Methods and compositions for measuring the pressure of an oxygen-containing gas on an aerodynamic surface, by oxygen-quenching of luminescence of molecular sensors is disclosed. Objects are coated with luminescent films containing a first sensor and at least one of two additional sensors, each of the sensors having luminescences that have different dependencies on temperature and oxygen pressure. Methods and compositions are also provided for improving pressure measurements (qualitative or quantitative) on surfaces coated with a film having one or more types of sensor.
OTHER PUBLICATIONS


Fig. 20.

\[ \frac{I_0}{I} \text{ AND } C_p \]

- \( \triangle \) \( I_0/I \) data
- \( \diamond \) \( C_p \) data
$p/p_0 \text{ AND } p^*/p_0^*$
M = 0.88
\alpha = 4
wind-off
\[ M = 0.88 \]
\[ \alpha = 4 \]

wind-on
SURFACE PRESSURE MEASUREMENT BY OXYGEN QUENCHING OF LUMINESCENCE

The invention was made with government support under the following grants: NASA-Ames University Consortium under Interchange No. NCA2-296 and Interchange No. NCA2-474, and NASA Graduate Student Researchers Program Fellowship. The government may have rights in the invention.

This is a divisional of the prior application Ser. No. 07/370,275, filed Aug. 20, 1990, now U.S. Pat. No. 5,186,046. The benefit of the filing date of which is hereby claimed under 35 U.S.C. §120.

TECHNICAL FIELD

This invention relates to surface pressure measurements based on quenching of luminescence by an oxygen-containing gas in contact with the surface of an object.

BACKGROUND OF THE INVENTION

Convenient and inexpensive methods for determining pressure maps of surfaces, particularly aerodynamic objects, have long been sought. Static pressures over the surface of an aerodynamic body are presently determined using pressure orifices or pressure taps, which are drilled into the surface of the body and connected via tubing to multiplexed electronic pressure scanners external to the surface of interest. Hundreds or even thousands of pressure orifices may be required to map an entire surface. Since the pressure orifices are usually separated by a significant distance, a continuous pressure map is not achieved. The current method for determining pressures between the orifices is to interpolate them by computational fluid dynamics (CFD). See Erisman, A. M and Neves, K. W., Sci. Am. 257, 163 (October 1987) and Jameson, A., Science, 245, 361 (1989).

Wind tunnel experiments provide the data to validate CFD models. Data is also used to gain an understanding of flow so as to guide development of new CFD models. A method for collecting continuous pressure data in wind tunnels would provide the information needed to eliminate some of the uncertainty in CFD models. Several methods have been used in an attempt to provide a convenient method for determining static pressure on aerodynamic surfaces. Digital holographic interferometry is one process whereby interference fringes are counted, and the distances between fringes are processed into pressure distribution information of the surface of an airfoil. See Merzkirch, W., Flow Visualization (Academic Press, New York, 1974). This technique, however, is valid only for symmetrical airfoils. In 1980, Peterson and Fitzgerald (Peterson, J. I. and Fitzgerald, R. V., Rev. Sci. Instrum., 51, 670 (1980)) proposed oxygen quenching of fluorescent dyes for flow visualization in a wind tunnel. In their experiment, the luminescent dye was adsorbed onto silica particles. The coating was rough and adherence was a problem. No attempt at quantitation was made.

The methods and compositions described herein are based on molecular photoluminescence. Luminescence is a broad term which encompasses both fluorescence and phosphorescence. Electromagnetic radiation in the ultraviolet or visible region is used to excite molecules to higher electronic energy levels. The excited molecules lose their excess energy by one of several methods. Fluorescence refers to the radiative transition of electrons from the first excited singlet state to the singlet ground state (S₁→S₀). The lifetime of fluorescence is relatively short, approximately 10⁻⁸ to 10⁻¹⁰ seconds. However, intersystem crossing from the lowest excited singlet state to the triplet state often occurs and is attributed to the crossing of the potential energy curves of the two states. The triplet state so produced may return to the ground state by a radiative process known as phosphorescence. Phosphorescence is the radiative relaxation of an electron from the lowest excited triplet state to the singlet ground state (T₁→S₀). Because the transition that leads to phosphorescence involves a change in spin multiplicity, it has a low probability and hence a relatively long lifetime (10⁻¹⁴ to 10 seconds). Also, due to the lower energy of the triplet state, the wavelength of phosphorescence is longer than the wavelength of fluorescence. Herein, the term "sensor" is used to refer to luminescent molecules.


The oxygen quenching properties of platinum porphyrins have been used for the determination of oxygen in vivo. For example, U.S. Pat. No. 4,810,655 is directed to methods and compositions for measuring oxygen concentrations, particularly for monitoring oxygen in the blood with a fiber-optic catheter. In one important aspect of the present invention, the inventors have recognized that there is a problem with prior techniques of pressure measurement based on oxygen quenching of luminescent indicators, in particular, the phosphorescence of certain porphyrin derivatives has a temperature dependency in addition to a pressure dependency. Accordingly, pressure measurements based on a coating containing a single sensor of this type can be in error if there is a fluctuation in the temperature. Previously, it had been reported that there was no temperature dependence of the brightness of a particular luminescent indicator coating. See Ardasheva, M. M., et al., Zhur. Prik. Mek. 4, 24-30 (1985), English translation. To the contrary, the present inventors have found that for the systems reported herein, the temperature dependency of luminescence is an effect which must be corrected for when temperatures on the surface of an object vary more than approximately 0.5°C.

There are also previous reports to the effect that, independent of pressure measurements, temperature sensitive phosphors have been used to measure surface temperature of aerodynamic surfaces. See, for example, Bradley, L. C., Rev. Sci. Instr., 24(3), 1953; and Baker, H. D. et al., Temperature Measurement in Engineering, Vol. II (Omega Press, Stamford, Conn.) 190-191 (1960). None of these prior reports have incorporated two different types of sensors as disclosed herein into a sin-
the following equation (a form of the Stern-Volmer law):

\[
\frac{I_o}{I} = A + B(p/p_0)
\]  

where \( I \) is the intensity at pressure \( p \) and \( I_o \) is the pressure at reference pressure \( p_0 \) and \( A + B \) are constants that added together equal one. From the collected luminescences emitted by a plurality of sensors, it is possible to create two ratio fields:

\[
\frac{I_{io}}{I_o} = r_1 \text{ or } \frac{I_{io}}{I_o} = r_2
\]

where the ratio or \( r_1 \) is primarily pressure dependent, but also has some temperature dependence. The ratio \( r_2 \) is temperature dependent only. Thus, \( r_2 \) can be used to obtain accurate values of \( p/p_0 \) from \( r_1 \). In an alternative embodiment, \( I_{io} \) and \( I_{io} \) are replaced by \( I_o \), the emission from sensor C that is independent of oxygen pressure and independent of temperature. Even if the luminescence properties of the three sensors are not ideal (e.g., the sensor B has a temperature dependence and slight pressure dependence), this difficulty can be taken care of in a calibration.

Also disclosed are paints that contain the necessary molecular species to carry out the methods described above. For example, a pressure sensitive paint for purposes of the present invention will generally comprise sensors A and B, or sensors A, B, and C, where the sensors are as described above; a solvent; and molecules that form a film containing the sensors upon evaporation of the solvent. The pressure sensitive paint can be used to coat an object for carrying out the methods described above.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic drawing of the instrumentation used for calibration;

FIG. 2 shows a calibration curve for platinum octaethylporphyrin in silicone resin sprayed onto an aluminum plate covered with white paint, taken with the apparatus of FIG. 1. \( I_0 \) is the phosphorescence intensity at atmospheric pressure, \( p_0 \), \( I \) is the phosphorescence intensity at pressure \( p \). In this graph \( FT(I_0/I) = A + B(p/p_0) \), with \( A = 0.32 \) and \( B = 0.70 \), the values from a linear least squares fit;

FIG. 3 shows the apparatus used with a subsonic wind tunnel at NASA-Ames;

FIG. 4 shows an in-lab calibration curve for rhodamine B in silicone resin sprayed onto an aluminum plate covered with white paint taken with the apparatus shown in FIG. 1.

