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(54) PRESSURE SENSITIVE PAINT

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(57) **ABSTRACT**

A method of calibrating pressure sensitive paint is provided comprising the steps of: illuminating the paint under a range of pressures and temperatures; measuring the intensity of light emitted by the paint following each illumination thereby measuring decay curves; and performing a curve fit of the decay curves to determine characteristic constants. These constants can then be used to generate a model of decay curves and a polynomial relating pressures and temperatures for ratios of intensities over gated areas of the model decay curves can be calculated. Pressure determination at the calibrated paint can then be performed by illuminating the paint, measuring the intensity of light emitted by the paint over two of the gated areas, determining the ratio of the gated area intensities and finally determining the pressure and/or temperature from the polynomial using the determined ratio of the gated area intensities.

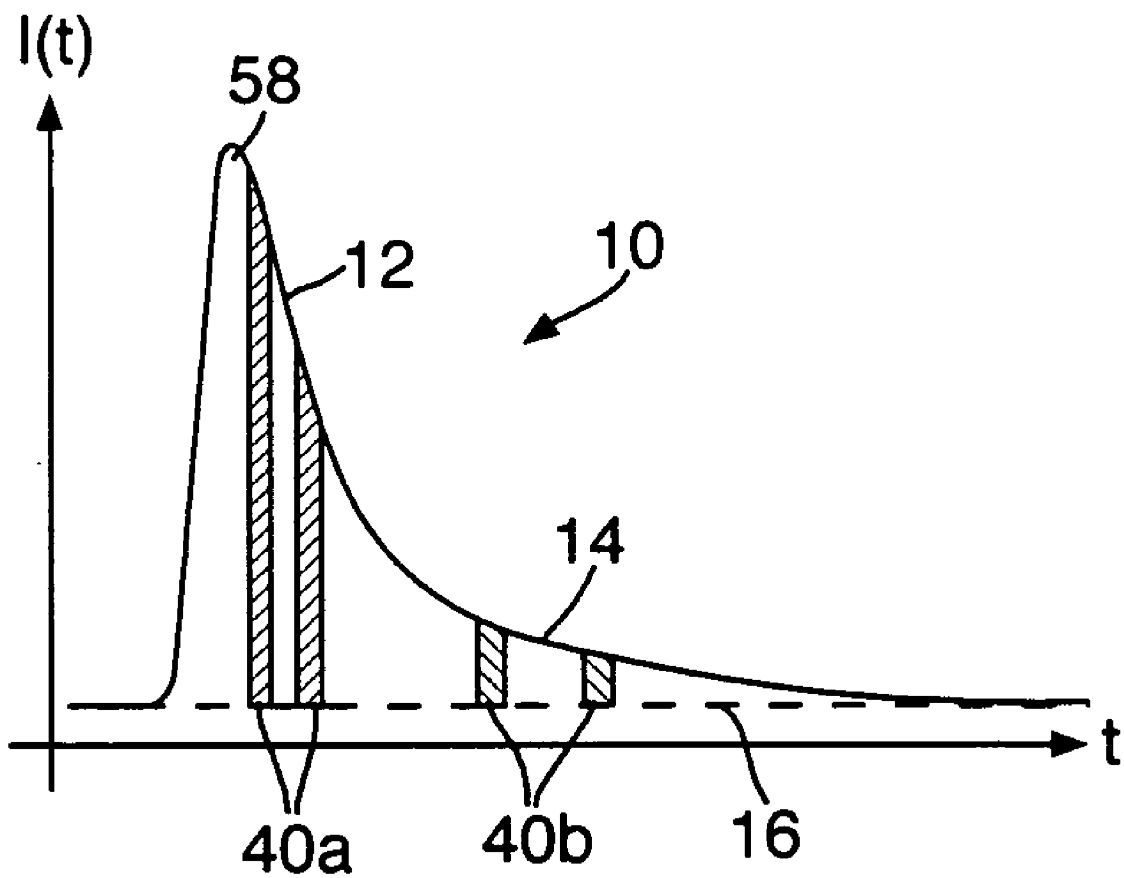


Fig.1.

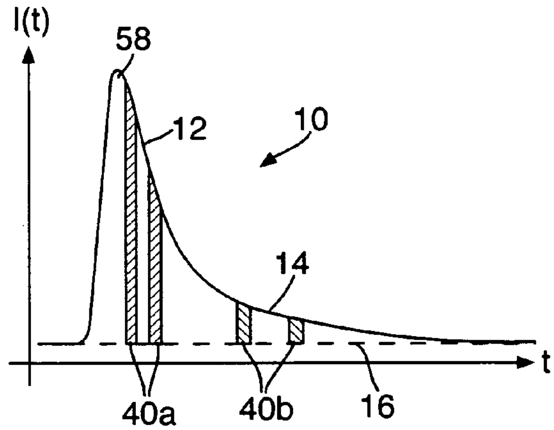


Fig.2.

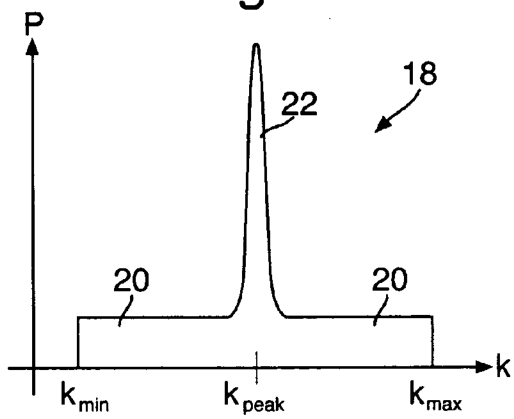


Fig.3.

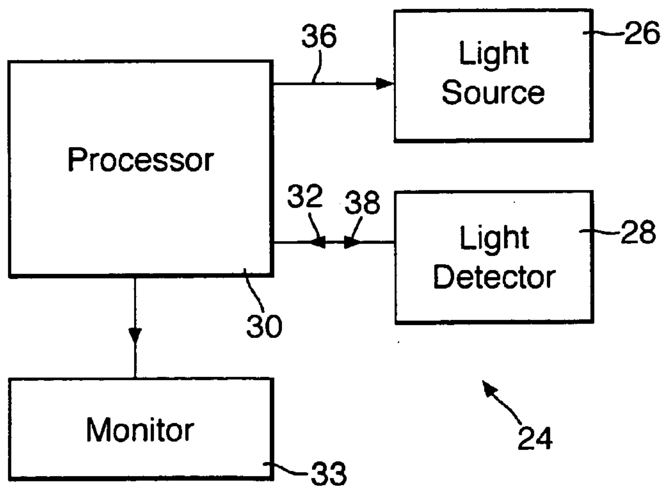


Fig.4(a).

