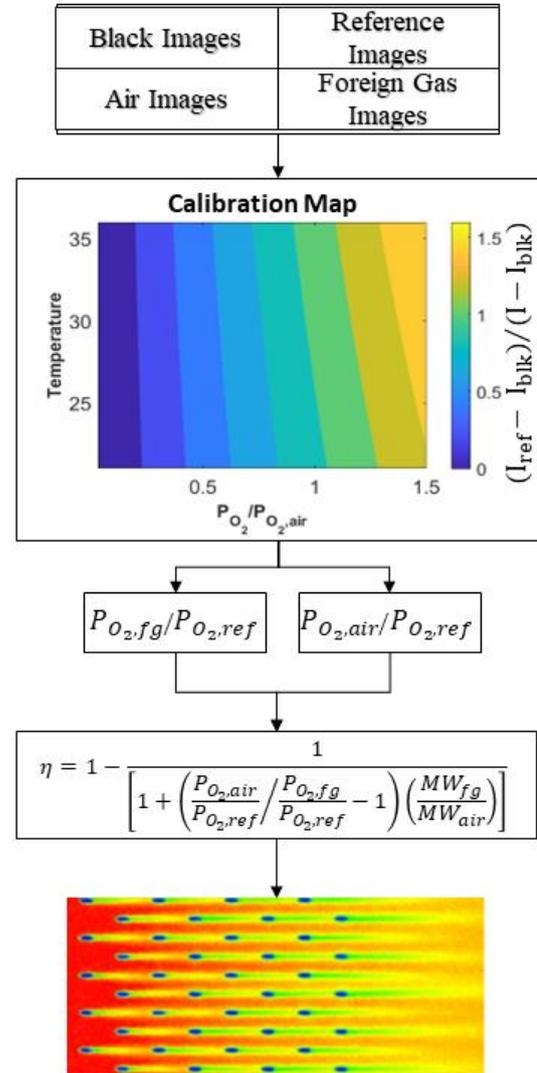

Figure 6. **Flowchart for PSP experimental procedure**

Regarding the partial pressures examined in this study, seven points of partial pressures were investigated, five of which were to simulate sub atmospheric conditions ($P_{O_2}/P_{O_2,ref} < 1$), one case was in atmospheric partial pressure conditions ($P_{O_2,ref}$) and the last one was for a pressurized case ($P_{O_2}/P_{O_2,ref} > 1$).

A contour of PSP emitted intensity values can be calculated, as shown in Figure 7. The x-axis

5

denotes the partial pressure of oxygen, which is normalized with respect to the reference partial pressure under atmospheric conditions. The y-axis represents the continuous temperature range which was achieved. The contour values refer to the intensity ratio $((I_{ref} - I_{blk})/(I - I_{blk}))$. The intensity of the paint (I) decreases as the partial pressure of oxygen increases. The same behavior is seen for the paint's temperature sensitivity; as we move from lower to higher temperatures of the calibration copper block, the intensity emitted decreases. The contour calibration map was created by fitting three-dimensional intensity points to a surface. A second order polynomic fitting curve was used in the x and y direction which are related to the pressure and temperature dependency, respectively. The calibration map is described by a two-variable equation:

$$\frac{I_{ref} - I_{blk}}{I - I_{blk}} = A + B\left(\frac{P_{O_2}}{P_{O_2,ref}}\right) + CT + D\left(\frac{P_{O_2}}{P_{O_2,ref}}\right)^2 + E\left(\frac{P_{O_2}}{P_{O_2,ref}}\right)T + FT^2 \quad (8)$$

where constants A, B, C, D and F are polynomic coefficients that depend on pressure and temperature sensitivity as well as the instrumentation used for the specific experiments.
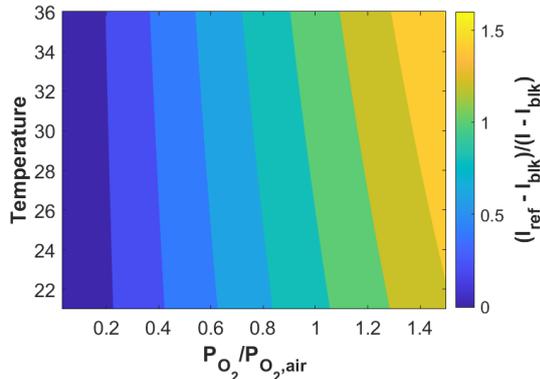

