Optical Altitude Sensor Based on Pressure Sensitive Paints (PSP)

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ABSTRACT
The altitude is one of the most important measurements in aviation. Since atmospheric pressure decreases with increasing altitude, static pressure readings can be indicative of altitude. The purpose of this paper is to present a novel fibre optic based system that incorporates PSP at the tips to first determine pressure and temperature, and later used to determine altitude. The use of PSP to measure pressure is well established and has been employed in a wide range of applications. PSP relies on the quenching behaviour by oxygen, which can be related to pressure. Temperature can also be simultaneously determined. In the presented system, the fibre is used to deliver illumination light to the PSP and also collect any subsequent emissions via total internal reflection. The porous reflective layer ensures that PSP luminophores are effectively illuminated with their subsequent emissions returned back into the fibre. The system was demonstrated in the Manchester environmental chamber.

NOMENCLATURE

a	lapse rate, the rate of temperature change in different atmospheric regions
A,B	coefficients used in PSP analysis
g	acceleration due to gravity
h	altitude
h_1	base altitude of specific atmospheric region
I	measured intensity of PSP
I_{ref}	measured reference intensity of PSP
p	pressure
p_1	starting pressure of atmospheric region
p_s	static pressure
p_{ref}	measured pressure reference
R	ideal gas constant
T	temperature
T_1	starting temperature of atmospheric region
τ	decay lifetime

1. INTRODUCTION

The Pitot tube, invented by Henri Pitot in the early 1700s, was modified to its modern form in the 1800s by Henry Darcy. Pitot-static tubes consist of cylindrical hollow tubes that point into and perpendicular to the airflow. The function of these tubes in aircrafts is to determine the aircraft altitude and airspeed relative to the surrounding air. The purpose of this paper is to demonstrate a novel system, comprising of fibre optic bundles, oriented perpendicular to the flow, with tips that are carefully coated with PSPs to determine altitude.

The PSP system relies on luminescence quenching behaviour in the presence of oxygen. The next few sections briefly summarise basic PSP principles and the relations and assumptions that are needed to reveal altitude. The design of the proposed fibre optic system is presented and discussed. Other relevant issues including areas for further research is also discussed.

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2. PRINCIPLES OF PSP

The use of pressure sensitive paints (PSP) to measure pressure is well established and has seen a wide range of applications the aerospace arena. Examples include measurement of pressure distribution of surfaces in turbo machinery[1], wind tunnels for both high and low speed airflows [2, 3] and cryogenic testing. A new application area to measure altitude using PSP is presented in this paper. This paper does not aim to discuss the principles of luminescence and PSP in great detail since they are well known, and a number of good reviews have been published that can used as reference[4-9].

As a generic summary, PSPs contain luminophores that cause electrons to be promoted to higher energy levels when they are illuminated with UV light. These do not stay permanently excited and return back to their original state by either a radiative (luminescence) or non-radiative process. Non-radiative processes include internal heat and vibrational losses, or by oxygen quenching, where the energy is transferred to nearby oxygen molecules. Figure 1 illustrates these various energy transitions. Complying with the conservation of energy, these processes compete and are mutually exclusive; therefore increased oxygen levels will increase the probability of transferring energy to oxygen molecules, quenching radiative luminescence. Since pressure can be related to oxygen, the oxygen quenching behaviour of PSPs can be used to determine pressure.

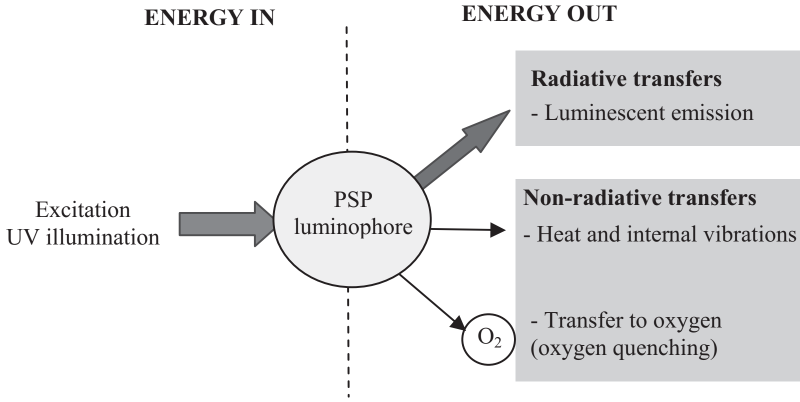

Figure 1. Overview of PSP energy transitions

There are two effective methods in which this can be achieved – radiometric intensity method, and the temporal lifetime decay method. The intensity based method relies on a continuous light source, and luminescent intensity is expected to decrease with increases in pressure. The relative change in intensity can be related to a relative change in pressure and the Stern-Volmer equation is often used to mathematically relate these terms, and is commonly expressed in the following form shown in equation 1. Calibration is required to determine coefficient values. Second and third order polynomial relations are occasionally used to offer a higher degree of calibration.