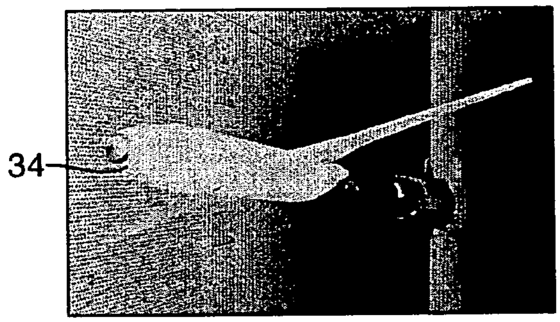


Fig.4(b).

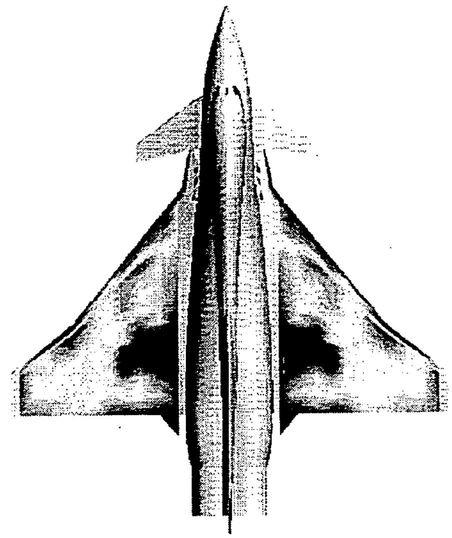


Fig.5.

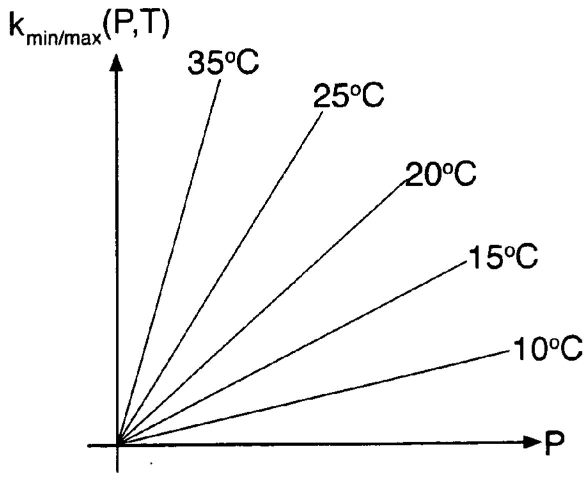
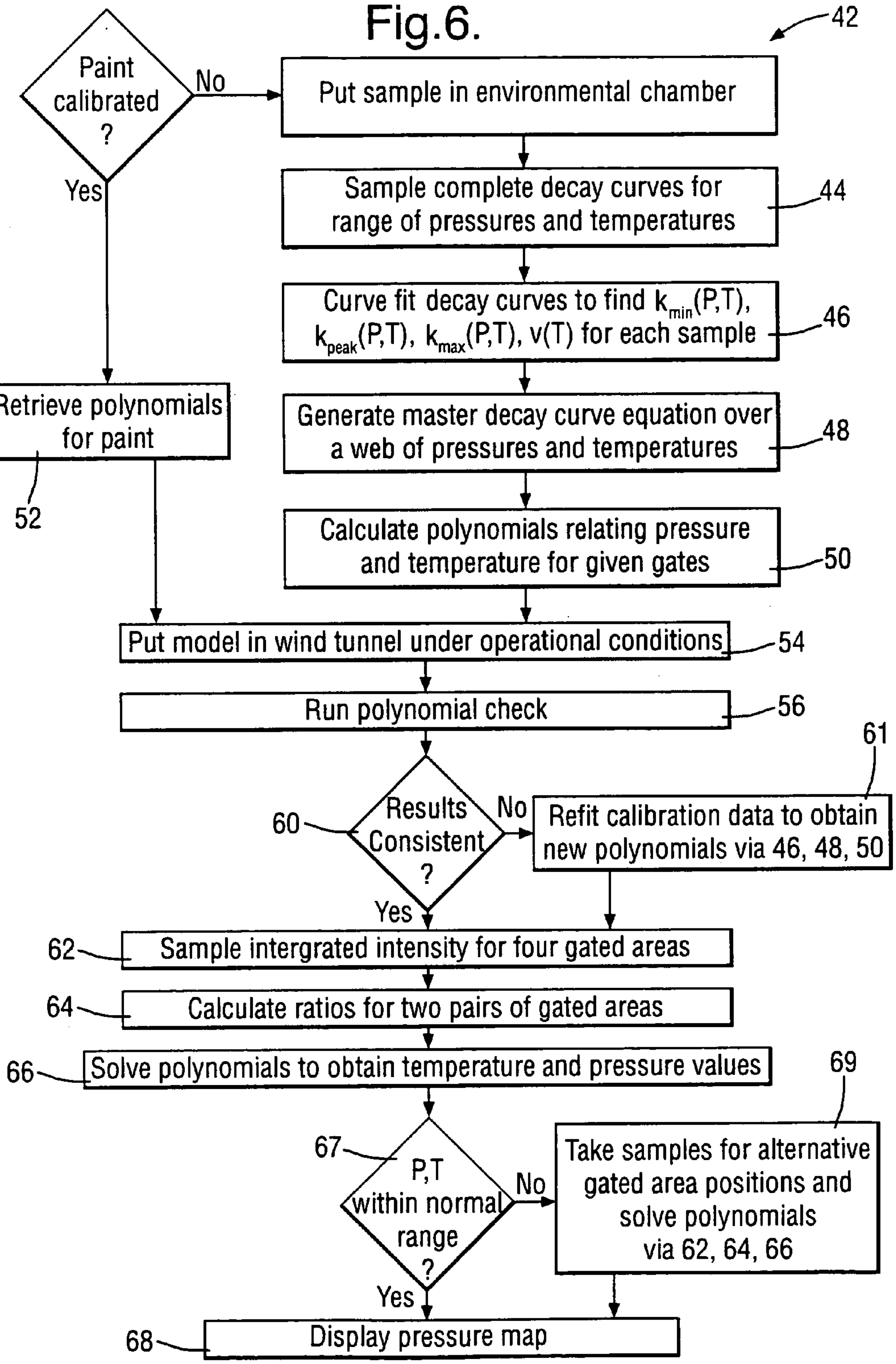


Fig.6.