FIG. 5 shows a schematic of an image processing sequence.

FIG. 6 shows the NACA-0012 airfoil taken at a wind speed of \( M = 0.36 \). Locations of pressure taps and intensity profile are indicated.

FIG. 7 shows intensity data profiles across the chord of the wing as extracted from FIG. 6 with the wind on \( (I) \), and reference data as extracted with the wind off \( (I_o) \), at the same location.

FIG. 8 shows an in situ calibration curve showing \( I_0/I \) vs. \( p/p_0 \) at \( M = 0.36 \)

FIG. 9 shows a comparison of actual \( (p/p_0) \) and predicted \( (p'/p'_0) \) pressure ratios for \( M = 0.36 \).

FIG. 10 shows the NACA-0012 airfoil taken at a wind speed of \( M = 0.66 \). Locations of pressure taps and intensity profile are indicated. The shock boundary is also shown.

FIG. 11 shows intensity data profiles across the chord of the wing as extracted from FIG. 10 with the wind on \( (I) \), and reference data as extracted with the wind off \( (I_o) \), at the same location.
FIG. 12 shows an in situ calibration curve showing \( p/p_0 \) vs. \( L_0/I \) at \( M=0.66 \).

FIG. 13 shows a comparison of actual \( (p/p_0) \) and predicted \( (p*/p_0^*) \) pressure ratios for a single linear fit at \( M=0.66 \).

FIG. 14 shows a dual calibration curve of \( p/p_0 \) vs. \( L_0/I \) for \( M=0.66 \), representing best fits for variations in temperature of data under the shock wave and elsewhere on the airfoil. The lower line is data from the leading edge; the upper line is data from the trailing edge.

FIG. 15 shows a comparison of actual \( (p/p_0) \) and predicted \( (p*/p_0^*) \) pressure ratios for a dual linear fit, representing two different temperature regions on the airfoil at \( M=0.66 \).

FIG. 16 shows calibration curves for 6.0° C., 23.7° C., and 30° C. \( L_0 \) for each curve was measured at 23.7° C.

FIG. 17 shows a schematic of Boeing Transonic Wind Tunnel (BTWT). The tunnel is a closed-circuit, single-return system that is vented to the atmosphere at conditions. In order for an oxygen-sensitive sensor to produce a physical reaction, the sensor must be exposed to oxygen in the air exchanger. A cross section of the test section measures 8 by 12 feet.

FIG. 18 shows a schematic of a Boeing Transonic Wind Tunnel (BTWT) test section and test apparatus. FIG. 19 shows the Boeing commercial transport wing taken at a wind speed of \( M=0.86 \). Locations of pressure taps (arrow B) and intensity profiles (arrows A and C) are indicated.

FIG. 20 shows a comparison of \( L_0/I \) data and \( C_p \) data for alignment purposes.

FIG. 21 shows an in situ calibration curve showing \( p/p_0 \) vs. \( L_0/I \) at \( M=0.86 \) for data corresponding to lower arrow (C) in FIG. 19.

FIG. 22 shows an in situ calibration curve showing \( p/p_0 \) vs. \( L_0/I \) at \( M=0.86 \) for data corresponding to upper arrow (A) in FIG. 19.

FIG. 23 shows a comparison of actual \( (p/p_0) \) and predicted \( (p*/p_0^*) \) pressure data corresponding to the lower arrow (C) in FIG. 19.

FIG. 24 shows a comparison of actual \( (p/p_0) \) and predicted \( (p*/p_0^*) \) pressure data corresponding to the upper arrow (A) in FIG. 19.

FIG. 25 shows a comparison of actual \( (p/p_0) \) and predicted \( (p*/p_0^*) \) pressure data corresponding to the upper arrow (A) using calibration data from the lower arrow (C) in FIG. 19.

FIG. 26 shows a wide angle view of a Boeing commercial transport wing. The wind speed is zero, and the angle of attack is 4 degrees. Notice the uneven lighting on the surface of the wing.

FIG. 27 shows a wide angle view of a Boeing commercial transport wing. The wind speed is \( M=0.88 \), and the angle of attack is 4 degrees. Shock patterns have developed, but uneven source lighting is still evident.

FIG. 28 shows a ratioed image representing a continuous pressure map of a Boeing commercial transport wing. (The image of FIG. 26 has been divided by the image of FIG. 27.) The wind speed is \( M=0.88 \), and the angle of attack if 4 degrees. The white edging is due to a small model translation during air flow.

FIG. 29 shows a ratioed image of FIG. 28 to which computerized false color has been added for greater enhancement of the pressure patterns.

FIG. 30 shows a Boeing commercial transport wing taken at a wind speed of \( M=0.70 \). The plot in the upper right corner represents luminescence intensity.

FIG. 31 shows a Boeing commercial transport wing taken at a wind speed of \( M=0.90 \). The plot in the upper right corner represents luminescence intensity.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention focuses on an oxygen-sensitive luminescent film coating for pressure measurement and mapping of surfaces and methods based thereon. Generally, the purpose of the present invention is to quantitatively map static pressure distribution and provide a new “real-time” flow visualization method for surfaces, especially aerodynamic surfaces. The methods and coatings described herein can be tested both in wind tunnels and in actual flight.

The object to be coated in accordance with the present invention can be any one where surface pressure is desired to be measured or visualized. Preferably, the object will be one that has some aerodynamic application, including airfoils of all types, rotors (e.g., of helicopters), propellers, fixed wings, turbine blades, and the like.

In order for an oxygen-sensitive sensor to produce desired results, it must first be applied to the surface of interest. Aerodynamic testing requires a very thin and smooth surface. For example, in a wind tunnel a thin, smooth surface is required to avoid accidental “tripping” of the airflow over the surface. In general, the luminescence response of the film is independent of thickness, so that even if thickness is non-uniform, the pressure-measuring method described herein could still be used with sufficient accuracy. However, uniform films are preferred.

The specific method to be used for coating is not necessarily limited as long as the desired smoothness of coating is achieved. The preferred method involves an airbrush spraying technique where the reservoir cup is filled with solution containing the sensors and polymer resin. The solution is aspirated using an inert gas which then directs the spray onto the surface.

Other possible methods of producing uniform films are an electrostatic method, a robotics method and a shrink fit method. The electrostatic method involves charging the surface to be painted, and then charging the paint with the opposite charge so that the paint is attracted to the surface. This method minimizes overspray while producing a thin and uniform coating.

The robotics method involves using a computer-controlled robotics sprayer that is capable of producing very uniform films on non-uniform surfaces. This method might be useful for coating an airfoil with a clear, smooth, and uniform film.

The “shrink-fit method” involves the following steps. First, a clear, smooth, uniform film is prepared by pouring a polymer solution onto a smooth surface (e.g., glass or a solid organic polymeric surface), and allowing it to dry. After drying, the film is peeled off and placed on an airfoil. Employing a shrink-fit method involves tightly wrapping the polymeric film around the airfoil. Then, both are heated and returned to room temperature. This procedure can provide a tight adherence of the polymer to the surface.

