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MEASUREMENT OF PRESSURE DISTRIBUTION BY MEANS OF INDICATOR COATINGS

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One of the most important problems of experimental aerodynamics is the investigation of the pressure distribution over the surface of a model. Such investigations are necessary both in order to understand the pattern of gas flow over the model and in order to determine the load on aircraft structures and control elements, as required for structural design purposes.

At present tapped models are used for solving this problem. The tappings are connected by tubes with various transducers [1]. When models of complex shape are being investigated, it is often necessary to measure the pressure at hundreds of points, in particular on thin moving wings and control surfaces. The use of pressure commutators for this purpose is not a complete solution, since it remains necessary to construct a tapped model and, moreover, the distribution obtained is discrete and does not give a continuous picture.

Even more complicated is the problem of measuring the pressure distribution over the surface of a rotating propeller or turbine or compressor blade. The high cost of tapped models and the complexity of the experiment limit the possibilities to gravimetric measurements.

Recently, therefore, a number of authors have attempted to develop new methods of investigating pressure. In [2] the tappings in the model were connected by tubes to the wall of the tunnel, where the outlets were closed by a membrane. The membranes were exposed to a coherent light beam. As the pressure varied, the membranes were deflected, which led to a change in the form of the interferograms. However, in this case, too, tapping tubes are necessary, which limits the number of measuring points. At the same time, methods using pressure-sensitive coatings capable of giving a continuous distribution pattern have also been proposed.

In this connection, an attempt has been made to use the pressure dependence of the selective light scattering by liquid crystal films [3]. The low sensitivity of the available films to pressure and their high sensitivity to temperature and shear led the authors to the conclusion that on the pressure-measurement interval $0-3 \cdot 10^5$ Pa necessary in wind tunnels, the available films cannot be used.

To investigate the pressure distribution in high-entropy flows it has been proposed [4] to use the pressure dependence of the melting point of certain thermal indicators.

However, so far it has not been possible to develop thermal indicators with an adequate pressure dependence of the melting point. The main obstacle is the fact that as the pressure dependence of the melting point increases so does the sublimation rate.

In this article we examine a method of investigating the pressure distribution based on the fact that oxygen molecules quench the luminescence of the organic luminophores acriflavine and beta-aminoanthraquinone [5].

There are two ways of explaining the process of quenching of the luminescence brightness of excited organic luminophores by oxygen molecules. One is based on the assumption of a chemical reaction between the excited luminophore molecules and the oxygen, and the other on the assumption of resonant energy transfer.

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For continuous illumination the luminescence quenching process can be described by the relation [6]: $J(p) = J_0(1 - Kn\theta_0)$, where J_0 is the brightness of the luminescence in the absence of oxygen, $J(p)$ is the brightness at the pressure p; K is the equilibrium constant; n_o is the concentration of the oxygen molecules dissolved in the indicator film; and θ is the order of the reaction with respect to oxygen. In the case of a bimolecular reaction between the oxygen molecules and the excited luminophore molecules $\theta = 1$. In accordance with Henry's law, $n_o = ryp$, where r is the solubility of the oxygen in the indicator film; y is the mole fraction of oxygen in the gas; and p is the pressure of the gas flow at the point in question. In this case, $J = J_0(1 - K(ryp)^\theta)$.

For pulsed illumination the luminophore molecules are excited only during the illumination interval. At the end of the pulse the excited molecule concentration and the brightness of the luminescence decrease for two reasons: owing to the quenching of excited molecules by oxygen molecules and owing to radiative deactivation. Assuming that the decrease in brightness is determined by the simple superposition of these processes, we write

$$dn = -\left(n + vnn_o^\theta\right) d\tau, \quad n = n_i \exp\left(-\left(v\tau_0 n_o^\theta + 1\right)\tau/\tau_0\right),$$

where n is the concentration of excited luminophore molecules in the indicator film; v is the rate of quenching of the excited molecules by oxygen; τ is time, and $\tau = 0$ at the end of the excitation pulse; n_i is the initial excited molecule concentration at the end of the excitation pulse; and τ_0 is the radiative deactivation constant. The decrease in the brightness of the indicator films with increase in concentration implies that the order of the reaction with respect to the luminophore is equal to 1. As shown in [7], this effect is associated with the formation of dimers. Neglecting the absorption of the emitted light in the thin indicator film, we may assume that the brightness of the luminescence is proportional to the number of excited molecules per unit surface area:

$$J = \frac{\omega n\delta}{\tau_0} = \frac{\omega n_i\delta}{\tau_0} \exp\left(-\left(\tau_0 v n_o^\theta + 1\right)\tau/\tau_0\right),$$

where J is the brightness of the luminescence; δ is the thickness; and ω is the quantum yield of the luminescence. In more general form, $J = J_0 \exp\left(-f(p)\tau/\tau_0\right)$, where J_0 is the brightness of the film luminescence at the time $\tau = 0$; and f(p) is a function that depends on the law of quenching of the luminophore by oxygen. For $v = \text{const}$, $\theta = 1$

$$f(p) = bp + 1, \; b = vy\tau_0 r. \tag{1}$$

The sensitivity of the method $dJ/dp = -\frac{J_0\tau}{\tau_0}\left(f'(p) \exp\left(-f(p)\frac{\tau}{\tau_0}\right)\right)$ reaches a maximum at $\tau_{max} = \tau_0/f(p) = \tau_0/(bp + 1)$.

In the present study the pressure distribution over the model surface was determined by recording the brightness of the coating luminescence on film as it varies with the pressure. In order to obtain the necessary sensitivity, the model was photographed with a time lag after being illuminated by the exciting light pulse. The photographic density was a function of the brightness of the indicator luminescence and, in the last analysis, of the pressure at the corresponding point on the model surface:

$$D = D_0 + \gamma \lg\left(c \int_{\tau_d}^{\tau_d+\tau_e} J_0 \exp\left(-f(p)\,\tau/\tau_0 d\tau\right)\right),$$

where D_0 is the fog density; γ is the gamma value; D is the photographic density of the negative at the point (x, z); τ_d is the time lag reckoned from the triggering of the flash to the opening of the camera shutter; τ_e is the exposure; and c is a constant. In order to determine the pressure, it is necessary to photograph the model at various pressures in the working section of the tunnel. From the photographic densities it is possible to construct a calibration curve $D = \varphi(p)$, which can be used to interpret the negative obtained by photographing the model under the same conditions but in the flow. However, the density depends on J_0 and hence on the thickness of the indicator film and the illumination of each point of the model by the exciting light. This method of interpretation is laborious due to the need to construct a calibration curve for each point on the model surface. Since

$$D = D_0 + \gamma \lg (cJ_0\tau_0) - \gamma \lg f(p) + \gamma \frac{f(p)\tau_d}{\tau_0} \lg e + \\ + \gamma \lg (1 - \exp(-f(p)\tau_e/\tau_0)), \tag{2}$$

$dD/d\tau_d = \gamma f(p) \log e/\tau_0$ does not depend on J_0 and hence on the exposure to the exciting light and the thickness of the indicator film.

The following methods of interpretation are employed. After illumination by the light pulse the model in the flow is photographed several times with different time lags and the same exposures. If by means of a microdensitometer we subtract from the density of one photograph the density of another, we obtain

$$D' - D'' = \gamma f(p)(\tau'_d - \tau''_d) \lg e/\tau_0, \tag{3}$$

and given condition (1), $p = ((D' - D'')\tau_0/\gamma(\tau'd - \tau''d) \log e - 1)/b$. In this case it is necessary to know the gamma value of the negatives. If we again photograph the model after illumination with the same light pulse, reducing the aperture ratio of the lens by $m = 1.5$-3 times, or photographed through a neutral filter, and then find points on the photographs with the same densities (obtained for different time lags), then for these points we have

$$f(p) = \tau_0 \lg m/(\tau'_d - \tau''_d) \lg e. \tag{4}$$

Given condition (1), $p = (\tau_0 \log m/(\tau''d - \tau'd) \log e - 1)/b$. In this case, it is not necessary to use a linear interval of the characteristic density curve of the negative; it is only necessary that the photographs be taken at the time $\gamma \neq 0$. However, this method is clumsy, since it requires the analysis of a large number of photographs.