$$\frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \tag{1}$$

The temporal based method relies on measuring the PSPs decay response following a pulsed source excitation. The lifetime of luminescent decay is expected to be faster due to increases in pressure. Figure 2 exemplifies typical PSP responses, showing the effects of increasing pressure from both radiometric and temporal methods. Detailed analysis for both the intensity and the lifetime decay methods can be found in Lui and Sullian [7], and Bell et al.,[4]

Temperature Sensitivity: A major problem with PSPs is that they are also sensitive to temperature. In the intensity mode, there exists separate Stern-Volmer plot for each temperature, as illustrated in Figure 3. Consequently, the same intensity reading can represent a number of pressure readings, and therefore knowledge of the temperature becomes critical in deciding which calibration line to use to determine pressure. Since temperature is a function of a PSP's response, recent literature suggest that it can also be simultaneously determined using PSPs [10- 13].

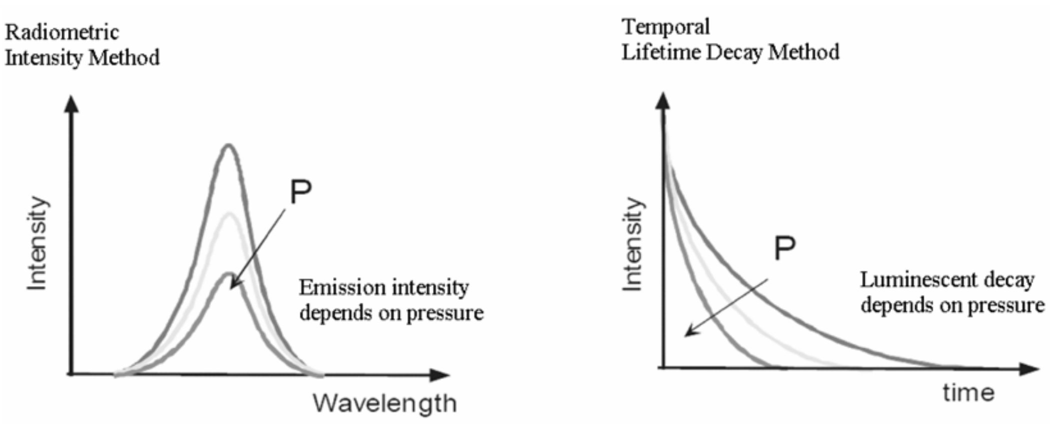

Figure 2. The effect of increasing pressure on PSPs.

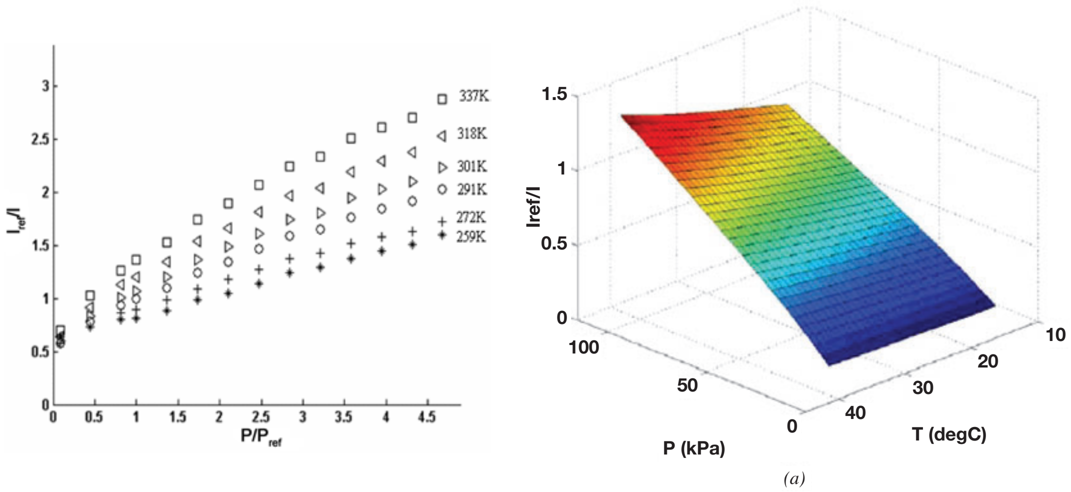

Figure 3. Left: Stern-Volmer calibration plot for each temperature. Right: 3D plot, showing the full intensity characteristics due to changes in pressure and temperature. Taken from Nakakita et al.,[14]