The mode of application of the film should generally be such that the resulting films are very thin (preferably approximately 10–20 microns in thickness). Film thickness may be determined using an ultraviolet/visible spectrometer by measuring the optical absorption of a sensor in the film and then applying the well-known Beer’s law. Thickness should not decrease permeability, but rather, should only slow the rate of diffusion and...
therefore the rate of response. Oxygen permeability will vary with the particular polymer chosen. Standard methods of measuring oxygen permeability with particu-
lar polymer films may be used to evaluate the permea-
bility.

The sensor must also be uniformly distributed in the film. For porphyrins, the individual molecules should be separated by at least about 50 Å to prevent triplet-
triplet deactivation. This intermolecular separation cor-
responds to a porphyrin concentration of about 10^{-2} mol-
lar.

Generally, thin, uniform films containing the sensors are prepared using precursor compositions comprising the sensors dissolved in a solvent along with a suitable film-forming material. Functionally, the solvent must be able to dissolve the sensor molecule and be sufficiently volatile to produce a smooth film. The solvent is prefer-
ably a volatile organic material that will dissolve the sensors and evaporate within a convenient time after application of the composition onto the surface. The specific nature of the solvent is not critical for the pur-
poses of the present invention and may range over a wide variety of materials. Nonlimiting examples of the solvent are 1,1,1-trichloroethane, butyl alcohol, and isopropyl alcohol.

Thin films are also not believed to be limited except that they must be sufficiently oxygen permeable so that an oxygen-containing gas can quench lumines-
cence of the sensors contained in the film during pres-
sure measurements and they must be compatible with the sensors they contain. Generally, the film-forming material will produce the film on the surface of the object upon evaporation of the solvent. Thus, the film-
forming material will preferably be chemically identical to the final film material itself, dissolved in a solvent. However, the film-forming material may also be a film precursor, such as an oligomer that forms the final film during or after evaporation of the solvent. Film forma-
tion may occur as a result of chemical reaction of a precursor with constituents of air, the action of heat or light on the precursor, or chemical interaction of differ-
ent precursor molecules contained in the solvent, etc. In a particularly preferred embodiment, a silicone polymer is employed as the film-forming material. For example, a thermoplastic silicone copolymer, such as Petrarch MB or a dimethyl polysiloxane polymer solution (e.g., GP-197, Genesee Polymers Corporation), may be used as the film-forming materials. In this example, upon evaporation of the solvent, the final polymeric film is deposited without any significant chemical reaction taking place. Silicone co-polymers such as silicone-pol-
yurethane or silicone-polyester co-polymers may also be used as the film-forming polymers.

Fortuitously, it has been discovered that if the surface of the object to be coated with the luminescent film described above is first rendered white, the emitted luminescence is brighter than if the surface is other than white, e.g., a black surface. In fact, the luminescence is almost undetectable when the film covers a black sur-
face. Although not wishing to be bound by a particular theory of operation, the inventors believe that a white background provides a reflective surface off of which unabsorbed exciting light can scatter back into the film containing the sensor. The light, therefore, has a second chance to excite a sensor molecule. The enhancement effect is so large, it is suspected that many of the pho-
tons make multiple passes through the film due to total internal reflection properties of the film. The emission from the sensor is also scattered off the white surface so that a detector can detect a larger signal.

The choice of the type of white covering for the backing is important. Some white coatings have been observed to darken after long exposure to air and ultra-
 violet light. Some coatings, when covered by a lumines-
cent film, are susceptible to degradation, either by the exciting light or by singlet oxygen produced in the photochemical reaction of oxygen with the luminescent species (e.g., a porphyrin). Thus, the white covering should be insensitive to the exciting light and/or a sin-
glet oxygen quencher should be added to the covering.

Exemplary white coverings are paints such as Rust-
Oleum White Gloss Paint and Krylon Glossy White Spray Paint (#1501). The Krylon has proved advanta-
geous for the present purposes, as it exhibits the least amount of darkening after extended exposure to the exciting light. For wind tunnel tests, a generic commer-
cial paint, commonly used for painting aerodynamic models may be used for the white backing.

The backing should be as white as possible, since yellowed or beige tones do not produce optimal signal enhancement. It is also contemplated that the white covering could be a composite or a chemical modifica-
tion of the surface, such as an oxide coat, as long as the surface is smooth and is able to increase the lumines-
cence signal.

The sensors of the present invention are roughly divided into three types, represented by sensors A, B, and C. In some embodiments, the luminescence coat-
ings of the present invention will be comprised of sen-
sors A and B, or sensors A, B, and C. The properties of these three types of sensors are as follows:

Sensor A: This sensor produces luminescence at λ_A with an intensity I_A that is dependent on pressure but also has some temperature dependence (for example, platinum octaethylporphyrin (PtOEP) in a silicone pol-

gymer).

Sensor B: This sensor produces luminescence at λ_B with an intensity I_B that is dependent on temperature but which has little or no pressure dependence.

Sensor C: This sensor produces luminescence at λ_C with an intensity I_C that is relatively independent of temperature and pressure.

A preferred type of sensor A is a phosphorescent porphyrin. The most preferred sensor A is platinum octaethylporphyrin, abbreviated herein as PtOEP. This metalloporphyrin produces phosphorescence, the inten-
sity of which can be directly related to the partial pres-
sure of oxygen in the atmosphere based on the theoreti-
cal considerations presented above. The excitation/e-
mission spectrum for PtOEP displays a strong excita-
tion band in the near ultraviolet region of the visible spectrum at approximately 380 nm and a weaker band in the green region at approximately 540 nm. PtOEP phos-
phoresces in the red region of the visible spectrum at approximately 650 nm. PtOEP is the preferred sensor A due to its large phosphorescence quantum yield (ap-
proximately 90%) and its long triplet lifetime (approxi-
mantely 100 microseconds).

Sensor B produces luminescence that is dependent upon temperature but has little or no pressure depen-
dence. Some examples of sensor B are the following: rhodamine B, yttrium vanadate: europium microcrys-
tals, and europium thonyl trifluorocetatoacetonate.

The preferred sensor B is a fluorescent species. The short lifetime inherent to fluorescence can statistically decrease the change of oxygen quenching to the degree
that the luminescence is virtually unaffected by oxygen. The most preferred type of fluorescent species is rhodamine B (a laser dye). Reportedly, rhodamine B has a fluorescent lifetime of only four nanoseconds and a strong fluorescent yield that is dependent on temperature. See Romano et al. Appl. Phys. 49, 527–533 (1989), who have demonstrated the ability of this molecule to be incorporated into a thin film for temperature distribution mapping for biological purposes. FIG. 4 shows a laboratory calibration curve for rhodamine B in silicone resin sprayed onto an aluminum plate covered with white paint taken with the apparatus of FIG. 1. The sample chamber (14) is thermally regulated and temperature is validated with an Omega Model HH71 thermocouple thermometer with digital readout. In FIG. 4, the intensity I at temperature T is ratioed to the intensity I, at temperature T,. (the lowest temperature measured). The slope of a least squares fit is reported as -0.01945 (or approximately 2% per degree C) with an intercept of 1,2499.

The inventors have tried other materials for sensor B. In particular, when yttrium vanadate: europium was utilized in microcrystalline form, no pressure dependence was found. It was discovered that it should be produced in microcrystalline form to shield the metal center from quenching by molecular oxygen. Moreover, phosphorescence surprisingly increased with temperature, roughly 0.8%/°C. Lanthanum oxysulfide: europium microcrystals are also suitable, but they have a smaller temperature response, 0.4%/°C. "Microcrystalline" refers to crystals having a size in the range of about 0.5-2 microns.