Subtracting the density of a negative obtained by photographing the model at the same pressure over its entire surface p_{0s} (without a flow) from the density of the corresponding points of a photograph of the model in the flow for $f(p)\tau_e/\tau_0 \ll 1$, we obtain $f(p) = \alpha p_{0s} + \beta(D_{0s} - D)$, where α and β (the constants for the two photographs) are determined from the known pressures at the two points, which can be measured by means of a tap. Given condition (1),

$$p = \alpha_1 p_{0s} + \beta_1(D_{0s} - D). \tag{5}$$

From Eq. (1) it follows that when $f(p) = bp + 1$, $dD/dp = -\gamma(b\tau_d/\tau_0) \log e$, i.e., the sensitivity increases with increase in the time lag. However, as the time lag increases, the exposure $\int_{\tau_d}^{\tau_d+\tau_e} J d\tau$ decreases due to the decrease in the brightness of the luminescence of the indicator film and when it reaches certain values γ begins to tend to zero. As τ_d decreases the exposure increases, and when it reaches certain values γ again tends to zero. Accordingly, it is necessary to select values of the exposure and hence τ_d corresponding to a linear interval of the dependence $D = D_0 + \gamma \lg \left(c \int_{\tau_d}^{\tau_d+\tau_e} J d\tau \right)$. Relations (3)-(5) are valid if equilibrium has been established between the concentration of the oxygen adsorbed in the coating and the gas flow pressure for each point of the model surface. The time, reckoned from the moment of introduction of the model into the flow or from the moment of stabilization of the tunnel conditions, in which this equilibrium is established with given accuracy, can be estimated from the relation

$$\varepsilon = (p - p(\tau))/(p - p_i) = \exp(-\alpha_m \tau/r\delta),$$

where ε is the given measurement accuracy; p is the pressure measured at the point of total equilibrium; $p(\tau)$ is the pressure measured at the time τ; p_i is the pressure before the introduction of the model into the flow; and α_m is the mass transfer coefficient. Since the necessary stabilization time $\tau \geq -\delta r \ln \varepsilon/\alpha_m$ is inversely proportional to α_m, it will have its greatest value when the flow velocity is equal to zero. The time that the model must spend in the flow before illumination can be determined experimentally beneath the vacuum bell of a laboratory rig.

For luminescent indicator films based on acriflavine or beta-aminoanthraquinone introduce into a matrix consisting of silochrome, starch, sugar, and polyvinylpyrrolidone, the thickness of the coating did not exceed 40 μm. In this case the time required for the oxygen concentration in the film to stabilize within 2% was not more than 2 min.