An optical way of correcting for temperature is by combining temperature sensitive paints (TSP) or thermographic phosphors to the original PSPs to form binary paints. They must be insensitive to pressure changes and have different emission wavelengths so that their emissions can easily be differentiated. The determined temperature will dictate which calibration equations to use. In some cases, these dual luminophore characteristics are found in single PSP luminophores. Binary/multi-luminophore paints can also be calibrated to eliminate the need for initial intensity and pressure references (I_{ref}, p_{ref}) [15]. Figure 4 illustrates the emission spectra for binary paints. Since pressure affects only one luminophore, whilst temperature affects both, the pressure insensitive luminophore can act as an internal reference proving additional corrections for illumination levels, coating thickness and luminophore concentration. The model is sometimes referred to as the ‘intensity ratio’ method. Bell et al.,[4] reports this method being the most successful in providing compensations for errors common in the standard intensity approach. The disadvantage of such approach is that two separate detections are required, usually requiring beam splitters and two detectors.

In the temporal mode, the decay lifetime can be related to the pressure using

$$I = I_{t=0} e^{\frac{t}{\tau}} \tag{2}$$

The lifetime of luminescent decay, τ, is expected to lower (faster decay) at higher pressures. The method is immune from many errors that affect the intensity method including errors from non uniform illumination, coating thickness and dye concentration. Some PSPs exhibit multi-exponential decays with exponential components that are affected independently by temperature and pressure. Characterising these can enable the simultaneous determination of temperature and pressure [10-13]. The relationship is often expressed in polynomial form with calibration that reveals coefficient values.

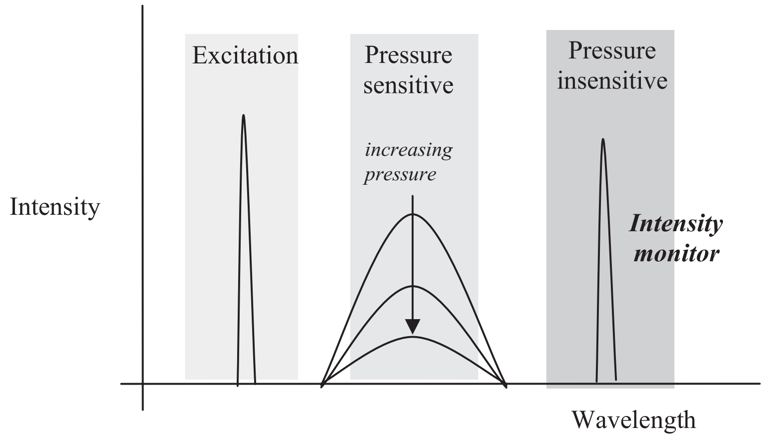

Figure 4. Exemplified emission spectra of binary paint, consisting of a pressure sensitive element and a pressure insensitive intensity monitor.

3. CONVERSION TO ALTITUDE

The previous section showed that pressure sensitive paints can be used to determine both the temperature and pressure. This section will present the relations and assumptions that are needed to determine altitude.

The altitude is one of the most important measurements in aviation. Since atmospheric pressure decreases with increasing altitude, static pressure readings can be indicative of altitude. The use of air pressure is the most widely used method by almost every aircraft to determine altitude. The composition of air at sea level according to the U.S Standard Atmosphere is shown in Figure 5. Over 99% of the air is comprised of nitrogen (78.08%) and oxygen (20.95%), leaving less than 1% for other gases. Assuming the volumetric percentage of oxygen remains constant at 21%, PSP can be calibrated to reveal altitude. According to the US standard atmosphere, the number density (m^{-3}) of both nitrogen and oxygen varies proportionally, up to a height of 85km [16]. With the effects of the other gases remaining at around 1%, there is little change in the volumetric oxygen percentage, which remains to be approx 21% up to a height of 85km. This would be higher than most aircraft envelope ceilings.

