A simultaneous luminescence pressure and temperature mapping system is developed including improved dye application techniques for surface temperature and pressure measurements from 5 torr to 1000 torr with possible upgrade to from 0.5 torr to several atmospheres with improved camera resolution. Adsorbed perylene dye on slip-cast silica is pressure (oxygen) sensitive and reusable to relatively high temperatures (~150°C). Adsorbed luminescence has an approximately linear color shift with temperature, which can be used for independent temperature mapping and brightness pressure calibration with temperature.
FIG. 1
$K_0 = 0.0011 \text{ l/torr}$

$a = -0.0023 \text{ l/C}$

$b = -0.0040 \text{ l/C}$

FIG. 2

$\frac{I_g}{I_{oo}}$

FIG. 3

$c = 0.0024 \text{ l/C}$
Applicable Range

FIG. 5a

Ro

3.0
2.5
2.0
1.5
1.0
0.5
0

absorbed film thickness, arb. units

FIG. 5b

c (1/C)

Ko (1/torr)
FIG. 7c

pressure, torr

FIG. 7d

temperature, C

data points

FIG. 7c

FIG. 7d

5,818,057
1. Technical Field of the Invention

The present invention relates generally to pressure and temperature mapping systems, and more particularly to simultaneous temperature mapping systems for use at high temperatures.

2. Discussion of the Related Art

Advanced diagnostic techniques capable of nonintrusive global measurements of aerodynamic pressure and heating distributions on models tested in hypersonic wind tunnels will significantly enhance the design and assessment process of future aerospace vehicles. Considerable progress has been made in measuring global temperature distributions with time, hence global heating distribution, via relative intensity thermographic phosphor and infrared emission techniques, but global pressure measurements at hypersonic conditions continue to elude experimental aerothermodynamicists.

Pressure mapping techniques using photoluminescence offer a potential savings in time and expense for wind-tunnel testing over conventional pressure instrumentation (i.e., discrete measurements via transducers) and are sought for hypersonic wind-tunnel applications.

Luminescence pressure mapping techniques have been developed and tested broadly by government agencies, industries, and universities for low-speed applications. Current techniques use oxygen sensitive luminophores in polymer binders for pressure sensitive paints which can be applied to a variety of surfaces. Paint applications, however, are limited in high-temperature stability and time response by polymers. Temperature effects on induced luminescence further complicate pressure measurements in high-speed application with aerodynamic heating. Recent work was done to calibrate temperature effects on paint luminescence for wind-tunnel measurements using separate temperature mapping data. The results of this work and similar applications may expand near-term testing capabilities for relatively low enthalpy, long test duration facilities, but innovative solutions are needed for the bulk of hypersonic testing (i.e., M>6, moderate to high enthalpy, blowdown and impulse facilities) including an internal method for thermal calibration, higher-temperature stability and faster response times.

It is accordingly an object of the present invention to provide a system for simultaneously mapping temperature and pressure.

It is another object of the present invention to provide a system for simultaneously mapping temperature and pressure at high temperatures.

It is a further object of the present invention to provide a system for simultaneously mapping temperature and pressure with reduced response time.

It is another object of the present invention to provide a system for simultaneously mapping temperature and pressure which is suitable for use in hypersonic facilities.

Additional objects and advantages of the present invention are apparent from the drawings and specification which follow.

SUMMARY OF THE INVENTION

According to the present invention, the foregoing and additional objects are obtained by providing a method for simultaneous mapping of temperature and pressure on an article, including the steps of applying a luminescent material, preferably perylene, to the surface of the member, exciting the luminescent material, measuring the resulting emissions, and determining the pressure and temperature on the surface of the member. The luminescent material may be excited using a blue light or long-wave ultraviolet light and the resulting emissions are measured using a two-color imaging system. The preferred method for applying the luminescent material is polishing the surface of the member, saturating the surface with the luminescent material, heating the saturated member, and repoling the heated member. The member may be a slip-casted ceramic.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a figure showing the mounting of test samples; FIG. 2 is a graph showing emission brightness vs. pressure model at constant temperatures; FIG. 3 is a graph showing ratio difference vs. temperature; FIG. 4 is a graph showing color ratio data versus temperature; FIG. 5a is a graph showing temperature sensitivity and quenching constants vs. absorbed film thickness; FIG. 5b is a graph showing reference color ratio vs. adsorbed film thickness; FIG. 6a is a graph showing time vs. data points; FIG. 6b is a graph showing irradiance vs. data points; FIG. 6c is a graph showing pressure vs. data points; FIG. 6d is a graph showing temperature vs. data points; FIG. 7a is a graph showing color ratio vs. data points for sample region 2; FIG. 7b is a graph showing brightness vs. data points for sample region 2; FIG. 7c is a graph showing pressure vs. data points for sample region 2; FIG. 7d is a graph showing temperature vs. data points for sample region 2; FIG. 7e is a graph showing pressure vs. data points for sample region 3; FIG. 7f is a graph showing brightness vs. data points for sample region 3; FIG. 7g is a graph showing ratio data versus temperature; FIG. 7h is a graph showing luminescence pressure vs. data points; FIG. 7i is a graph showing luminescence pressure vs. data points.
FIG. 10b is a graph showing absolute pressure uncertainty for various imaging resolutions.