Sensor C is a molecular species that luminesces at an intensity that is relatively independent of temperature and pressure conditions. It is contemplated that a luminescent molecule exhibiting little or not temperature dependence of luminescence could be encapsulated into a gas-impermeable polymer (e.g., polyacrylonitrile) to dependence of luminescence could be encapsulated into a gas-impermeable polymer (e.g., polyacrylonitrile) to remove the infrared and near-infrared wavelengths, then through a bandpass interference filter (6) to obtain the appropriate excitation wavelength (e.g., a Melles Griot 50 nm bandpass interference filter centered at 400 nm). In order to form a spatially uniform irradiation beam, the light may be passed through a fiber-optic cable (8) and re-collimated with a lens (10) (e.g., a 4 inch focal length quartz lens). The collimated light then strikes a dichroic mirror (12) (e.g., a Corion dichroic mirror), which reflects light of wavelengths below a cutoff value (e.g., 500 nm) and transmits light of wavelengths above the cutoff value (e.g., 500 nm). The exciting light, after reflecting off the dichroic mirror, is directed through a porthole into a sealed pressure chamber (14), where it impinges on a thin film of the sensors (15); e.g., PtOEP in silicone resin coated onto a white-painted surface such as aluminum. The pressure in the pressure chamber can be carefully controlled for calibration purposes by means of a mechanical pump (not shown) attached to the pressure chamber by pressure tubing. Activation of such a pump and careful adjusting of the valves produces the desired pressure within the chamber. Pressure may be monitored and confirmed by standard pressure-measuring means (e.g., a piezoresistive pressure transducer, Omega Model #FX81, a Granville-Phillips 275 convection gauge or a closed tube manometer).

From the pressure chamber (14), both the reflected light and the luminescence pass out of the pressure chamber porthole. Wavelengths less than the cutoff value are deflected while those greater than the cutoff value are transmitted through the dichroic mirror. The luminescent light then passes through a second bandpass interference filter (16) (e.g., a Melles Griot 50 nm bandpass interference filter centered at 650 nm) and into the detector (e.g., a video camera (18)). Thereafter, the detected luminescent signal is sent to a computer or video recorder for processing (20).
In an apparatus that is not designed primarily for calibration as is the apparatus in FIG. 1, instead of a pressure chamber, the coated object would be in any desired environment in which an oxygen-containing gas is flowing past the object. For example, the object could be in a wind tunnel or could be in the open air.

Generally, the calibration made possible by the inclusion of sensors B and C may be conducted as follows:

For a given area on the surface to be measured, the luminescent intensities of sensors, A, B and C are measured. In order to use sensor B to correct for temperature variation across the surface, it will be necessary to choose a reference temperature. The reference temperature may be in the temperature prevailing across the surface of interest, under ambient "wind-off" conditions. Other convenient temperatures relevant to the pressure measurement may be chosen, such as the high or low extreme conditions. After measuring the intensity of luminescence of sensor B, the pressure measurement is related to pressure of the gas in the pressure chamber, the coated object would be in any environment in which an oxygen-containing gas is flowing past the object. For example, the object could be in a wind tunnel or could be in the open air.

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TARGA-8), may be advantageously employed. The TARGA-8 board digitizes the video signal to 8-bits and stores the image onto 512×480 discrete pixel locations. Preferably, the data is digitized by means of a software package over a specified area. Data from wind tunnel tests has been collected by a Macintosh II computer equipped with a data translation Quick Capture™ frame grabber board. The Quick Capture™ board has a spatial resolution of 640×480 square pixels and also captures 8-bit monochrome images. The software package employed by the inventors in connection with several tunnel tests, Image 2.0, was created by the National Institutes of Health. For purposes of signal averaging, several images may be added together and preferably stored as a 16-bit file. The software has been modified so as to allow ratioing of entire 16-bit files. Following image processing, the modified image may be viewed on screen and a hard copy of the image may be produced.

FIG. 5 shows a schematic image processing sequence. The subject (2) is irradiated with exciting light and the emitted phosphorescence is collected by video camera (4). The image is then digitized by an A/D converter (6) inside a computer (8) and then the processed image is stored. Thereafter, the image is converted to an analog signal by a DAC converter (10) also inside the computer (8), and finally the processed image is viewed on a video monitor (12).

In the above examples, the inventors do not intend to limit the invention to a particular type of camera, computer, software or frame buffer board, etc.

From the above description, and based on the example presented below, the inventors have demonstrated a novel method of qualitative flow visualization representing pressure and temperature changes on the surface of an object.

The following are some additional uses contemplated by the inventors for the compositions and methods disclosed herein:

1. Flow visualization: PtOEP is quenched by oxygen but not by other gases, such as nitrogen, argon, and the like. Therefore, if a non-quenching gas, preferably nitrogen, were forced out through small orifices along the leading edge of, e.g., an airfoil in a wind tunnel, the wind would blow the nitrogen across the wing according to the flow characteristics and cause the luminescence to be brighter where nitrogen came into contact with the porphyrin. (The nitrogen would inhibit quenching by oxygen). The result is a flow pattern characteristic of the particular conditions at the time of the experiment. A distinct advantage of this method over many present methods is the ability of the material to return to its original state immediately following the experiment. The experiment may be repeated time after time with little or not reconditioning required for extended exposure to the exciting light.

2. In-flight studies: It is feasible to use the present methods on airplanes in flight. The coating would be placed on a part of the aerodynamic surface. From inside the plane, the surface would be illuminated by excitation sources and monitored, preferably by video cameras. The experiments would preferably be done at night to avoid interference from stray light. If very bright excitation were used (e.g., flash or lasers synchronized with fast shutters on the video camera), it should be possible to work in the presence of background light.

The following examples are presented to illustrate the advantages of the present invention and to assist one of ordinary skill in making and using the same. These examples are not intended in any way to limit the scope of the disclosure or the protection granted by letters patent hereon.

EXAMPLES

Instrumentation

A schematic of the instrumentation used to verify the assertion that thin films of silicon polymer containing PtOEP will exhibit a luminescence whose oxygen pressure dependence obeys the Stern-Volmer law is shown in FIG. 1. This FIGURE is discussed in detail above.

Materials

The molecular pressure sensor used in this investigation, PtOEP, was selected for its large phosphorescence quantum yield (approximately 90%) and its long triplet lifetime (approximately 100 μs). These characteristics are similar to that of platinum (II) tetraphenylporphyrin, which was reported some time ago. The molecule phosphoresces at approximately 650 nm when irradiated with light of 380 nm.

The PtOEP solution is prepared by mixing 0.10 gram of PtOEP in one liter of Genesee Polymers GP-197 dimethylosiloxane polymer solution. The solution is spray coated onto the surface of interest. The solvent (mainly 1,1,1-trichloroethane) evaporates, leaving a smooth film. Best results are obtained by the application of several thin coats, and allowing each coat to dry between applications. It has also been found that precoating the surface with a commercial epoxy based white spray paint, such as a white Krylon spray paint, prior to PtOEP application greatly increases the luminescence intensity signal as seen by the camera. The PtOEP film, itself, is very thin (between about 10 and 20 μm). Through experimentation, it has been determined that the I/I ratios are not significantly affected by variations in thickness over this range.