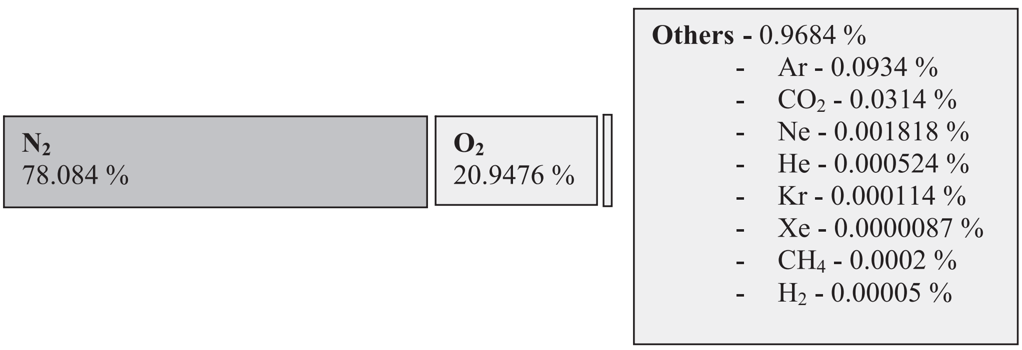

Figure 5. Composition of air at sea level according to the US Standard Atmosphere. Data extracted from Lide [16]

The relationship between air pressure with respect to height is not linear, but logarithmic and there are many layers in the atmosphere where this relationship behaves differently depending on whether it is an isothermal or non-isothermal region. Unlike temperature, pressure does not remain constant in isothermal regions, but varies at different rates. Figure 6 graphically illustrates the pressure and temperature profiles based on the International Civil Aviation Organization (ICAO) Standard Atmosphere. Table 1 indicates this in a table format.

Although the working temperature range of most PSPs is between 10 – 50 ˚C, whilst the atmospheric temperature at altitudes where aircrafts can fly can be much less –57 ˚C (216K), there have been a number of PSPs that have been reported to be successfully calibrated and tested at cryogenic conditions with temperatures reaching 100K (-173’C) [17-19].

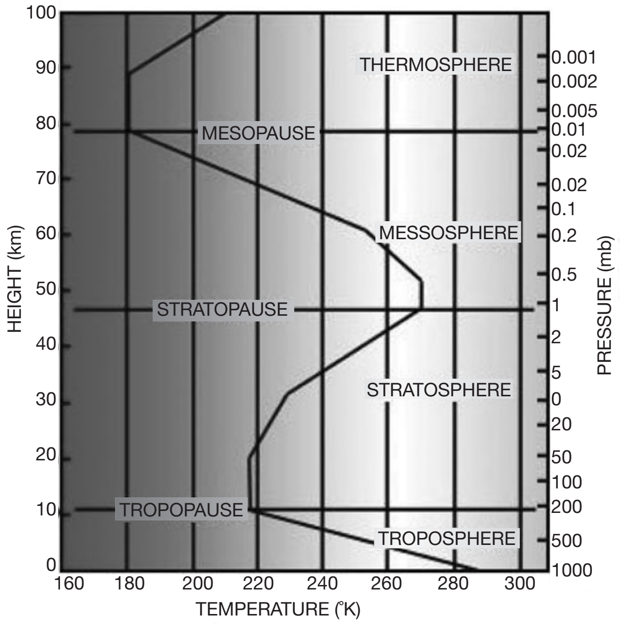

Figure 6. Vertical temperature profile of the ICAO Standard Atmosphere. Taken from the UK Met Office[20]

Table 1. Table to show various pressure and temperature values at different regions in the atmosphere.

Region	Altitude (km) h_1	Temp (K) T_1	Pressure (Pa) p_1	Lapse Rate (K/km) a
Troposphere	0	288.16	101325	–6.5
Tropopause	11	216.66	22630.5	0.0
Stratosphere	20.1	216.66	5474.27	+1.0
Stratosphere	32.2	228.66	867.749	+2.8
Sratopause	47.3	270.66	110.874	0.0
Mesosphere	52.4	270.66	58.9822	–2.0
Mesosphere	61.6	252.66	18.2033	–4.0
Mesopause	80.0	180.66	1.03719	0.0

The altitude and temperature is related according to the following relation. T_1, h_1 and p_1 are the temperature, altitude and pressure values at the start of each atmosphere layer.

$$T = T_1 + a(h - h_1) \tag{3}$$

The pressure can be can be related to the altitude by the following equations. Detailed derivation can be found in Anderson[21]

non-isothermal regions:

$$p = p_1 \left(\frac{T}{T_1} \right)^{\frac{g}{aR}} \tag{4}$$

isothermal regions:

$$p = p_1 e^{-\left(\frac{g}{RT}\right)(h-h_1)} \tag{5}$$

By rearranging equations (3-5), the following relations can be derived for determining altitude. The equations are a fuction of static pressure (p) and temperature (T), which can both be determined using PSP.