42
Paint calibrated ?
No
Yes
Put sample in environmental chamber
Sample complete decay curves for range of pressures and temperatures
44
Curve fit decay curves to find $k_{min}(P,T)$, $k_{peak}(P,T)$, $k_{max}(P,T)$, $v(T)$ for each sample
46
Generate master decay curve equation over a web of pressures and temperatures
48
Retrieve polynomials for paint
52
Calculate polynomials relating pressure and temperature for given gates
50
Put model in wind tunnel under operational conditions
54
Run polynomial check
56
61
60
Results Consistent ?
No
Yes
Refit calibration data to obtain new polynomials via 46, 48, 50
62
Sample intergrated intensity for four gated areas
64
Calculate ratios for two pairs of gated areas
66
Solve polynomials to obtain temperature and pressure values
69
67
P,T within normal range ?
No
Yes
Take samples for alternative gated area positions and solve polynomials via 62, 64, 66
68
Display pressure map

PRESSURE SENSITIVE PAINT

[0001] This invention relates to a sensor system using pressure sensitive paint wherein the paint is illuminated and its luminescence is measured to provide information about the pressure and temperature in the environment of the paint. Luminescence is taken to mean fluorescence or phosphorescence.

[0002] Pressure sensitive paint contains a luminescing molecule, such that incident light may cause electrons in the molecule to be excited to higher energy levels. This excitation energy may be released as the electron falls back to a lower energy level by emission of one or more photons. This process may be quenched by exposure to oxygen as the presence of oxygen provides an alternative mechanism for energy loss that does not involve light emission. As the emission of light from pressure sensitive paints is dependent on oxygen concentration, pressure sensitive paints may be calibrated to measure oxygen concentrations in fluids or may be calibrated to measure the local pressure of a fluid where the oxygen concentration of that fluid is known. For example, a sensor system using a pressure sensitive paint may be used in blood or ground water analysis or in wind tunnel testing.

[0003] For renal and ground water analysis, the end of an optical fibre is coated in a pressure sensitive paint and immersed in blood. Light pulses are passed down the optical fibre to illuminate the pressure sensitive paint and the luminescence of the paint is measured to derive the oxygen concentration of the blood or of the ground water.

[0004] For wind tunnel testing, an aerodynamic structure (normally a model of a building or vehicle, an aircraft model being an obvious example) is painted with the pressure sensitive paint and placed in the airflow within a wind tunnel. The model is then illuminated with pulses of light and the resulting luminescence of the pressure sensitive paint measured. As the oxygen concentration in the air is known and fixed, the luminescence gives an indication of the air pressure and hence air flow over the model.

[0005] However, there is a major problem with pressure sensitive paints that must be overcome in that the luminescence of the paints is dependent upon both pressure and temperature. Hence, the local temperature of the pressure sensitive paint must also be known if unambiguous pressure information is to be gained.

[0006] A sensor system using pressure sensitive paint is disclosed in EP-A-0,252,578. The sensor system disclosed in this document is used to measure oxygen concentration in blood using the method described generally above. The pressure sensitive paint is chosen such that it has a relatively long-lived decay rate (i.e. the rate of decay from excited states, be it by luminescence or quenching). The rate of luminescence gradually decreases with time, i.e. it is gradually extinguished as shown in **FIG. 1**. The decay rate of the pressure sensitive paint is measured by integrating the intensity of light received by a photodetector over two time intervals. The first interval is measured during the extinction of the luminescence and the second interval is measured at the tail of the curve to provide a baseline. The baseline corresponds to any dark current and ambient light in the photodetector and is subtracted from the integrated intensity measured during extinction. The oxygen concentration is derived by comparing the integrated intensity against a formula that includes coefficients reflecting the temperature of the pressure sensitive paint. To solve the equation requires a measurement of the temperature and this is performed using a thermocouple. Hence, in addition to the optical fibre being coated in pressure sensitive paint, the sensor system must also comprise a second sensor at extra expense and complexity. Furthermore, the accuracy of the oxygen concentration determination is reliant upon the accuracy of the thermocouple.

[0007] A second way of addressing the temperature-dependency problem is disclosed in EP-A-0,472,243. Here, the pressure sensitive paint further comprises a second type of luminescing molecule that is temperature dependent only. The two types of luminescing molecule are chosen so that they emit light at slightly different wavelengths such that their intensities can be measured separately although, in practice, there is always some overlap. This overlap in conjunction with imperfect optical filtering in detectors can lead to cross-correlation. In principle, the temperature information provided by the second type of molecule allows the pressure information to be extracted from the temperature/pressure information provided by the first type. However, it is thought that this method suffers from, an inherent disadvantage in that the two types of molecule may interact with each other. For example, light emitted by one type of molecule may be absorbed by the other leading to further luminescence and a misrepresentative luminescence decay curve. Furthermore, some temperature-dependent only paints rely on trapping fixed concentrations of oxygen. However, this is impractical to achieve as the oxygen concentration is affected by temperature cycling and changes in permeability in the paint matrix.

[0008] From a first aspect, the present invention resides in a method of calibrating pressure sensitive paint comprising the steps of:

[0009] (a) illuminating the pressure sensitive paint under a range of pressures and temperatures;

[0010] (b) measuring the intensity of light emitted by the pressure sensitive paint following each illumination thereby measuring decay curves; and

[0011] (c) performing a curve fit of the decay curves to the general form

$$I(t) = a \cdot e^{-k_{peak} t} + \frac{b}{t}\left(\frac{e^{k_{\min} t} - e^{k_{\max} t}}{k_{\max} - k_{\min}}\right)$$

[0012] where t is time elapsed and a, b, k_{peak}, k_{min} and k_{max} are determined by the curve fit.

[0013] In the context of the claims and the corresponding statements of invention, the term 'pressure' is intended to mean pressure of oxygen as sensed by the pressure sensitive paint and so includes both local air pressure (e.g. as would be the case for a paint-coated model in a wind tunnel) and also local oxygen concentration (e.g. as would be the case in renal or ground water analysis).

[0014] A range of pressures and temperatures may include a plurality of pressures and one temperature, one pressure and a plurality of temperatures or a plurality of pressures and a plurality of temperatures.

[0015] When the decay curves are measured, they may be measured continuously (e.g. as a series of points such that the complete decay curve can be traced) or by measuring at selected points or regions along the decay curve.

[0016] For the avoidance of doubt, the scope of the invention should not be construed in strict compliance with the equation above. Equivalent forms of the equation are also intended to fall within the scope of the claims. For example, merely rearranging the above equation would yield an equivalent form, as would mere substitution of selected constants and variables. For example, k_{max} could be replaced by the quantity $k_{peak}+c$ where c is a constant that remains fixed across all decay curves.

[0017] Optionally, the method may further comprise the steps of measuring the intensity of light emitted by the pressure sensitive paint prior to illumination to give a background intensity value and subtracting the background intensity value from the decay curve prior to performing the curve fit of step (c). This allows the ambient light or any dark current in the light detector to be subtracted to leave only the light emitted by the pressure sensitive paint in response to the illumination.