Results

Laboratory calibration curves are determined by taking phosphorescence intensity readings (gray level values) of a PtOEP sample over a pressure range of approximately 0.10 to 1.0 atmosphere. Intensity values for a specified square of 100 pixels near the center of the video image are obtained by averaging the values for five different frames at each pressure. The standard deviation for the averaged readings is typically less than one part in two hundred. Dark noise values, taken while the camera lens is covered, are subtracted from intensity readings. The resulting intensity reading at 1.0 atmosphere, or ambient pressure, po, is taken to be Io. The data indicates a nearly linear relationship between I/I vs. p/po as predicted by the Stern-Volmer relation (see FIG. 2). The intercept, A, and the slope, B, are determined by least squares fitting to be 0.32±0.01 and 0.70±0.01, respectively, at an ambient temperature of 23°C. Notice that the sum of A and B is nearly unity.

WIND TUNNEL MEASUREMENTS

I. Tests at NASA-AMES

In order to prove the feasibility of the basic pressure-measuring method employing a single phosphor of type A, PtOEP, under actual operating conditions, wind tunnel tests were conducted at NASA-Ames Research Center in Moffett Field, Calif.
Instrumentation
A schematic of the equipment used in the wind tunnel tests at NASA is shown in FIG. 3. The wind tunnel (2) is an indraft type, capable of reaching wind speeds of Mach number 0.66. The test section (4), with an approximate 18-inch by 18-inch cross section, is made of clear plastic, so that objects may be viewed while undergoing testing. The wing (6) used for the experiment was a NACA-0012 symmetrical airfoil (3 inches in chord and 10 inches in span). A single row of 16 pressure orifices was located across the chord of the wing in the center of the span. When installed in the test section, the wing was fixed at a five degree angle of attack. The entire airfoil was first spray painted with a commercial white epoxy based paint, then spray painted with the PtOEP/silicone resin solution. A positive pressure was applied through tubing connected to the pressure orifices during the painting process so as not to plug the orifices with paint. Air (7) enters the test section for the right-hand side of FIG. 3 and moves to the left-hand side where it exists.

The airfoil in the test section was illuminated from the side, approximately 6 inches from the closest end of the wing. Top illumination was impossible, because the top surface did not pass ultraviolet light. The light source (8) was an Electro-lite Corporation, Model ELC-250 UV lamp. The lamp had its own filter that passed light with wavelengths below 400 nm. The same RCA vidicon camera (10) used for calibration of the porphyrin was used for this experiment. The camera was mounted outside and above the test section, and directly over the airfoil. A 50 nm bandpass interference filter, centered at 650 nm, covered the camera lens. The distance between the airfoil surface and the camera lens was approximately 10 to 12 inches. The TARGA 8 system in the IBM AT computer (12) accessed the data and stored it in a digitized form. A Panasonic black and white monitor (14) displayed both live and digitized images taken by the TARGA 8 frame buffer system.

The controlling software package for the TARGA-8 board was again modified for this experiment to allow averaging of pixel data across a chord of the wing. One hundred frames of data were taken for each of five adjacent rows of pixels. The five rows were then added vertically to produce a single horizontal row of data. Each discrete pixel location thus contained the resulting summation of 500 gray level values. Data was taken for a dark noise reading, a wind-off condition, and a wind-on airfoil. The shock wave on the wing can be seen in the raw luminescence image of FIG. 10. The corresponding luminescence profiles are shown in FIG. 11. The intensity of the PtOEP phosphorescence is greater at the shock wave, because the oxygen partial pressure is less in this area. FIG. 12 shows a calibration curve for p/p₀ versus Io/I for M=0.66. The solid line shows the best linear fit. The large gap between the two sets of data points corresponds to the significant static pressure difference on either side of the shock boundary. The linear correlation of this data is poorer than that of the data for M=0.36. FIG. 13 shows actual pressure data and pressure data predicted from the calibration curve (p'/p₀). On the upwind side of the shock boundary, the luminescence predictions are systematically high, while on the downwind side the predictions are systematically low. This suggests that two calibration curves be used, one for the lower pressure region and one for the higher pressure region. If the pressure ratio information for the trailing edge of the airfoil is fit to a separate line than the pressure ratio data for the leading edge (FIG. 14), a much better correlation to actual data results (FIG. 15).

To compare the variance in the two sets of data, the F ratio is calculated. The F ratio is defined as follows:

\[ F = \frac{S_{1}}{S_{2}} \]

where \( S_{1} \) is the estimated standard deviation of the standard deviation for the dual fits was deter-
In the wind tunnel was approximately 65°F. During degradation of the film. As would be expected for a probability of generating a number this large is less than its respective number of degrees of freedom. The F wind speeds, the use of the dual linear fit greatly im-
molecule whose major dependence on temperature is exciting light was blocked between readings to prevent the same, while the slopes changed significantly. At higher winds, the use of the dual linear fit greatly im-
proves the correspondence between pressures measured directly, and those determined from luminescence intensity data.

In the NASA experiment, ambient room temperature in the wind tunnel was approximately 65°F. During airflow, however, the temperature of the air in the test section dropped to between 50°C and 60°F. Therefore, I_1 and I_2 were not measured at the same temperature. During previous calibration runs in the inventors’ laboratory, the I_1 and I_2 data were taken at the same temperature. Ambient temperature in most cases was near 75°C. As mentioned earlier, the surface temperature across the wing itself varied several degrees from leading edge to trailing edge. From this information, it has been determined that, for future testing, it will be important to know the temperature on the surface of the object to accurately predict surface pressure without the use of pressure taps for calibration. Of course, if a sensor of type B as defined herein is also contained in the coating, a dual linear fit would not be necessary; rather, a correction could be made for temperature variation over the entire surface of the coated object by measuring luminescence of sensor B separately and processing the data as described above.

Significant drift in intensity for the I_1 data indicated possible variations in the light source and/or photodegradation of the porphyrin material. These conditions combined to cause slight inconsistencies between the directly measured p/p_0 values and the p'/p_0 and p*/p_0* values determined from luminescence intensity data. Incorporation of a pressure and temperature independent sensor C would help correct for light source drift.

Summary

The results of the work presented above are summarized as follows. Calibration curves of I_1/I vs. p/p_0 show a nearly linear relation, as theoretically expected. Thin, smooth, uniform films of PtOEP in a silicone resin matrix can be sprayed onto surfaces whose pressure field is desired. A white background for the film greatly enhances signal-to-noise. Ratios of “wind-on” images to “wind-off” images is achieved with image processing hardware and software. The entire process is much more flexible and inexpensive when compared to conventional pressure measuring techniques. The resulting pressures determined from I_1/I_4 data agree with pressure tap measurements to within one percent. PtOEP will degrade after extended exposure to ultraviolet light. However, a fresh coat of PtOEP may be applied on top of the old film, or the film and paint may be stripped, and a new coat of each applied.

The techniques discussed here produce curves indicative of the surface pressure of an aerodynamic object. These results support the feasibility of pressure-mapping aerodynamic surfaces in wind tunnels using luminescence quenching and image processing techniques.

II. Test at Boeing

To better understand and prepare for the types of conditions that might be encountered in actual industrial wind tunnel operations, further wind tunnel tests were conducted in a relatively large transonic wind tunnel at the Boeing Company. The Boeing transonic wind tunnel provided access to higher wind speeds and conditions more representative of actual flight than those found in the smaller model wind tunnel at NASA.

The tests provided valuable insight to the types of situations that would require special attention in actual routine use.

Instrumentation

The Boeing transonic wind tunnel (BTWT) is a closed-circuit single-return system that is vented to the atmosphere (see FIG. 17). The normal continuous-flow operating range is from Mach 0.3 to 1.1 A two-stage fan, powered by a pair of electric motors providing approximately 54,000 horsepower, moves the air in the tunnel. The 8 by 12 foot test section provides the flexibility to test a wide variety of scaled aerodynamic models.