Figure 7. UniFIB two-dimensional calibration map

Figure 8 shows calibration intensity ratios of the UniFIB paint for 5 different temperatures. The calibration curves begin to diverge faster as we progress from sub atmospheric to pressurized conditions, indicating that the paint becomes more sensitive to temperature as we progress from sub atmospheric to pressurized conditions. As the pressure increases, the slope of the curve decreases, indicating that the pressure sensitivity of the paint decreases as the pressure partial of oxygen increases. The pressure and temperature sensitivity of the UniFIB paint for ambient temperature and pressure conditions are 0.044/kPa at 20 °C and 0.01 % /°C at 100kPa, respectively.

The comparison contour plot between the home calibration and the manufacturer's calibration is shown in Figure 9. The same polynomic fitting procedure was used for the manufacturer's data, ensuring that the comparison is valid. According to the contour plot, the highest deviations from the manufacturer's data are spotted to the edge pressure regions, where the partial pressure of oxygen ratio is close to 0 and 1.5. The point of zero deviation shifts to lower pressures as temperature rises.
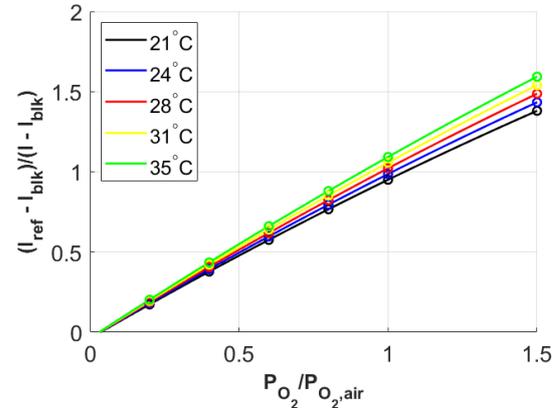

Figure 8. UniFIB one-dimensional calibration map for five different temperatures.

The locus of zero deviation points can be plotted based on this behavior. A red dashed line represents this locus in Figure 9. The divergence from the manufacturer's specifications increases with a positive sign as we move diagonally rightwards from the zero-deviation curve. On the contrary, the intensity ratio difference increases with a negative sign as one moves diagonally leftward from the curve.
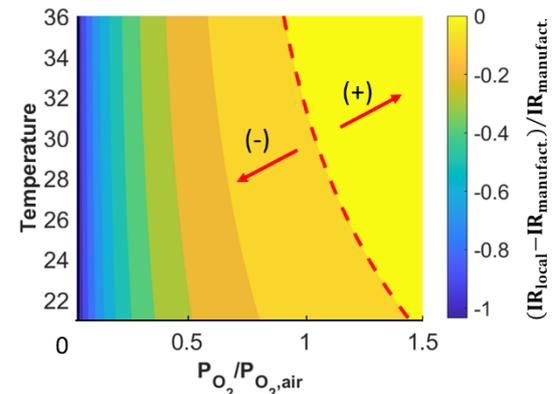

Figure 9. Comparison of the calibration map with the manufacturer's specifications.