[0018] Preferably, a simplified form of the equation in step (c) is used during curve fitting, namely

$$I(t) = I_0\left(v \cdot e^{-k_{peak}t} + \frac{1-v}{t}\left(\frac{e^{k_{\min}t} - e^{k_{\max}t}}{k_{\max} - k_{\min}}\right)\right)$$

[0019] where I_0 is the peak intensity measured and v is determined by the curve fit.

[0020] It has been found beneficial to use a temperature range that extends substantially from −20° C. to +50° C. Moreover, we have found illuminating the pressure sensitive paint incrementally over the temperature range in 10° C. steps to be preferable.

[0021] Optionally, a plurality of decay curves are measured at each temperature and pressure value and the plurality of decay curves are integrated or averaged prior to curve fitting. This allows better statistics to be collected and helps to remove any fluctuation in operational conditions between one illumination and the next. In a currently preferred embodiment, substantially 500 decay curves are measured at each temperature and pressure value.

[0022] Optionally, the method may further comprise the steps of: generating a model of decay curves over the range of pressures and temperatures from the determined values of a, b, k_{peak}, k_{min} and k_{max} or v, k_{peak}, k_{min} and k_{max}; and calculating a polynomial relating pressures and temperatures for ratios of intensities over gated areas of the model decay curves. This is a convenient way of manipulating the data ready for use in taking pressure measurements from the now-calibrated pressure sensitive paint. It is convenient because a relatively simple polynomial can be stored for reference rather than the entire model of decay curves, something that would require far greater computer memory.

[0023] Preferably, the position of the gated areas within the model decay curves are determined with reference to the model of decay curves. Alternatively, the positions of the gated areas may be predetermined. Optionally, a first pair of gated areas are determined to occupy the rapidly-decaying portion of the model decay curves and a second pair of gated areas are determined to occupy the gradually-decaying portion of the model decay curves. A further optional feature is to determine alternative gated area positions for the model decay curves according to different pressure and temperature regimes, thereby forming an alternative polynomial. This allows higher precision calibration and pressure and/or temperature measurement at extreme pressures and/or temperatures. For example, three temperature regimes and one pressure regime may be used, the three temperature regimes corresponding to low temperatures, mid-range temperatures and high temperatures.

[0024] From a second aspect, the present invention resides in a method of determining pressure comprising the steps of:

[0025] (i) illuminating a pressure sensitive paint calibrated as described above;

[0026] (ii) measuring the intensity of light emitted by the pressure sensitive paint following illumination over two of the gated areas;

[0027] (iii) determining the ratio of the gated area intensities; and

[0028] (iv) determining the pressure and/or temperature from the polynomial using the ratio of the gated area intensities determined in step (iii).

[0029] This allows less data collection in that measurements need only be taken for the gated areas and not for the entire decay curves. This reduces the amount of computer memory required to store the data and expedites data processing.

[0030] Preferably, the method further comprises the steps of measuring the intensity of light emitted by the pressure sensitive paint prior to the illumination of step (i) to give a background intensity value and subtracting the background intensity value from the measurements of the gated areas prior to determining the ratio of the gated areas in step (iii).

[0031] Optionally, intensity measurements are taken and compared against intensity measurements taken during calibration and, if the results are not consistent, a new polynomial is calculated with reference to the new intensity measurements. This allows compensation for any differences in experimental set up that may occur, for example because the pressure sensitive paint was calibrated at a location remote from the pressure measurement location. For example, the pressure sensitive paint may be calibrated at its point of manufacture and then sold to a third party for use in their own wind tunnel test facilities.

[0032] Preferably, in step (ii), the light emitted over two pairs of gated areas is measured, in step (iii), ratios of both pairs of gated areas are determined and, in step (iv), the determination is performed using both determined ratios. This is to the benefit of accuracy. Optionally, a first pair of gated areas are determined that occupy the rapidly-decaying part of the decay curve and a second pair of gated areas are determined that occupy the gradually-decaying part of the decay curve.

[0033] Optionally, the pressure and/or temperature determined by reference to the polynomial is/are checked against the pressure and temperature regimes and, if the polynomial used does not correspond to the pressure and temperature regime determined, steps (ii), (iii) and (iv) are repeated using the appropriate alternative gated area positions and appropriate alternative polynomial.

[**0034**] One application of the present invention is in illuminating a model coated in pressure sensitive paint that is positioned in a wind tunnel. Preferably, the intensity of light emitted from a plurality of portions of the model are measured and the pressure at each portion is determined. This allows a pressure map of the model's surface to be compiled.

[**0035**] From a third aspect, the present invention resides in a computer program comprising program instructions for causing a computer: to receive data in the form of decay curves from a pressure sensitive paint measurement apparatus, and to perform a curve fit of the decay curves to the general form

$$I(t)=a\cdot e^{-k_{peak}t}+\frac{b}{t}\left(\frac{e^{k_{\min}t}-e^{k_{\max}t}}{k_{\max}-k_{\min}}\right)$$

[**0036**] where t is time elapsed and a, b, k_{peak}, k_{min} and k_{max} are determined by the curve fit.

[**0037**] Preferably, the computer program further causes the computer to perform the curve fit to a simplified form of the above equation, namely

$$I(t)=I_0\left(v\cdot e^{-k_{peak}t}+\frac{1-v}{t}\left(\frac{e^{k_{\min}t}-e^{k_{\max}t}}{k_{\max}-k_{\min}}\right)\right)$$

[**0038**] where I_0 is the peak intensity measured and v is determined by the curve fit.

[**0039**] Optionally, the computer program further causes the computer: to generate a model of decay curves from the determined values of a, b, k_{peak}, k_{min} and k_{max} or v, k_{peak}, k_{min} and k_{max}; and to calculate a polynomial relating pressures and temperatures for ratios of gated areas of the model decay curves. Preferably, the computer program further causes the computer to determine the position of the gated areas with reference to the model of decay curves. Alternatively, the computer program may assign fixed positions for the gated areas.

[**0040**] Optionally, the computer program may cause the computer: to receive data corresponding to measurements from the gated areas; to determine the ratio of intensities from the gated areas; and to determine the pressure and/or temperature from the polynomial.

[**0041**] The present invention also extends to a carrier having thereon any computer program described above and to a computer when programmed with any of the computer programs described above.

[**0042**] The present invention also extends to a pressure sensitive paint measurement apparatus comprising a light source for illuminating the pressure sensitive paint, a light detector for measuring light emitted by the pressure sensitive paint and the computer described above when programmed to receive data in the form of decay curves from the light detector. Preferably, the light source is a Nd-YAG laser and, optionally, the light detector is an avalanche photodiode. Optionally, the apparatus further comprises an analogue-to-digital converter operable to digitise the data provided by the light detector.