DETAILED DESCRIPTION OF THE INVENTION

The effects of oxygen interaction on luminescence yields and lifetimes are well documented for many substances; since oxygen is an active quencher of fluorescence and phosphorescence. For some materials, quenching rates and efficiencies are large enough to make them useful as oxygen indicators. Theory predicts the quenching process to obey the Stern-Volmer equation:

\[
\frac{I}{I_0} = 1 + K_0 [Q] \left(1 + \frac{1}{\lambda}(h)\right) \frac{P}{Q}
\]

for constant temperatures, where \(I_0\) and \(I\) are the fluorescence intensities in the presence and absence, respectively, of oxygen. In a mixed gas such as air, the oxygen concentration \([O_2]\) is simply replaced by the partial gas pressure. \(K_0\) is the oxygen quenching coefficient which can be calibrated for many different luminescent materials.

Few guidelines exist for luminescence temperature dependence in oxygen sensors. Temperature is known, however, to affect quantum yield, quenching (Stern-Volmer) coefficient, and solubility and diffusion rates in binders.

Following initial luminescence measurements and calibration on ceramic test samples, perylene dye was applied to ceramic models and tested in a hypersonic wind tunnel. Models tested included a 0.02 scale model of a proposed personnel launch vehicle (HL-20) and a 0.0075 scale shuttle orbiter model. Both models represent configurations that had been previously slip-cast and tested using two-color luminescence thermography and infrared mapping techniques. The luminescent perylene dye (Greengold) has reported 3s connectors in a ceramic block with butt-welded 0.076-mm diameter type K thermocouple wire and 0.51-mm diameter leads. As many as 5 test samples were mounted per test.

Through a test chamber window, image sampling regions are indicated in FIG. 1 with numbers 1 through 4. Region 1 is taken from an analysis sample prepared with low dye concentration. Regions 2 and 3 are from a test sample with optimum dye concentration and region 4 is taken from a test sample with much greater dye concentration. The test chamber was constructed from a 20.5-cm-diameter pipe, lined with 2.54-cm thick low-density alumina ceramic insulation, fitted with an electrical resistance heater and O-ring sealed with a 2.54-cm thick quartz viewing window.

Chamber pressure was controlled via a vacuum pump and venting to atmosphere and was measured with a 1000 torr variable capacitance pressure transducer and Hastings vacuum gage down to 0.1 torr. Chamber insulation was effective in providing stable temperatures up to 150°C, taking approximately 4 to 6 hours for the chamber to cool from 150°C to room temperature at 0.5 torr.

Measurements made in the vacuum oven revealed an approximately linear shift in quantum efficiency \(I_0\) and quenching coefficient \(K_0\) in Equation (1) with temperature. Experimental data could be approximated to first order from Eqn. (1) for green brightness measurements as

\[ \frac{I}{I_0} = \frac{(1 + \alpha T)}{1 + K_0(1 + \beta T)} \]

where \(I_0\) is a calibration coefficient for reference brightness at zero pressure and temperature, \(\alpha\) and \(\beta\) are temperature constants for quantum yield and oxygen quenching and \(K_0\) is the quenching constant at zero temperature with \(P\) being measured air pressure, assuming constant oxygen ratio. A
plot of Eqn. (4) with experimentally derived constants is shown in FIG. 2 for air pressure at constant temperatures. An approximately linear shift in emission color with temperature was observed from adsorbed perylene dye from $20^\circ$ C. to $150^\circ$ C. with a two-color imaging system. This characteristic was not expected but is highly desirable for temperature measurement and calibration. This allows for development of a system with a single dye application and simplifies filtering of broadband emission for diagnostics. In addition, color-ratio measurements were found to be independent of pressure and excitation irradiance. A linear approximation for green-to-red brightness ratio with temperature is given as

$$\frac{I_2}{I_1} - R_0 = cT$$

where $c$ is the color-ratio temperature sensitivity and was found to be constant over a broad range of applications. $R_0$ is a calibration coefficient for color ratio at zero temperature and was found to vary from sample to sample with apparent film thickness. A plot of Eqn. (5) is shown in FIG. 3 for temperature with experimentally derived constant $c$.