non-isothermal regions:

$$h = h_1 + \frac{T_1\left(\left(\frac{p}{p_1}\right)^{-\frac{aR}{g}} - 1\right)}{a} \tag{6}$$

isothermal regions:

$$h = h_1 - \ln\left(\frac{p}{p_1}\right)^{\left(\frac{RT}{g}\right)} \tag{7}$$

4. METHODOLOGY, DISCUSSIONS AND SYSTEM DEMONSTRATION

The previous sections have shown the theoretical procedure and parameters required for determining altitude. This section focuses on the practical side and discusses how these pressure and temperature measurements are made, including overall schematic and probe tip design.

Fibre optic probes, with tips coated with PSP would protrude perpendicular to the flow, in a similar setup to Pitot tubes in order for static pressure measurements to be made. Quartz multimode fibre, due to its high UV transmission characteristics is used to deliver excitation light and return emission light. UV light enters the fibre and travels through the fibre-core via total internal reflection to illuminate the PSP. To maximise coupling efficiency, a laser beam is focused onto the fibre using a coupling lens with the appropriate focal length to match the numerical aperture of the fibre. The subsequent emissions travel down and out of the same fibre. The same coupling lens is used to collimate the emission signal that later passes through to the dichoric mirror to ensure emissions are separated from reflected laser light. The optical output signal passes through a wavelength specified optical filter, and finally to the detector where it is converted to an electrical signal. However, as the intensity ratio mode, that requires two detectors, is utilised, the signal is first split before passing through independent filters and detectors.

Since no spatial resolution is required, point measurements with high accuracy is more beneficial. A PMT is a good choice detector for both intensity and temporal approaches, since it has excellent low light detection capability with superior SNR, and good temporal resolution, with rise and fall times in the nanosecond regime. The electrical signal is digitised by the data acquisition system and stored for analysis. The analysis determines intensity ratios, which are coupled with calibration data to reveal pressure and temperature. These feed into atmospheric relations to reveal altitude. This process is neatly summarised in the schematic shown in Figure 7. The same setup could also be used to determine multi-exponential lifetimes of a single PSP, or two separate decay lifetimes of multi-luminphore PSPs.

In conventional PSP experiments, the light source illuminates the front surface of the subject, with the detector usually situated normal to this surface. With the current fibre optic setup, the detection is made on the back surface. It is therefore crucial for the PSP layer to be porous and thin since it is not directly exposed to the airflow. The PSP layer is made from a porous transparent pedant material (polymer co-polymerized with pyridine derivative) that allows oxygen diffusion to the luminophores. Ruthenium bathophenanthroline perchlorate was chosen as the pressure sensitive luminophore as it has been repeatedly demonstrated to exhibit significant oxygen sensitivity in its luminescence at low temperatures in polymer based binders [17]. Its typical excitation wavelength is 470nm, emitting useful radiation peaks between 600nm and 700nm. Further details on its calibration data are provided in Reference 2. La_2O_2S:Eu was chosen as the pressure insensitive luminophore to provide the temperature correction and dictate which calibration equations to use. Its typical excitation wavelength is 470nm, emitting useful radiation peaks at 512nm and 537nm. It exhibits temperature sensitivity from -200˚C to 100˚C. Reference 5 provides further details on its calibration characteristics. This luminophore is encapsulated by a nonporous polymer material. Both luminophores are pending to the pyridine derivative. Although typical excitation wavelenghts for both luminophores is 470mm, it was found that a high powered third harmonic Nd:YAG laser (355 mm) could sufficiently provide the required excitation radiation.