[**0043**] Preferably, the apparatus further comprises a display and wherein the computer is programmed to cause the display to show the determined pressure and/or temperature. Optionally, the apparatus may further comprise a model bearing the pressure sensitive paint and a wind tunnel.

[**0044**] The invention will now be described, by way of example only, by reference to the accompanying drawings in which:

[**0045**] **FIG. 1** is a plot of the typical luminescence intensity (I) of the pressure sensitive paint versus time (t);

[**0046**] **FIG. 2** is a plot of population (p) versus decay rate (k);

[**0047**] **FIG. 3** is a block diagram of a sensor system according to an embodiment of the present invention for use in wind tunnel testing;

[**0048**] **FIG. 4**(*a*) is a perspective view of a pressure sensitive paint-covered model for use in the sensor system of **FIG. 3** and **FIG. 4**(*b*) is a pressure map of the similar model showing the local pressures across the model's surface at the moment of illumination;

[**0049**] **FIG. 5** is a plot of the maximum or minimum decay rate (k_{max} or k_{min}) versus pressure (P); and

[**0050**] **FIG. 6** is a flow diagram of a method of operating the sensor system of **FIG. 1**.

[**0051**] A luminescence decay curve **10** obtainable with a sensor system according to the present invention is reproduced in **FIG. 1** and shows the intensity of light emitted during and after illumination by a flash of light. As can be seen, after the initial rapid increase in intensity (the rise is not instantaneous because of the response time of the light source used), there is extinction of the luminescence intensity that is approximately exponential but that is comprised of two distinct parts. The first part is characterised by a rapid extinction **12** that is followed by a far more gradual extinction **14** that continues to meet asymptotically a baseline **16** corresponding to any dark current and ambient light present in the light detector used. The shape of the decay curve **10** responds both to variations in temperature and in pressure.

[**0052**] We have found that the shape of the luminescence decay curve **10** can be represented satisfactorily by the equation:

$$I(t)=a\cdot e^{-k_{peak}t}+b\sum_{i=\min}^{i=\max}e^{k_i t}$$

[**0053**] where a and b are constants, t is time elapsed and k is the decay rate. Assuming a continuous distribution of decay rates allows the second term to be integrated over k to give:

$$I(t) = a \cdot e^{-k_{peak}t} + \frac{b}{t}\left(\frac{e^{k_{\min}t} - e^{k_{\max}t}}{k_{\max} - k_{\min}}\right)$$

[0054] This can be rewritten to incorporate a parameter v, the proportion of luminophores that decay as k_{peak} in the paint matrix, as follows:

$$I(t) = I_0\left(v \cdot e^{-k_{peak}t} + \frac{1-v}{t}\left(\frac{e^{k_{\min}t} - e^{k_{\max}t}}{k_{\max} - k_{\min}}\right)\right)$$

[0055] where I_0 is the peak intensity measured and k_{peak}, k_{min} and k_{max} are characteristic decay rates that will be descirbed fully below.

[0056] To appreciate the above equation requires consideration of the physical process of light emission and how it is influenced by oxygen quenching. Oxygen present in an air-stream passing over a model acts to stop light emission from luminophores (the luminescing molecules). However, the degree of quenching in any particular area of the model depends on the local environment of the luminophores within the paint matrix because this determines the accessibility of the luminophores to the oxygen. There are a number of possible sites within the paint matrix for the luminophores to occupy that have varying degrees of accessibility for oxygen. For example, migration of oxygen molecules to some luminophore sites may be either particularly easy or particularly difficult whilst, at the molecular scale, the concentration of oxygen is not necessarily homogeneous. This variety of sites leads to a variation in the degree of quenching within an area. The presence of oxygen stops light emission from an otherwise luminophore because of the alternative de-excitation route though loss of energy by quenching. Moreover, this alternative energy-loss mechanism proceeds far more quickly that the light emission route, thereby increasing the decay rate for the sites affected (remembering that decay rate is the rate of decay be it either by light emission or by quenching).

[0057] Variation in decay rate can be represented by a population distribution and we have found that the population distribution **18** illustrated in **FIG. 2**, although simplified, is adequate to realise accurate pressure determination. As will be readily apparent, this population distribution **18** assumes a superposition of a uniform population distribution **20** between a minimum decay rate (k_{min}) and a maximum decay rate (k_{max}) and a spike **22** centred at k_{peak}. The position of k_{peak} relative to k_{min} and k_{max} varies between different paint compositions. The physical interpretation of the population distribution **18** is as follows. The spike **22** at k_{peak} represents a proportion of sites and corresponds to a typical open and unhindered site, quite possibly voids in the polymers. The uniform distribution **20** corresponds to a spectrum of sites where oxygen access is hindered due to an intimate relation between luminophore and substrate. For the cases of hindered sites at the k_{min} end, there is little or no trapped oxygen and this results in low decay rates. At the k_{max} end, the hindered sites tend to trap any oxygen molecules that reach the luminescing molecule resulting in high decay rates. A spectrum of high decay rates results because the degree of hindrance is variable.

[0058] The shape of the luminescence decay curve **10** of **FIG. 1** can be explained with reference to the equations and physical model discussed above. The initial luminescence at the rapid extinction part **12** of the decay curve **10** is dominated by light emission from unhindered sites, i.e. those comprising the spike **22** at k_{peak} in the population distribution **18** and sites with trapped oxygen. These sites give rise to the first term in the equation, $v.\exp(-k_{peak}t)$ and the fast end of the spectrum of decays. As the initial burst of luminescence diminishes, luminescence from hindered sites that do not trap oxygen progressively dominates such that they form the gradual extinction part **14** of the curve. As explained above, hindered sites that trap oxygen are far less likely to emit light and hence only fractionally contribute to the decay curve **10**.

[0059] The population distribution **18** is affected both by changes in temperature and pressure. An increase in pressure leads to the greater presence of oxygen due to Henry's Law of Gas Solvation. This, in turn, causes increased quenching with the effect that the population distribution **18** shifts to higher decay rates. As will be appreciated, a decrease in pressure has the opposite effect. Hence, a change in pressure leads to a shift in k_{max} and k_{min}, but the magnitude and position (k_{peak}) of the spike **22** relative to the uniform population distribution **20** remains the same due to the linear dependence of all decay rates on pressure. Turning now to the temperature dependency, an increase in temperature leads to higher decay rates and we believe also leads to a conversion of hindered sites into unhindered sites, such as voids in the polymer. Hence k_{max}, k_{peak} and k_{min} shift to higher decay rates and the magnitude of the spike **22** increases relative to the uniform distribution **20**. The latter effect is reflected in the parameter v that appears in the above equations, this 'v-factor' being the proportion of luminophores that occupy voids (sites contributing to k_{peak}) in the paint matrix. As will be appreciated, the opposite is seen for a decrease in temperature.