Image sampling regions consisted of 10x10 element pixel arrays and were averaged and treated as point data. Individual brightness response was calibrated separately for each sample region and color using a calibrated uniform intensity light source, or integrating sphere, with micrometer controlled aperture brightness and 2855K color temperature. Intensity light source, or integrating sphere, with micrometer controlled aperture brightness and 2855K color temperature. (Photometric units in candelas/m²).

Data was taken simultaneously for regions 1 through 3 in a recent experiment (see FIG. 6), and from a previous experiment for region 4, in which temperature, pressure and excitation irradiance were varied. Experiment results are shown in FIG. 4 for color ratio data versus temperature. Color-ratio bias (coefficient $R_0$ in Eqn. (5)) is shown to vary from regions 2 to 3 on the same sample disk. Sensitivity coefficient ($c$ in Eqn. (5)) is shown to vary, however, to be constant for regions 2 through 4, approaching zero in region 1 for thinner adsorption. Determination of quenching constants showed similar values for regions 1 through 3 ($K_0=0.001$ torr⁻¹), and much lower value for region 4 ($K_0=0.0005$ torr⁻¹).

From this data and similar observations FIGS. 5(a) and (b) were constructed as a guide for future dye applications. Stable values of temperature sensitivity and quenching constants ($c$ and $K_0$) are shown to exist over a range of film thicknesses. Irradiance was varied. Experiment results are shown in FIG. 4 for color ratio data versus temperature. Color-ratio bias coefficient $R_0$ in Eqn. (5) is shown to vary from regions 2 to 3 on the same sample disk. Sensitivity coefficient ($c$ in Eqn. (5)) is shown to vary, however, to be constant for regions 2 through 4, approaching zero in region 1 for thinner adsorption. Determination of quenching constants showed similar values for regions 1 through 3 ($K_0=0.001$ torr⁻¹), and much lower value for region 4 ($K_0=0.0005$ torr⁻¹).

Values of $K_0$ used in uncertainty calculations were 200, 1000 and 4000, respectively, for the present imaging system and performance estimates for 10-bit and 12-bit systems. FIGS. 10 (a) and (b) show calculations using Eqn. (6), and $K=0.001$ torr⁻¹ at $25^\circ$ C., for relative pressure uncertainty in vacuum and absolute uncertainty over full range. Calculations show that the present system is operable from 5 torr to 1000 torr with greater than 1 signal-to-noise and from 0.5 torr to several atmospheres with higher imaging resolution.

Relatively bright luminescence was observed from adsorbed perylene dyes with blue-light excitation for temperatures up to $150^\circ$ C. and greater in vacuum and atmospheric, and was measured using standard video. Comparative applications of a porphyrin dye were vaporized or permanently quenched under similar test conditions. A plot of Eqn. (4) with experimentally derived constants is shown in FIG. 2 for air pressure at constant temperatures. In subsequent testing and later in wind-tunnel applications, pressure and temperature data are derived from Equations (4) and (5) in the following manner. First it is assumed that $K_0$, $a$, $b$, and $c$ are constants which can be applied to all points on a sample or model surface. In a typical application, a "wind-off" measurement is first made for static pressure, temperature and separate color brightness
What is claimed is:

1. A method for simultaneous mapping of temperature and pressure on a member, comprising:
   applying exactly one luminescent material to the surface of the member;
   exciting the luminescent material;
   measuring the resulting emissions; and
determining the pressure and temperature on the surface of the member.

2. The mapping method of claim 1 wherein the luminescent material is perylene dye.

3. The mapping method of claim 1 wherein the luminescent material is excited using a blue light.

4. The mapping method of claim 1 wherein the luminescent material is excited using long-wave ultraviolet light.

5. The mapping method of claim 1 wherein the emissions are measured using a two-color imaging system.

6. The mapping method of claim 1 wherein the luminescent material is applied by:
   polishing the surface of the member;
saturating the surface with the luminescent material;
heating the saturated member; and
repolishing the heated member.

7. The mapping method of claim 1 wherein the member is a ceramic model.

8. The mapping method of claim 7 wherein the ceramic model is a slip casted ceramic.