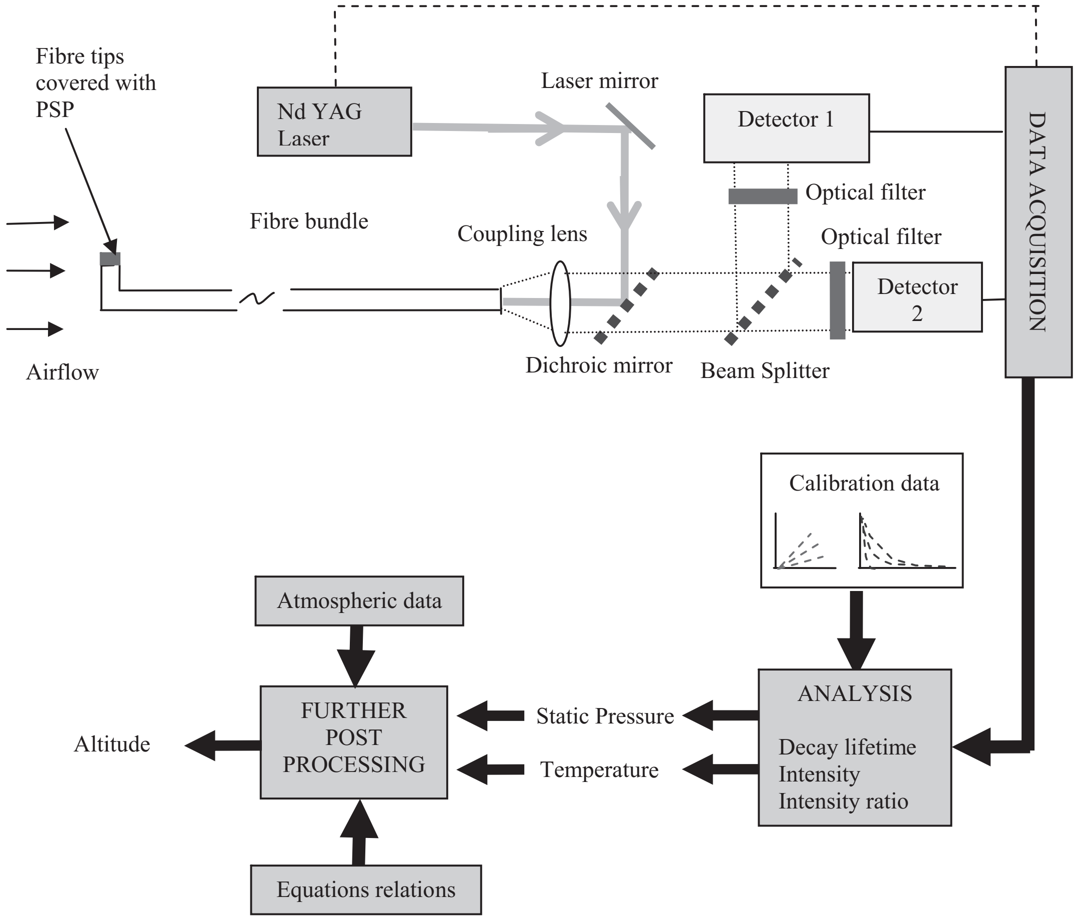

Figure 7. Schematic and flow diagram of PSP system to measure altitude and airspeed

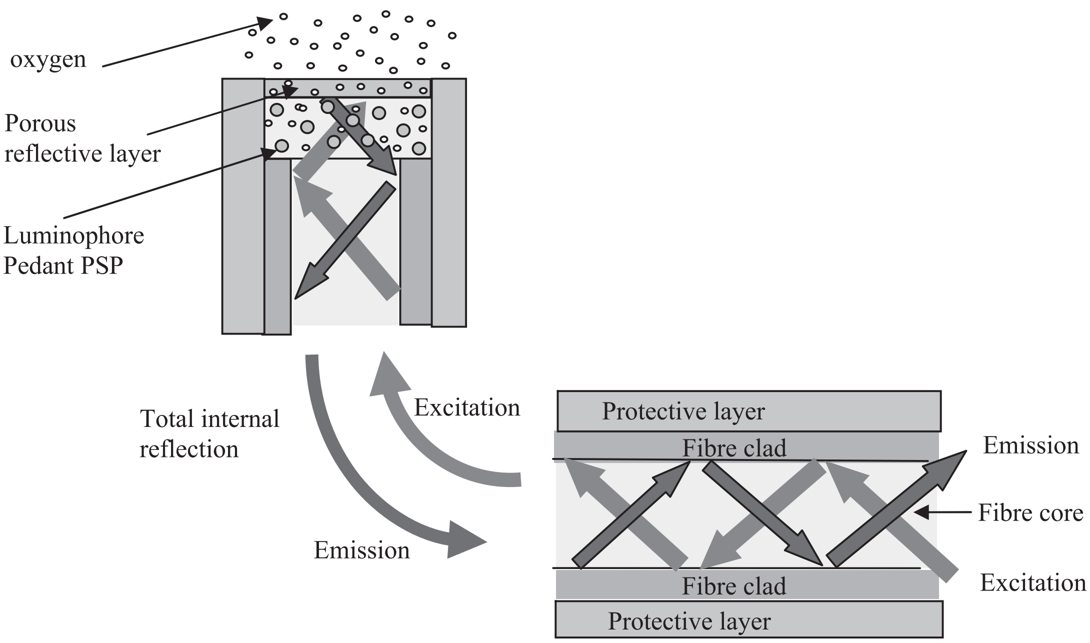

Figure 8. Fibre tip design, illustrating total internal reflection inside the fibre and the purpose of the porous reflective layer.