[0060] We have realised that because the v-factor is dependent on temperature alone, it alone could be used to determine temperature. In practice, k_{max} is not well determined from curve fitting but is fixed in relation to k_{peak}. However, in principle, pressure and temperature can be determined from curve fitting and generating values of k_{min}, k_{peak} and v.

[0061] A sensor system **24** for use with pressure sensitive paint in wind tunnel testing will now be described with reference primarily to **FIGS. 3, 4*a*** and **6**. The sensor system comprises a light source **26**, a light detector **28**, a processor **30** for controlling the light source **26** and light detector **28** and for collecting and analysing a signal **32** provided by the light detector **28** and a monitor **33** for displaying information. The processor **30** may be, or example, a personal computer suitably programmed to implement the present invention. The light source **26** and light detector **28** look towards an aircraft model **34** that has been coated in pressure sensitive paint (such as that shown in **FIG. 4*a***). The light source **26**, light detector **28** and model **34** are located within a wind tunnel such that, in operation, air is blown over the model creating a varying pressure profile that reflects the aerodynamic performance of the model **34**. The processor **30** is located external to the wind tunnel such that it can be accessed by an operator during operation of the wind tunnel.

[0062] In this embodiment, the light source **26** is Nd-YAG laser operating at 532 nm. However, there are many other suitable alternatives that meet the requirement of producing bright flashes of light and that can be driven at high repetition rates typically in the kHz range.

[0063] The light detector **28** of this embodiment is an avalanche photodiode **28**. This type of device collects light from only a small part of the model and, as such, provides a one-dimensional profile of that part of the surface of the model. Where two-dimensional pressure profiles are required, these can be obtained simply by scanning the light source **26** and light detector's field of view across the surface of the model **34** such that it collects light from different parts of the model's surface.

[0064] The processor **30** is a personal computer and is used to control the sensor system **24**. The processor **30** is linked to both the light source **26** and the light detector **28** such that signals can be sent to the light source and can be exchanged in both directions with the light detector. The processor **30** includes an analog-to-digital converter (ADC) for receiving measurements from the light detector **28**. Accordingly, the processor **30** sends a signal to the light detector **28** to take a measurement of the decay curve **10** and then converts the analogue signal **32** to a corresponding digital value, thereby effectively performing a digital sampling of the decay curve **10**.

[0065] The processor **30** regulates use of the sensor system **24** as follows. Once the operational conditions in the wind tunnel are met, i.e. the wind tunnel fan is up to speed and the painted model **34** is in position, an operator can command the processor **30** to capture data from the model **34**. Upon this command, and before the model **34** is illuminated during each data collection run, the processor **30** sends a signal **36** to the photodiode **28** to sample the light it is receiving over a number of successive time slots and pass the values to the processor **30** via the ADC. The processor **30** then calculates the average baseline value per unit time from the digitised data. Hence, a measurement of the dark current and ambient light in the photodiode **28** is obtained and this can be used as a baseline subtraction for data taken after illumination of the model **34**. Once the baseline value has been determined, the processor **30** sends a signal **38** to the light source **26** such that the light source **26** produces a flash illumination microseconds after the baseline data sampling and coincidentally sends the first of a series of signals **36** to the photodiode **28**. The series of signals **36** sent to the photodiode **28** act as gate signals to start and end time intervals **40*a,b*** of data sampling. During each time interval **40*a,b***, the photodiode **28** is run such that the integrated light intensity over that interval **40*a,b*** is sampled. At the end of each time interval **40*a,b***, the value measured by the photodiode **28** is passed to the processor **30** via the ADC where it is digitised before being subject to data processing, such as subtraction of the baseline value, as will be described below.

[0066] Furthermore, the method described above can be performed consecutively such that when the data from the last time interval **40*b*** has been collected, the processor **30** causes first a new baseline sampling and determination stage and then causes the light source **26** to produce a second light flash and the same data collection routine to be run as described above. This procedure can be repeated as many times as is desired. The extra data collected in this way may be used to improve statistics, i.e. to determine pressure and/or temperature by averaging a number of decay curves or may be used to obtain successive values of pressure and/or temperature where high-resolution time intervals are required.

[0067] The sensor system **24** may be operated such that the photodiode **28** samples data over many short and successive snapshots to produce a series of data points that indicate the decay curve **10** of **FIG. 1**. If sufficient data points are sampled, the decay curve **10** may then be fitted using standard curve-fitting techniques to derive the coefficients k_{min}, k_{max}, k_{peak} and the v-factor. However, performing a curve fit for every decay curve **10** collected by the photodiode **28** is very slow and is prone to correlations. Hence, an alternative method has been devised, and will be described with reference to **FIG. 6**.

[0068] First, a batch of pressure sensitive paint must be calibrated before it can be used for pressure measurements, as indicated in **FIG. 6** by **42**. This is performed by using small samples of the pressure sensitive paint in an environmental chamber, where the baseline value is determined prior to illuminating the model and sampling whole decay curves **10** at **44** with an avalanche diode **28**, i.e. illumination readings are sampled continuously via an ADC throughout the extinction of the luminescence, for a representative range of pressures and temperatures. In this example, 500 decay curves **10** were sampled at each of sixteen conditions, corresponding to 10° C. steps over the temperature range −20° C. to +50° C. for two different airflow speeds (and hence pressures on the model), as indicated at **44**. The 500 curves were averaged to produce an average decay curve for each condition. However, the number of decay curves measured and the number of temperature and pressure conditions may be varied freely according to need.

[0069] The average decay curves are curve fitted at **46** to derive k_{peak} as a function of pressure and temperature, k_{min} as a function of pressure and temperature and v as a function of temperature alone (k_{max} can be fixed to the value of k_{peak}, e.g. $k_{max}=k_{peak}/0.6$). From this, a master decay curve equation (i.e. a model) can be generated at **48**. Moreover, notional gates **40*a,b*** can be found from the master decay curve equation and the integrated light intensity represented by the areas of these gated areas **40*a,b*** calculated. Two pairs of notional gates **40*a,b*** are used: the first pair **40*a*** occupy the rapid extinction part **12** and so is sensitive to high decay rate sights and the second pair **40*b*** occupy the low extinction part **14** and so are sensitive to low decay rate sights, as shown in **FIG. 1**. The ratio of intensities **IR1** and **IR2** between the pairs of gated areas **40*a,b*** can then be calculated. The ratios will be functions of pressure and temperature (i.e. **IR1**(P,T) and **IR2**(P,T)) and they can be expressed as polynomials in pressure and temperature: these polynomials are calculated at **50** and stored in the processor.