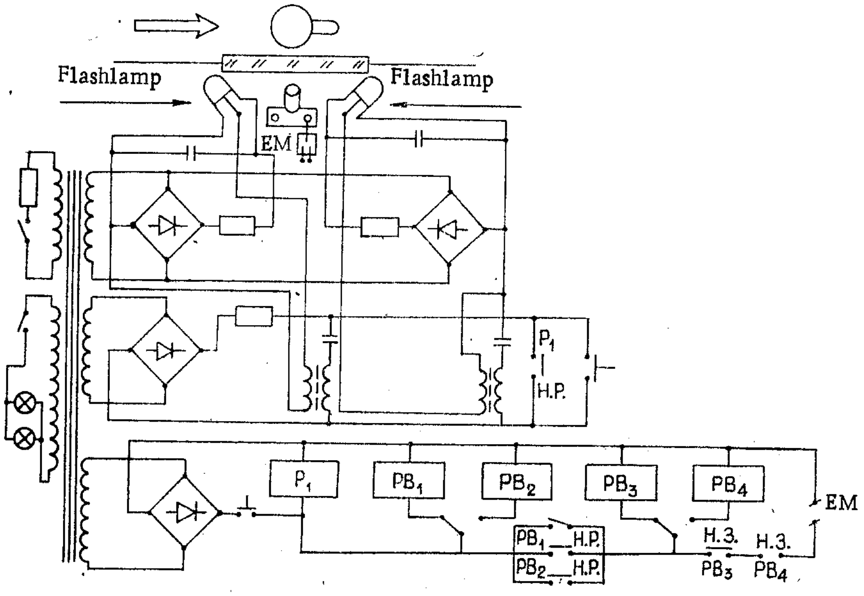

Fig. 1

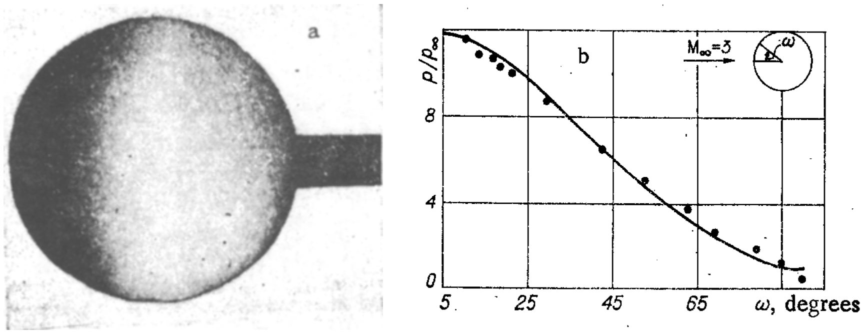

Fig. 2

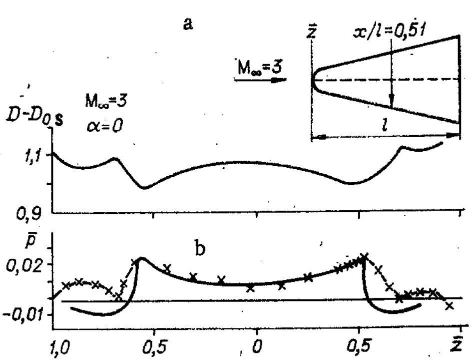

Fig. 3

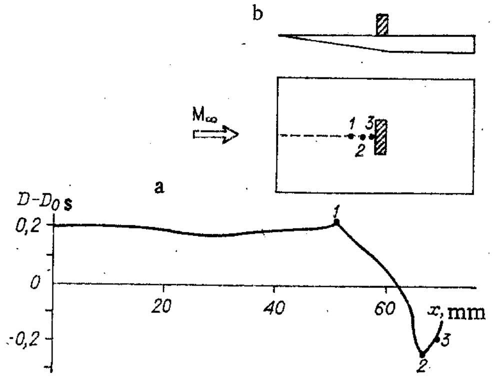

Fig. 4

Furthermore, Eqs. (3)-(5) are valid if the measurement error Δp due to the flow of oxygen through the indicator film is sufficiently small. By analogy with [8] this error can be estimated using the relation

$$\Delta p = \frac{\delta d}{r\alpha_m}(\partial^2 n_e/\partial x^2 + \partial^2 n_e/\partial z^2),$$

where d is the diffusion coefficient. In order to calculate the measurement error from this relation, it is necessary to have the values of $\partial^2 n_e/\partial x^2$ and $\partial^2 n_e/\partial z^2$, which are not known before the experiment; accordingly, this relation can be used only after carrying out the experiment, it being sufficient to estimate the error solely at the points with the greatest concentration gradient (at the points with the greatest photographic density gradients) and thereby check whether the measurement error is significant.