The porous reflective layer at the end of the tip does not only provide protection to the PSP paint from high speed flows, it helps to reflect illumination light to luminophores and emissions back into the fibre optic. This layer ensures luminophores have a greater chance of being illuminated and their emissions returned. Figure 8 illustrates the PSP fibre optic tip being illuminated, and luminescence being returned. The outer protective layer blocks any oxygen diffusion from the sides that may contribute to dynamic pressure, and also ensures that the fibre optic tip remains damage free. There are a number of sources of errors associated with the present set-up, which require further investigation. These include: a) luminophores nearer the fibre optic may not be able quench oxygen effectively; and b) luminophores that have the ability to quench, especially the ones that are further away from the fibre and nearer to the airflow, may not receive sufficient illumination; and also may not be able to send their emissions back through the fibre. Other sources of errors are discussed in the next section.

Initial tests of the fibre optic based system were conducted in the environmental chamber of the National Grid High Voltage Research Centre at the University of Manchester. The chamber allows the variation of air density, pressure (*0* to *4.5 bar*), and temperature (*190K to 343K*). The temperature and pressure are monitored by thermocouples and Kulite pressure transducers. A combination of filters matching the emission spectra of the luminophores was used to capture the emitted light. The present tests were conducted at pressures from 0.5 to 4.5 bar and temperatures from 255 to 340K. It is

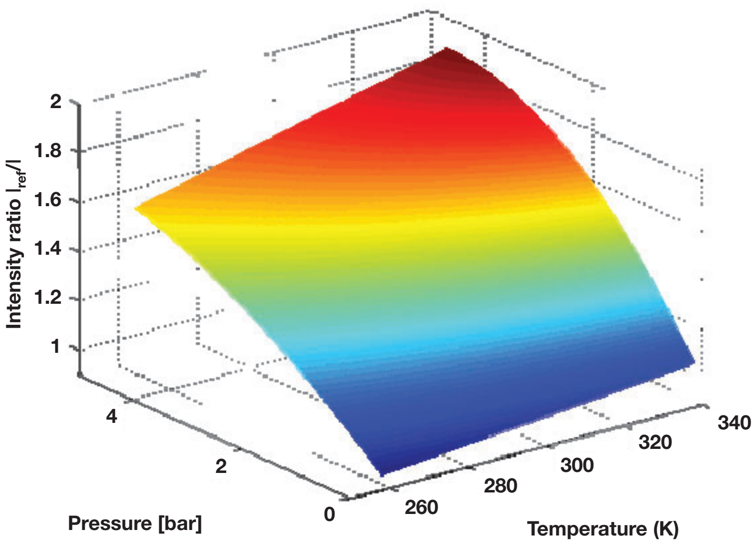

Figure 9. PSP sensitivity to pressure and temperature plot.

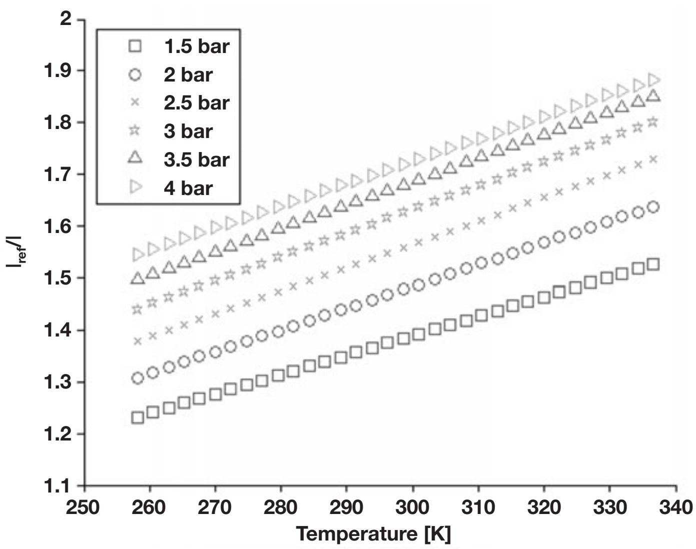

Figure 10. Temperature sensitivity of PSP at various pressures.

envisaged that tests will be conducted at lower pressures corresponding to values at higher altitudes. From the plot of I_{ref}/I vs. P/P_{ref}, where I_{ref} and P_{ref} correspond to the ambient conditions, the pressure sensitivity of the paint defined as $PS = \Delta(I_{ref}/I)/\Delta(P/P_{ref})$ was determined. This plot is presented in Figure 9. By taking the ratio of I_{ref} to I, the effect of paint thickness and luminophore concentration could be eliminated. The temperature sensitivity of the PSP for different pressures tested is presented in Figure 10. The maximum temperature sensitivity of the paint $((\Delta I_{ref}/I)/\Delta T)$ was estimated as 0.46%/°K.