[0070] Confidence can be placed in the above method because curve fitting decay curves showed that the linearity of the various decay rates (k_{min}, k_{max} and k_{peak}) to pressure at constant temperature is excellent and because extrapolations to zero pressure were very similar and correspond to the radiative decay rate. A representative graph is shown in **FIG. 5**. Not only that, but when the full pressure and temperature dependency of the decay rates were derived, they were sufficiently different for the expressions to be solved for temperature and pressure. It is essentially the differing sensitivities to temperature that allow **IR1**(P,T) and IR2(P,T) to be solved for pressure and temperature. That, in turn, is due to differing sensitivities of k_{min}, k_{peak} and k_{max} to temperature.

[**0071**] Where the pressure sensitive paint has already been calibrated and the polynomials determined, these polynomials may simply be retrieved from the processor **30** as indicated at **52**.

[**0072**] With the polynomials relating the gated areas **40***a,b* known, the sensor system **24** can now be operated in a quick and efficient manner. With a painted model **34** placed in the wind tunnel that is in an operational condition, as indicated at **54**, a quick data sampling step is performed at **56** to check data taken during the calibration process **42**. At **60**, the results obtained at **56** are checked against those obtained at **42** to see if they are consistent. If they are consistent, data collection can proceed as normal. If they are not consistent, the calibration data is refitted at **61** and polynomials recalculated according to steps **46**, **48** and **50**. The data collection then proceeds using the new polynomials.

[**0073**] At **62**, the processor **30** is used to run the baseline averaging procedure described above, and then to produce an initial illumination flash from the light source at **56** and to produce a series of signals to send to the photodiode **28** to mark the start and end of each gate **40***a,b* during which the photodiode **28** will be integrating the light intensity that it receives. The gates **40***a,b* must match the predetermined gates **40***a,b* for which the polynomials have been calculated. Synchronisation is achieved by setting the peak intensity **58** in any decay curve **10** as t=0: the first gate **40***a,b* is set to start at least 200 ns after t=0 due to the response time of the photodiode **28** and because of its non-linear response to rapidly-changing signals. Of course, it is possible to set other positions as t=0, although the delay to the first gate should be altered accordingly.

[**0074**] When data has been sampled by the photodiode **28** over the four designated gated areas **40***a,b* at **62**, the processor **30** can calculate the intensity ratios for the rapidly-decaying pair of gated areas **40***a* and for the gradually-decaying pair of gated areas **40***a* at **64**. The pair of polynomials can then be solved to derive the two unknowns that they contain, namely pressure and temperature, as indicated at **66**.

[**0075**] At this stage, the derived values of pressure and temperature are checked against threshold values at **67**. Where the values exceed or are below threshold values, the data collection steps **62** and **64** are repeated, but for different gate positions. This is because at high pressures, the decay rate increase due to the increased concentration of oxygen leading to more quenching and so the decay curve shows a faster extinction: in this instance it is beneficial to have the gated areas closer to t=0. Conversely, the decay curve **10** shows a more gradual extinction for low pressures and so spacing the gated areas further away from t=0 and increasing their separation is beneficial as otherwise the gated areas **40***b* that are supposed to occupy the gradual extinction part **14** of the decay curve **10** may occupy the rapid extinction part **12** instead. In this embodiment, three sets of gate positions were used (and all the area ratios IR1 and IR2 are calculated for the three cases at **50**) corresponding to normal conditions, low pressures and high pressures. Of course, this step may be omitted without departing from the scope of the invention and the number of sets of gate positions may be varied according to need.

[**0076**] With the pressure and temperature determined, either at the first instance at **66** or through a second, high-precision data collection routine at **69**, the pressure at the area on the model's surface that the photodiode **28** was viewing can be found. As mentioned previously, the photodiode **28** can be scanned across the surface of the model **34** to build up a two-dimensional pressure map. The pressure values may then displayed on a monitor **33** or the like in any number of ways as indicated at **68**. For example, colours or greyscale can be assigned to pressure values to produce a pressure map or a representation of the model's surface or a map, may be presented as a series of isobars across a representation of the model's surface. An example is shown in **FIG. 4**(*b*) where pressure values are represented using greyscale.

[**0077**] It will be readily apparent to those skilled in the art that variations to the above described embodiment are possible without departing from the scope of the invention defined in the appended claims.

[**0078**] For example, whilst the above embodiment describes use of the sensor system **24** in wind tunnel testing, it can be readily adapted for use in blood or ground water analysis. In these alternative applications, the end of an optical fibre is coated in pressure sensitive paint and connected to the light source **26** and light detector **28** via an optical coupler such that light from the light source **26** can pass down the optical fibre and light emitted by the paint can travel back to the light detector **28**. The paint-coated end of the optical fibre is then placed within a blood or ground water sample and the method performed as described above. As will be readily apparent, the data collected by the light detector **28** will correspond to the luminescence intensity of the pressure sensitive paint and the same data analysis can be performed to extract partial pressure of oxygen in the blood or ground water (and hence the oxygen concentration).

[**0079**] Whilst the embodiment described herein before employs an avalanche photodiode **28** as a light detector, a charge coupled device (CCD) would be a good alternative. This type of device has the advantage that it provides a two-dimensional array of pixels that can be used to represent a two dimensional array of spot pressures on the part of the model **34** that the CCD is viewing. Furthermore, a CCD is inherently an intensity integrating device and therefore is well suited to measuring light intensities integrated over gated time intervals **40***a,b*. In addition, intensified detectors such as a streak camera could be used for fast gating. Fast gating is a problem in that the time intervals between gated areas may be less that the time needed to retrieve the light intensity measured by each pixel in the CCD (this essentially involves discharging a capacitor and so is determined by the time constant of the capacitor). Another way around this problem is to use more than one CCD or to divide the pixels into separate arrays, e.g. use alternate lines of pixels to measure alternate gated areas or divide the array into four quadrants, one for each gated area.

[**0080**] As an alternative to using an ADC to digitise data collected from the avalanche photodiode thereby effectively sampling the decay curve **10**, a simpler scheme such as using a timer to collect data over a series of boxcar gates may be used. The main disadvantage of this scheme is that the position of the boxcar gates is fixed and so the flexibility to move the gated areas according to the shape of the decay curve is lost.

[0081] Two pairs of intensity ratios obtained from four gated areas **40***a,b* are used to obtain pressure and temperature information, but satisfactory results can be obtained by taking two ratios from three gated areas **40***a,b*. Conversely, more than two ratios can be taken for further accuracy. This can be achieved by taking more pairs of intensity integrations, or by calculating various combinations of ratios between a number of grated areas **40***a,b*.