The model initially used for pressure-sensitive paint testing was a Boeing commercial transport half-model, measuring approximately 5 feet from mid-fuselage to wing tip. Half-models are scaled representations of airplanes that have been split on the vertical centerline. Aerodynamicists use half-models, instead of full models, for reasons such as cost efficiency, effective model size enlargement between the rows of pressure taps and Pressure tap readings were collected by electronic pressure scanners to allow for comparison with results obtained from luminescence imaging.

The experimental set-up at BTWT is shown in FIG. 18. The same imaging equipment used at NASA-Ames for wind tunnel testing was used for the Boeing tests. The data acquisition system consisted of the RCA Vidicon camera, the IBM AT personal computer, and the TARGA-8 frame grabber. In addition, a Macintosh II, equipped with a Data Translation QuickCapture™ frame grabber board and modified Image software for image processing, was employed for experimental use in capturing and displaying full frames of data. A Sony CCD, model XC-57, was also used on an experimental basis to determine its sensitivity to the PtOEP emission under actual wind tunnel operating conditions.

The commercial transport half-model possessed several chords of pressure taps drilled into its surface at several locations across the span of the wing. The camera was adjusted so that the top three rows of pressure taps could be captured within one digitized frame. The actual distance between the rows of pressure taps was approximately eight inches. Approximately 20 inches of
the model was visible in one digitized frame. Before installation of the half-model into the wind tunnel, the model's polished steel surface was spray-painted with an industrial white epoxy-based paint. Following positioning in the wind tunnel, and just prior to testing, the half-model was spray-painted with the Genesee silicone resin solution containing PtOEP. As with the NACA-0012 model, positive air pressure was applied through pressure tap tubing during the painting process, so as not to plug the orifices with paint.

Inside the tunnel, the half-model was illuminated by four Electro-lite Corporation, Model ELC-250 UV lamps. The filters covering the light sources passed wavelengths between 300 and 400 nm, and also those above 700 nm. All lamps and cameras were securely attached to a vented wall located just inside the wind tunnel test section. Secure attachment to the structure was essential, as the force of moving air at high Mach numbers was strong enough to dislodge loose articles during wind tunnel operation. Cameras were attached via BNC cables to the IBM AT and Macintosh II computers located outside the wind tunnel.

The Image software used on the Macintosh II computer allowed for each acquired frame of data to be summed into a data base, pixel by pixel. The acquisition and summation process for each frame took place in less than one second. Sixty-four full frames of 8-bit data were collected, added together, and stored as 16-bit files. As with the IBM personal computer, individual files were kept for each of the dark noise, the wind-off, and the wind-on situations.

**EXPERIMENTAL**

The commercial transport half-model, installed in the wind tunnel and coated with the Genesee/PtOEP paint, was ready for luminescence testing. The half-model was draped with a black cloth between tests to reduce photodegradation effects. The Electro-lite lamps were turned on and allowed to warm up prior to testing. After final adjustments had been made, the wind tunnel floor was vacuumeed to reduce the number of dirt particles circulating in the tunnel during testing. Impacts from dirt and small debris cause chips in the paint on the leading edge of the model wing. Chips in the paint convert the smooth laminar flow of air over the wing to turbulent airflow, which is undesirable for this testing. The "cap," or the sliding cover that surrounds the vented side walls and ceiling of the tunnel, remained open for access to the cameras.

Just prior to test initiation, the RCA camera lens was covered, and a dark noise reading was taken with the IBM computer. Sixty-four frames of dark noise data were also recorded and stored on the Macintosh II computer. The camera lens cover was then removed, and the sliding wind tunnel "cap" was sealed. All lights in and surrounding the wind tunnel test section were turned off, with the exception of the excitation light sources. Wind-off readings were recorded on both the IBM and Macintosh computers. Ambient temperature in the wind tunnel test section was also recorded.

Following wind-off data acquisition, the wind tunnel was put into operation. During testing, wind speeds ranged from $M_a = 0.70$ to $M_a = 0.95$. Following stabilization of wind tunnel conditions, wind-on data was recorded on both IBM and the Macintosh computers. Ambient wind tunnel temperature was also recorded. While intensity data was being collected, thermal images of the half-model were also being taken with an Inframetrics infrared camera system. Images taken with the Inframetrics camera were also digitized on the Macintosh II computer and stored for future reference.

When wind-on data acquisition was complete for one run, power to the fans was terminated, and the wind came to a stop. Before the cap was opened, another set of wind-off data was taken with the macintosh II computer. Ambient temperature was recorded. The cap for the tunnel was then opened enough to allow one person in to cover the camera lens. A set of second dark noise data was recorded on the Macintosh II computer. The second wind-off and dark noise readings were taken due to significant ambient wind tunnel temperature increases during tunnel operation. Temperature increase is attributed to heating of the air by the fans used to propel the wind. Ambient temperature increased from approximately 15° C. to approximately 50° C. inside the tunnel during one test. Consequently, the intensity of the wind-off image taken after the test decreased dramatically from the initial pre-test reading. The decreased porphyrin intensity would require correction to achieve correct pressure information. In addition, the cameras and other equipment attached to the vented walls inside the test section also were heated by the wind during the test. The dark noise of the RCA camera, being temperature dependent, increased significantly between pre-test and post-test readings. Increased dark noise readings produced a smaller dynamic range for the intensity data, and consequently less precision in the quantitative results.

The preceding test procedure was repeated for each Boeing transonic wind tunnel test. Data was recorded both on the IBM/TARGA system and the Macintosh/QuickCapture system for each test.

**Results**

Here, $p/p_0$ refers to pressure data taken from pressure taps on the model surface, and $p^*/p_0^*$ refers to pressure data predicted from dual fit intensity information.

Quantitative data for the Boeing tests was collected on the IBM/TARGA image processing system. The TARGA software in the IBM AT computer was programmed so as to collect 100 points of data at each pixel location in a chord both above and below the desired row of pressure taps. The results consisted of dark noise, wind-off ($I_o$), wind-on ($I$) and $I_o/I$ information. A digitized raw image, representing the area of the wing from which one set of data was collected, is shown in FIG. 19. The pressure tap row and the locations where intensity data was taken are indicated with arrows. The actual distance between the two rows where intensity data was collected was approximately ten centimeters. The digitized image of the wing was recorded by the Macintosh II and Data Translation frame grabber board. Sixty-four frames of data were collected and averaged for dark noise, wind-off, and wind-on images. Dark noise was subtracted from both wind-off and wind-on data. The resulting images were then ratioed to produce $I_o/I$ data.

The first step in converting luminescence data to quantitative pressure data was to align the pressure tap information with the intensity data so as to obtain the necessary information for creating calibration curves. Alignment was generally accomplished by plotting $I_o/I$ ratios taken by the IBM system and $C_P$ vs. $C_{p}$. Ambit of chord length. It is readily seen that the two sets of data are directly related and aligned. After converting $C_P$ to $p/p_0$, a calibration curve of $C_{p}^*/C_{p}^*$ vs. $C_p$.
was created. Calibration curves were determined for a wind speed with Mach number 0.86 and an angle of attack of 3 degrees for one pressure tap row. These curves are shown in FIGS. 21 and 22. Notice the similarities in the slopes and intercepts for the two curves. As with the NASA data, the data points for the shock wave and the data for the trailing edge were fit to different curves to account for temperature differences. By the method described above, values for calculated pressure ratios \((p^*/p_o^*)\) were then determined from the appropriate calibration curves. FIGS. 23 and 24 compare the calculated pressures \((p^*/p_o^*)\) and the measured pressures \((p/p_o)\) for the two rows of data taken at a Mach number 0.86 and an angle of attack of 3 degrees. In FIG. 25, the slope and intercept data for the bottom row of intensity data is used to predict \(p^*/p_o^*\) for the top row. The agreement is very good, indicating that, with proper temperature calibration, pressure values over the surface of the wing may be predicted accurately and with good precision using data from limited numbers of pressure tap rows.