UNCERTAINTY ANALYSIS

At this point, we would like to understand the sensitivity of certain inputs and their impact on the parameters of interest, film cooling effectiveness η. The primary uncertainty parameters in the calibration setup are the partial pressure of oxygen measured using oxygen sensors and the temperature measured using thermocouples. The expression for the individual sensitivity coefficients of

effectiveness with respect to the measured parameters can be introduced via the chain rule:

$$\delta\eta = \frac{\partial \eta}{\partial P_{O_2}} \frac{\partial P_{O_2}}{\partial IR} \delta IR \tag{9}$$

The uncertainty in emitted intensity ratio can be expressed as a root mean square (RMS) of random standard uncertainties in pressure and temperature measurements.

$$\delta I = \sqrt{\left(\frac{\partial IR}{\partial P_{O_2}} \delta P_{O_2}\right)^2 + \left(\frac{\partial IR}{\partial T} \delta T\right)^2} \tag{10}$$

The extracted polyonymic calibration curve (Equation 8) and Equation 6 are used to calculate all the differentiations in Equations 9-10. Figure 10 shows the effectiveness uncertainty map for a temperature and partial pressure of oxygen uncertainty range. The green and red curves present the areas where the effectiveness uncertainty does not exceed 5% and 10%, respectively. The thermocouple uncertainty is estimated to be $\pm 0.5\,°C$. According to the manufacturer of the oxygen pressure sensors the measurement accuracy for the pressure range which were used in this study is 500 Pa [12]. Based on the contour map (Figure 9), the calculated uncertainty in effectiveness ($\delta\eta_m$) is 0.6%.

Another source of uncertainty is the fitting procedure that was used. The results show that the greatest intensity ratio divergence is 0.05 and occurs when the pressure ratio is 0.8. The mean fitting deviation for the entire pressure ratio range equals 0.019.
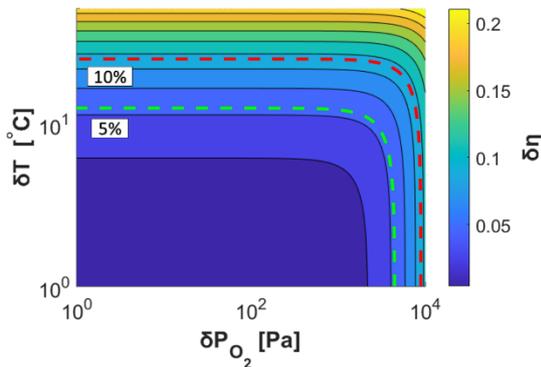

Figure 10. **Effectiveness uncertainty map.**

According to Equation 9, we can calculate the propagation of the fitting error. The uncertainty due to the fitting of the surface ($\delta\eta_{sf}$) for the maximum fitting divergence is 0.058.

$$\delta\eta_{ov} = \sqrt{(\delta\eta_m)^2 + \left(\delta\eta_{sf}\right)^2 + (\delta\eta_i)^2} \tag{11}$$

Finally, measurement uncertainty is caused by image intensity acquisition. The highest value is 0.0099 spotted for pressure ratio 1.5. The oxygen concentration inside the calibration cell is at its highest at this pressure ratio, resulting in a low-pressure signal (as the concentration of oxygen increases, the intensity emitted decreases). The mean intensity ratio uncertainty for the whole temperature and concentration domain is 0.008. The maximum uncertainty caused by the intensity ratio uncertainty ($\delta\eta_i$) is 0.0115.

The overall uncertainty in film cooling effectiveness can be calculated using the square error formula (Equations 11), which accounts for measurement instrument, surface fitting, and acquired image intensities uncertainties. The overall effectiveness uncertainty is 5.9%.

CONCLUSIONS

The current study presents a novel calibration setup for simultaneous observations of continuous temperature field and a broad range of oxygen concentration levels towards film cooling effectiveness measurements. The variation of the PSP calibration system lies in the creation of a continuous temperature gradient field. In this manner, the time of the experiments is rapidly reduced, with a single image the effect of a temperature on the emitted radiation can be extracted.

The comparison between this study's calibration curves and manufacturer's curves revealed that the greatest deviation occurs at the extremes of the partial oxygen pressure range. The levels of deviation are acceptable (intensity ratio deviation 0.15).

The detailed uncertainty analysis revealed that the main sources of uncertainty are related to the oxygen partial pressure and temperature measuring instruments, data surface fitting, and intensities captured by the camera. These uncertainties propagate to the film cooling effectiveness measurement. Typical levels of effectiveness uncertainty are less than 6%.

ACKNOWLEDGMENTS

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