1. A method of calibrating pressure sensitive paint comprising the steps of:

illuminating the pressure sensitive paint under a range of pressures and temperatures;

measuring the intensity of light emitted by the pressure sensitive paint following each illumination thereby measuring decay curves; and

performing a curve fit of the decay curves to the general form

$$I(t) = a \cdot e^{-k_{peak}t} + \frac{b}{t}\left(\frac{e^{k_{\min}t} - e^{k_{\max}t}}{k_{\max} - k_{\min}}\right)$$

where t is time elapsed and a, b, k_{peak}, k_{min} and k_{max} are determined by the curve fit.

2. A method according to claim 1, further comprising the steps of measuring the intensity of light emitted by the pressure sensitive paint prior to illumination to give a background intensity value and subtracting the background intensity value from the decay curve prior to performing the curve fit of step (c).

3. A method according to claim 1, wherein a simplified form of the equation in step (c) is used during curve fitting, namely

$$I(t) = I_0\left(v \cdot e^{-k_{peak}t} + \frac{1-v}{t}\left(\frac{e^{k_{\min}t} - e^{k_{\max}t}}{k_{\max} - k_{\min}}\right)\right)$$

where I_0 is the peak intensity measured and v is determined by the curve fit

4. A method according to claim 1, wherein the temperatures range extends substantially from −20° C. to +50° C.

5. A method according to claim 4, wherein the pressure sensitive paint is illuminated incrementally over the temperature range in 10° C. steps.

6. A method according to claim 1, wherein a plurality of decay curves are measured at each temperature and pressure value and the plurality of decay curves are integrated or averaged prior to curve fitting.

7. A method according to claim 5, wherein substantially 500 decay curves are measured at each temperature and pressure value.

8. A method according to claim 1, further comprising the steps of: generating a model of decay curves over the range of pressures and temperatures from the determined values of a, b, k_{peak}, k_{min} and k_{max} or v, k_{peak}, k_{min} and k_{max}; and calculating a polynomial relating pressures and temperatures for ratios of intensities over gated areas of the model decay curves.

9. A method according to claim 8, wherein the position of the gated areas within the model decay curves are determined with reference to the model of decay curves.

10. A method according to claim 9, wherein a first pair of gated areas are determined to occupy the rapidly-decaying portion of the model decay curves and a second pair of gated areas are determined to occupy the gradually-decaying portion of the model decay curves.

11. A method according to claim 9, wherein alternative gated area positions are determined for the model decay curves according to different pressure and temperature regimes, thereby forming an alternative polynomial.

12. A method according to claim 11, wherein three temperature regimes and one pressure regime are used.

13. A method of determining pressure comprising the steps of:

(i) illuminating a pressure sensitive paint calibrated according to claim 8;

(ii) measuring the intensity of light emitted by the pressure sensitive paint following illumination over two of the gated areas;

(iii) determining the ratio of the gated area intensities; and

(iv) determining the pressure and/or temperature from the polynomial using the ratio of the gated area intensities determined in step (iii).

14. A method according to claim 13, further comprising the steps of measuring the intensity of light emitted by the pressure sensitive paint prior to the illumination of step (i) to give a background intensity value and subtracting the background intensity value from the measurements of the gated areas prior to determining the ratio of the gated areas in step (iii).

15. A method according to claim 13, wherein intensity measurements are taken and compared against intensity measurements taken during calibration and, if the results are not consistent, a new polynomial is calculated with reference to the new intensity measurements.

16. A method according to claim 15 wherein, in step (ii), the light emitted over two pairs of gated areas is measured, in step (iii), ratios of both pairs of gated areas are determined and, in step (iv), the determination is performed using both determined ratios.

17. A method according to claim 10, wherein the first pair of gated areas occupy the rapidly-decaying part of the decay curve and the second pair of gated areas occupy the gradually-decaying part of the decay curve.

18. A method according to claim 11, wherein the pressure and/or temperature determined by reference to the polynomial is/are checked against the pressure and temperature regimes and, if the polynomial used does not correspond to the pressure and temperature regime determined, steps (ii), (iii) and (iv) are repeated using the appropriate alternative gated area positions and appropriate alternative polynomial.

19. A method according to claim 13, comprising the step of illuminating a model coated in pressure sensitive paint that is positioned in a wind tunnel.

20. A method according to claim 19, wherein the intensity of light emitted from a plurality of portions of the model are measured and the pressure at each portion is determined.

21. A computer program comprising program instructions for causing a computer:

to receive data in the form of decay curves from a pressure sensitive paint measurement apparatus; and

to perform a curve fit of the decay curves to the general form

$$I(t) = a \cdot e^{-k_{peak} t} + \frac{b}{t}\left(\frac{e^{k_{\min} t} - e^{k_{\max} t}}{k_{\max} - k_{\min}}\right)$$

where t is time elapsed and a, b, k_{peak}, k_{min} and k_{max} are determined by the curve fit.

22. A computer program according to claim 21, further causing the computer to perform the curve fit to a simplified form of the equation of claim 21, namely

$$I(t) = I_0\left(v \cdot e^{-k_{peak} t} + \frac{1-v}{t}\left(\frac{e^{k_{\min} t} - e^{k_{\max} t}}{k_{\max} - k_{\min}}\right)\right)$$

where I_0 is the peak intensity measured and v is determined during the curve fitting.

23. A computer program according to claim 21, further causing the computer: to generate a model of decay curves from the determined values of a, b, k_{peak}, k_{min} and k_{max} or v, k_{peak}, k_{min} and k_{max}; and to calculate a polynomial relating pressures and temperatures for ratios of gated areas of the model decay curves.

24. A computer program according to claim 23, further causing the computer to determine the position of the gated areas with reference to the model of decay curves.

25. A computer program according to claim 23, further causing the computer:

to receive data corresponding to measurements from the gated areas;

to determine the ratio of intensities from the gated areas; and

to determine the pressure and/or temperature from the polynomial.

26. A carrier having thereon a computer program according to claim 21.

27. A computer when programmed with the computer program of claim 21.

28. A pressure sensitive paint measurement apparatus comprising a light source for illuminating the pressure sensitive paint, a light detector for measuring the light emitted by the pressure sensitive paint and the computer of claim 27 when programmed to receive data in the form of decay curves from the light detector.

29. An apparatus according to claim 28, wherein the light source is a Nd-YAG laser.

30. An apparatus according to claim 28, wherein the light detector is an avalanche photodiode.

31. An apparatus according to claim 28 further comprising an analogue-to-digital converter operable to digitise the data provided by the light detector.

32. An apparatus according to claim 28 when dependent upon claim 25, further comprising a display and wherein the computer is programmed to cause the display to show the determined pressure and/or temperature.

33. An apparatus according to claim 28, further comprising a model bearing the pressure sensitive paint and a wind tunnel.

34-37 (canceled).

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