Small inconsistencies from pressure tap data do occasionally exist and may have one or more explanations. The most significant one is probably the fact that the shock conditions apparent on the wing are not always stable and actually move back and forth across the chord of the wing to a limited extent. The condition is evident in continuous video recordings of the model in the operating tunnel, and is especially true at high Mach numbers (those above 0.70) and at higher angles of attack (3 to 7 degrees). Averaging of data tends to smooth these unstable flow characteristics. Complete pressure tap data is recorded in less than four seconds, so the shock wave and other pressure conditions may be expected, in some cases, to vary slightly from luminescence data that has been averaged for one minute or more.

Other elements that may cause inconsistencies between pressure tap data and pressure data predicted from intensity information are: 1) camera movement in the wind tunnel; 2) model translation due to high wind conditions; and 3) high temperature effects in the recirculating wind tunnel. Camera movement, caused by vibration of the inner structure during wind-on conditions, may be reduced by mounting the camera to a stable structure not attached directly to the test section floor or walls. Model translation, or moving of the model backwards during airflow, may be corrected during the ratio process. It will be necessary to align the raw \(L_1\) and \(I\) data before beginning the ratio process. It will probably be helpful to put markers on the model in several locations to align the wind-off and wind-on data. High temperatures, resulting from operation of the large tunnel fans, cause a significant decrease in expected wind-on intensity. In some cases, such as the one shown in this example, wind-on data, while displaying characteristic shock wave information, is actually less intense than wind-off data. \(L_1/I\) ratios are therefore greater than unity, as predicted by a high temperature curve. A dark noise reading may be taken following wind tunnel operation to adequately account for increased noise during the wind-on readings.

Images taken with the Macintosh II also provide valuable qualitative information for aerodynamicists. Interesting pressure patterns, not apparent in wind-on images, become obvious upon the ratiing of wind-off to wind-on images. FIG. 26 displays the wind-off image of a larger Boeing commercial transport wing, taken with an 8 mm wide-angle lens. The wing is at an angle of attack of 4 degrees. The two modules attached to the leading edge of the wing (on the right) are nacelles, or engine housings. Local variations in light intensity are readily apparent on the wing’s surface. FIG. 27 displays the wing at the same angle of attack, but at a wind speed of \(\text{M}_w = 0.88\). Some pressure information is visible, but the uneven light intensity on the surface masks some of the pressure patterns. FIG. 28 displays a ratioed image of the wing. Here, the uneven light pattern is completely removed, and the resulting visible patterns represent the true pressure effects. (The white band surrounding part of the upper and trailing edge portion of the wing is due to model translation, which was discussed above). In FIG. 29, false color has been added by the computer to enhance the pressure patterns. Much of the information in this image had never before been accessible with conventional flow visualization methods.

To demonstrate differences in pressure patterns resulting from changing wind speeds, digitized images of another Boeing commercial transport wing at two different Mach numbers are shown in FIGS. 30 and 31. False color has also been assigned to these images to accentuate differences in the pressure distribution. In FIG. 30, the wind speed is \(\text{M}_2 = 0.70\). A narrow shock wave is visible on the leading edge of the wing. At a higher wind speed, drastic differences in pressure distribution over the wing’s surface are realized, as is seen in FIG. 32. The wing is at the same angle of attack (3 degrees), but the wind speed is \(\text{M}_w = 0.90\). Notice the difference in the location and shape of the shock wave. This type of data provides visual information which can be used by aeronautical engineers for immediate “onsite” evaluation of a wing design.

Video recordings of a wing in an operational wind tunnel by means of a video cassette recorder are very valuable for analyzing dynamic pressure information. On several occasions, luminescence data recorded on video tape has provided real-time dynamic information never before seen by conventional methods. For instance, a small dynamic pressure wave on the trailing edge of one Boeing commercial transport wing has been discovered that moves too quickly to be reliably captured by electronic pressure scanners. The existence of this “wavelet” is not yet fully understood, but such discoveries may lead to new aerodynamic design criteria.

**EFFECT OF BACKING ON LUMINESCENT INTENSITY**

The data in Table 1 shows that a white backing greatly enhances observed luminescence:

<table>
<thead>
<tr>
<th>Sample</th>
<th>%I</th>
</tr>
</thead>
<tbody>
<tr>
<td>film sprayed on white paint on aluminum plate</td>
<td>100</td>
</tr>
<tr>
<td>film on aluminum plate</td>
<td>15.0</td>
</tr>
<tr>
<td>film on TLC plate</td>
<td>29.2</td>
</tr>
<tr>
<td>film on clear glass</td>
<td>3.5</td>
</tr>
<tr>
<td>film on black paper</td>
<td>1.2</td>
</tr>
</tbody>
</table>

(Notes: all films were sprayed so as to have approximately the same thickness.)

While the present invention has been described in conjunction with preferred embodiments, one of ordinary skill after reading the foregoing specification will be able to effect various changes, substitutions of equivalents, and alterations of the subject matter set forth.
The method of claim 1, further comprising capturing the luminescences of said sensors from each said coated area with a video camera, digitizing said luminescences, using the digitized image produced by sensor B to calibrate the digitized luminescence produced by sensor A to a reference temperature, thereby producing a calibrated \( I_A \) value for each coated area that can be related to the pressure of said oxygen-containing gas on said surface.

17. The method of claim 16, which further comprises converting said calibrated \( I_A \) value from each area to an analog signal and routing said signal to a video monitor for viewing an image of said surface that indicates the pressure of said gas at each said area.

18. The method of claim 17, wherein said image provides real-time qualitative or quantitative gas flow visualization.

19. The method according to claim 1, which further comprises converting said calibrated \( I_A \) values to a digitized image, a photograph, or a video recording.

20. The method of claim 1, wherein said method is carried out in a wind tunnel.

21. A method of visualizing flow of an oxygen-containing gas over a surface of an object, which comprises:

- providing an object having a white surface coated with an oxygen-permeable film comprising sensor A, wherein upon irradiation of said film by an exciting wavelength of light, sensor A produces luminescence at an emission wavelength \( \lambda_A \) that is dependent on temperature and oxygen pressure;
- causing an oxygen-containing gas to flow over said surface;
- irradiating at least a portion of said surface with \( \lambda_A \) and \( \lambda_B \), while said oxygen-containing gas is flowing over said irradiated surface;
- detecting \( I_A \) and \( I_B \), for a plurality of smaller areas of said irradiated surface, and;
- comparing the \( I_A \) value for each smaller area to the corresponding \( I_B \) value for said smaller area to calibrate said \( I_A \) value to a reference temperature, thereby resulting in an indication of the pressure of said gas on said surface.