Although the apparatus used and shown in Figure 7 seems bulky and expensive, lasers and PMTs can eventually be replaced by inexpensive LEDs and Si-photodiodes, enabling the system to run at fractions of the cost and weight, which is another very important factor in aviation.

5. FUTURE WORK

Pitot tubes are proven to be accurate and used by nearly all aircrafts both civil and military. With the work is in its infancy, further research is yet required for it to successfully compete with existing technologies. There are however a few advantages that may make this technique worthwhile. The temperature and pressure of the air can be both determined simultaneously eliminating the need for additional temperature transducers. The PSP technique may allow further corrections to compensate for water vapour and humidity, however further research would be required to validate this. It is likely that the airflow effects over the probe would be similar to effects caused by existing pitot tubes since they share a similar geometry. The actual probe can be made to be smaller than pitot tubes, offering small reductions in drag. Although this may be negligible, the accumulated effect over an aircrafts lifetime in terms of flying hours for an entire fleet of aircrafts may be significant.

Pitot tubes commonly have heating elements to prevent them from becoming clogged with ice and having catastrophic consequences. A layer of ice on the PSP fiber probe-tip will experience differences in oxygen diffusion rates affecting luminophore quenching and overall pressure readings, which may result in similar disastrous consequences. However, this may be avoided; the system may utilise optical energy, possibly a high energy laser beam coupled into the fibre, to heat and increase the temperature at the tip without additional heaters. However, incorporating this additional feature will add further complexity to the system, and its consequential effects on PSP calibration will have to be further researched and evaluated before being implemented. Other effects that could have equally catastrophic outcomes are the effects of heavy rain and condensation on the probe tip.

Whilst some of the issues have been briefly addressed, there are other issues that go beyond the scope of this paper. There were assumptions made in the analysis that enables PSP to determine altitude. The full understanding of these assumptions, including limiting factors and consequences need to be further addressed. For example, it is assumed that the oxygen diffusivity rates remains constant at all speeds. There is a possibility that increased dynamic pressure may influence the reading of the free-steam static pressure. There may be a variation in oxygen diffusivity due to changes in dynamic pressure, even when the flow is perpendicular to its surface, or due to local pressure variations caused by the airflow. The effect will skew pressure readings, giving a false indication of the altitude. Increased diffusivity will increase PSP quenching, making the calibration indicative of a higher pressure, and consequently a lower altitude reading.

Other areas that will need to be further researched and carefully considered include the optimization of the probe design, testing the effects of different PSPs at a wider range of pressures, temperatures, and oxygen concentrations. The exact choice of PSP, binder, light source and detection methodology, in terms of SNR and sensitivity, needs be considered in order for the desired altitude to be completely covered. The uncertainty and accuracy will also need to be carefully assessed taking into account the effects of any assumptions.

6. CONCLUSIONS

The altitude is one of the most important measurements in aviation. Since atmospheric pressure decreases with increasing altitude, static pressure readings can be indicative of altitude. The use of PSP to measure pressure is well established and has been used in a wide range of applications. This paper discussed a new application area to measure altitude using PSP. PSP contains luminophores that luminesce when they are illuminated by UV light. PSP relies on quenching behaviour by oxygen, and can be used to determine pressure and temperature. Equations that related these to the altitude were presented and discussed, noting any assumptions that were made. The design of the presented system incorporated a PSP coated fibre optic. Total internal reflection delivered the laser to the PSP, and a porous reflective layer ensured that luminophores were effectively illuminated with their subsequent emissions returned back into the fibre. Initial experimental results were presented using the Manchester environmental chamber, which demonstrated the system operation. The advantages that were identified using the presented system include: pressure and temperature measurements can be made simultaneously; a smaller design may be possible offering reductions in drag; and optical heating via the laser can prevent ice formation. With the work in early development, sources of errors and areas for further research were also discussed.

7. ACKNOWLEDGEMENTS

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