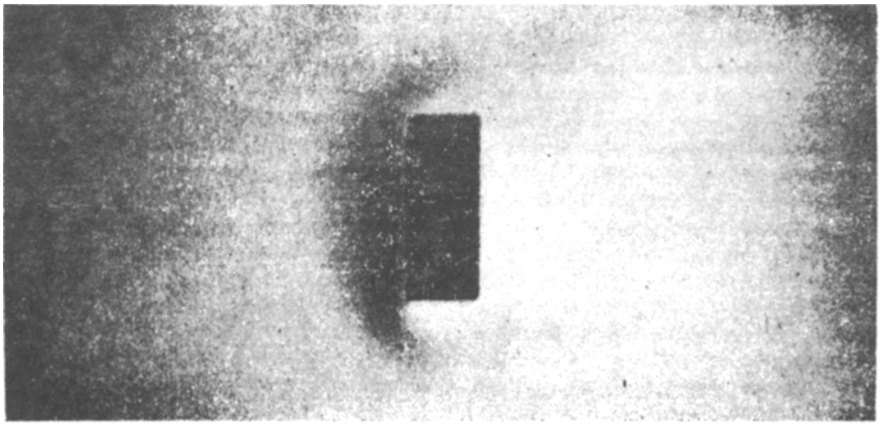

Fig. 5

The temperature dependence of the brightness of luminescent indicator coatings at air pressures $p = 10^3$-10^5 Pa was checked under laboratory conditions. It was found that when the luminophore film is heated from 20 to 30°C the brightness of the luminescence does not depend on temperature. As the temperature rises, the rate of reaction of the oxygen and the excited luminophore molecules increases, but the solubility of the oxygen in the film decrease Apparently, these processes are mutually compensatory, and the brightness of the luminescence remains constant on a certain temperature interval.

Experiments on models with luminescent indicator coatings were carried out in a hypersonic wind tunnel. The basic circuit of the illuminating system and a diagram of the experimental setup are shown in Fig. 1. During the experiment the model was photographed 0.3, 0.5, 0.8, and 1.2 sec after the flashlamps operated.

In Fig. 2a we have reproduced a photograph of a sphere in an airflow at $M_\infty = 3$, and in Fig. 2b the pressure distribution over the surface of the sphere obtained by means of an indicator coating and calculated from expression (5). The theoretical pressure distribution on the sphere is represented by the continuous curve [9].

The reference pressures for the determination of the parameters α_1 and β_1 were taken at the points $\varphi = 42$ and 86°. The mean-square error of the measurements was 12%.

In Fig. 3a we have plotted the results of photometric measurement of the negatives obtained by photographing the flat surface of a half-cone in a flow and without a flow. The ordinates $D - D_{0s}$ are the differences of the photographic densities of these negatives along a line corresponding to the section $x/\ell = 0.51$. In Fig. 3b we have plotted the distributions of the pressure coefficient $\bar{p} = [p(x, z) - p_\infty]/g$ over this section obtained by means of indicator coatings; here $p(x, z)$ is the pressure at the point investigated; p_∞ is the free-stream pressure; and g is the dynamic head. It should be noted that a weak pressure peak not detected by the tapping measurements passes through the point 1 (see Fig. 3a).

These experiments were carried out at different M_∞ but the same value of the parameter $(\kappa-1)/\kappa(\kappa+1)))\sqrt{\mu_0 T_\infty M_\infty/\mu_\infty T_0/\sqrt{\mathrm{Re}}}$, which ensured an identical pressure distribution pattern [11].

In investigating the gas flow on the flat surface of a delta wing by the laser knife method [12], an eddy, which apparently is also responsible for the pressure rise near the edge, was detected.

A similar effect is probably observed near the edge of the flat surface of a half-cone.

In order to check that the results of the pressure measurements do not depend on changes in the mass transfer between the coating and the gas flow, we carried out an experiment on a plate with a superstructure mounted at zero angle of attack in a flow with $M_\infty = 3$.

The results of photometric measurements on photographs of the plate in the flow and without a flow ($D - D_{0s}$ curve) are presented in Fig. 4a. The measurement line on the plate is indicated by the dashes (Fig. 4b). From the leading edge to point 1, beyond which the disturbing effect of the superstructure begins to make itself felt, $D - D_{0s}$ is constant, whereas on this interval the mass transfer coefficient α_m varies in inverse proportion to $\sqrt{x}$ [13], which shows that the results of the measurements do not depend on α_m.

The photograph reproduced in Fig. 5 shows the pattern of quenching of the luminescence of the indicator coating on the surface of a plate with a superstructure at $M_\infty = 3$. The pattern of density variation where the flow meets the superstructure, corresponding to regions of increased and reduced pressure, is clearly visible.

The luminescence indicator coatings developed are sensitive to air pressure on the interval 10^3-10^5 Pa. The sensitivity depends on the pressure range; for example, for the range $3 \cdot 10^3$-10^4 Pa, it is 600 Pa^{-1}.

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