2. The method according to claim 1, wherein said sensor A comprises a porphyrin.

3. The method according to claim 2, wherein said porphyrin is platinum octaethylporphyrin.

4. The method according to claim 1, wherein said sensor B comprises rhodamine B.

5. The method according to claim 1, wherein said sensor B comprises yttrium vanadate microcrystals doped with europium.

6. The method according to claim 1, wherein said film comprises a silicone polymer.

7. The method according to claim 1, wherein said oxygen-containing gas comprises air.

8. The method of claim 1, wherein \( \lambda_A = \lambda_B \) and \( \lambda_A \neq \lambda_B \).

9. The method of claim 1, wherein \( \lambda_A \neq \lambda_B \) and \( \lambda_A = \lambda_B \).

10. The method according to claim 1, wherein said irradiating is carried out with a constant light source.

11. The method according to claim 1, wherein said irradiating is carried out by means of a flashing light source.

12. The method according to claim 1, wherein said film is coated on a white aerodynamic surface.

13. The method according to claim 1, wherein said surface is stationary.

14. The method according to claim 1, wherein said surface moves through said gas.

15. The method of claim 1, wherein said comparing step comprises comparing \( I_B \) from each said smaller area of said surface to a first predetermined calibration curve relating luminescence of sensor B and temperature to obtain a measured temperature of each said smaller area, and using a second predetermined calibration curve relating luminescence of sensor A to temperature to calibrate \( I_A \) to a reference temperature, thereby producing a temperature-calibrated \( I_A \) measurement for each said area and relating said ratio to the pressure of said gas for each said area.

16. The method of claim 15, further comprising:

- providing an aerodynamic surface coated with an oxygen-permeable film comprising sensors A and B, wherein sensor A, upon irradiation with exciting wavelength \( \lambda_A \) produces luminescence at an emission wavelength \( \lambda_A \) of intensity \( I_A \) that is dependent on both temperature and oxygen pressure, and sensor B, upon irradiation with exciting wavelength \( \lambda_B \) produces luminescence at an emission wavelength \( \lambda_B \) of intensity \( I_B \) that is dependent on temperature and independent of oxygen pressure;
- causing an oxygen-containing gas to flow over said surface;
- irradiating at least a portion of said surface with \( \lambda_A \) and \( \lambda_B \), while said oxygen-containing gas is flowing over said irradiated surface;
- detecting \( I_A \) and \( I_B \), for a plurality of smaller areas of said irradiated surface, and;
- comparing the \( I_A \) value for each smaller area to the corresponding \( I_B \) value for said smaller area to calibrate said \( I_A \) value to a reference temperature, thereby resulting in an indication of the pressure of said gas on said surface.

22. The method according to claim 21, wherein said sensor A comprises a porphyrin.

23. The method according to claim 22, wherein said porphyrin is platinum octaethylporphyrin.

24. The method according to claim 23, wherein said film comprises a silicone polymer.

25. The method according to claim 21, wherein said luminescence produced by said sensor A at \( \lambda_A \) provides quantitative information on the pressure of said oxygen-containing gas flowing over said surface.

26. A pressure-sensitive composition, which comprises a solvent containing therein a plurality of sensors comprising sensors A and B, wherein upon irradiation by an exciting wavelength of light, sensor A produces luminescence that is dependent on temperature and oxygen pressure, and sensor B produces luminescence that is independent of oxygen pressure and dependent upon temperature; and molecules that form an oxygen-permeable film containing said sensors upon evaporation of said solvent.

27. The pressure-sensitive paint according to claim 26, wherein sensor A comprises a porphyrin.
28. The pressure-sensitive paint according to claim 27, wherein said porphyrin is platinum octaethylporphyrin.

29. The pressure-sensitive paint according to claim 27, wherein said sensor B comprises rhodamine B.

30. The pressure-sensitive paint according to claim 26, wherein said solvent is a volatile organic liquid.

31. The pressure-sensitive paint according to claim 26, wherein said molecules form a silicone polymer upon evaporation of said solvent.

* * * *
UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,341,676
DATED : August 30, 1994
INVENTOR(S) : Gouterman et al.

It is certified that error appears in the above-indicated patent and that said Letters Patent is hereby corrected as shown below:

On title page, item

<table>
<thead>
<tr>
<th>Column</th>
<th>Refs. Cited</th>
<th>Line</th>
<th>&quot;AIAA&quot; should read —AIAA—</th>
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<td>&quot;Inventors&quot; should read —inventors—</td>
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<td>9</td>
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<td>9</td>
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<td>45</td>
<td>&quot;an&quot; should read —and—</td>
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<td>15</td>
<td>&quot;generally&quot; should read —general—</td>
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<tr>
<td>10</td>
<td></td>
<td>27</td>
<td>&quot;Orien&quot; should read —Oriel—</td>
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<tr>
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<td>55</td>
<td>&quot;rij&quot; should read —rij—</td>
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<td>12</td>
<td></td>
<td>67</td>
<td>&quot;PC/At&quot; should read —PC/AT—</td>
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<tr>
<td>13</td>
<td></td>
<td>37</td>
<td>&quot;used&quot; should read —uses—</td>
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</table>

After "Callis, both of Seattle" insert —;David H. Burns, Seattle, Gamal-Eddin Khalil, Bellevue—
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

<table>
<thead>
<tr>
<th>COLUMN</th>
<th>LINE</th>
<th>Amendment</th>
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<tbody>
<tr>
<td>13</td>
<td>55</td>
<td>&quot;not&quot; should read &quot;no&quot;</td>
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<tr>
<td>17</td>
<td>10</td>
<td>&quot;mover&quot; should read &quot;more&quot;</td>
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<tr>
<td>18</td>
<td>15</td>
<td>&quot;Test&quot; should read &quot;Tests&quot;</td>
</tr>
<tr>
<td>20</td>
<td>65</td>
<td>After &quot;C_p&quot; (first occurrence), insert &quot;data, measured from pressure taps, on the same graph. FIGURE 20 displays a plot&quot;</td>
</tr>
</tbody>
</table>

Signed and Sealed this Tenth Day of January, 1995

Attest:

BRUCE LEHMAN
Attesting Officer
Commissioner of Patents and Trademarks
UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,341,676
DATED : August 30, 1994
INVENTOR(S) : Gouterman et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

<table>
<thead>
<tr>
<th>COLUMN</th>
<th>LINE</th>
<th>Original Text</th>
<th>Corrected Text</th>
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<tr>
<td>[75]</td>
<td>3</td>
<td>Inventors After &quot;Callis, both of Seattle&quot; insert --; David H. Burns, Seattle; Gamal-Eddin Khalil, Bellevue--</td>
<td>After &quot;Callis, both of Seattle&quot; insert --; David H. Burns, Seattle; Gamal-Eddin Khalil, Bellevue--</td>
</tr>
<tr>
<td>[73]</td>
<td>8</td>
<td>Assignee &quot;The Board of Regents&quot; should read --Board of Regents of The University of Washington--</td>
<td>&quot;The Board of Regents&quot; should read --Board of Regents of The University of Washington--</td>
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<tr>
<td>[56]</td>
<td>Refs. Cited (Publ. 9)</td>
<td>&quot;AIAA&quot; should read --AIAA--</td>
<td>&quot;AIAA&quot; should read --AIAA--</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>&quot;Inventors&quot; should read --inventors--</td>
<td>&quot;Inventors&quot; should read --inventors--</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>&quot;conditions&quot; should read --condition--</td>
<td>&quot;conditions&quot; should read --condition--</td>
</tr>
<tr>
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<td>9</td>
<td>&quot;not&quot; should read --no--</td>
<td>&quot;not&quot; should read --no--</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>&quot;sue&quot; should read --use--</td>
<td>&quot;sue&quot; should read --use--</td>
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<tr>
<td></td>
<td>9</td>
<td>&quot;an&quot; should read --and--</td>
<td>&quot;an&quot; should read --and--</td>
</tr>
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<td>10</td>
<td>&quot;generally&quot; should read --general--</td>
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</tbody>
</table>

Signed and Sealed this
Eleventh Day of April, 1995

Attest:

[Signature]

BRUCE LEHMAN
Commissioner of Patents and Trademarks

Attesting Officer