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VISUALIZATION OF HYPERSONIC FLOWS DURING COMBUSTION OF MAGNESIUM VAPOR

V. I. Alferov, E. A. Bozhkova, L. M. Dmitriev,
and A. A. Shinelev

Schlieren methods of visualization, which are based on the dependence of the optical path of the back light on density gradients, often cannot be used in the visualization of hypersonic flows in wind tunnels with low gas density. In this case it is possible to use spectral absorption [1], luminosity induced in a gas by electrical discharges [2] or by an electron beam [3], and chemoluminescence from a gas upon the introduction of a reactive additive [4]. The last method differs favorably from the others in its ability to visualize an individual streamline of a flow, which is important in the study of complex three-dimensional flows. This paper illustrates a method of flow visualization by introducing magnesium vapor into an air flow.

A hypersonic air flow with Mach number M = 5 is produced in a wind tunnel with an electric-arc gas heater. The flow parameters are p_0 = 2 MPa, T_0 = 2500 K, p = 10^4 Pa, T = 400 K, and v = $2\cdot10^3$ m/sec, where p_0 and T_0 are the pressure and temperature of an adiabatically stagnant gas, and p and T are the static parameters. A steel tube (a flattened tube with an inside cross section of 8 × 1 mm and a wall thickness of 1 mm) is placed in the flow. A magnesium plate is laid inside the tube space. The tube heats to 1200°C as a result of the enthalpy of the flow's stagnation, and the magnesium melts and boils, injecting vapor into the air flow. In the process, quasi-steady vaporization of magnesium is maintained by the heat supply to the tube as the incident gas flow stagnates. The flow rate of magnesium vapor, estimated from the outflow time, is 0.01-0.05 g/sec. The vapor entrained by the flow streamline reacts with atmospheric oxygen; this process is accompanied by luminosity from the gas. The emission spectrum consists of the vibronic bands of MgO. If we take the rate of the three-particle reaction $Mg + Mg + O_2 \to 2MgO$, which is $k_r \approx 10^{-32}$ cm^6/sec [5], as being characteristic of the combustion of metals, then for a particle density $N \simeq 1.4\cdot10^{17}$ cm^{-3} (the density of O_2 molecules in the incident flow), the characteristic combustion time for magnesium vapors turns out to be longer than $5\cdot10^{-3}$ sec, and greatly exceeds the characteristic time of other processes (diffusion, convective transport, radiation, etc.). Under these conditions, it also seems possible to use the nature of the change in luminosity to evaluate the processes that cause these changes.

Magnesium vapors are captured by the flow streamlines that pass by the upper end face behind the shock wave, and as the gas expands to a pressure $p_1 \approx p$ in the near wake [6], they are accelerated together with the gas to a velocity $v_1 \approx v$. Here the length of the acceleration section is a few bores, based on the transverse dimension (3 mm) of the nozzle. The temperature to which the gas that has stagnated in the shock wave cools can be estimated from the condition of adiabatic expansion:

$$\left(\frac{T_1}{T_0'}\right) = \left(\frac{p_1}{p_0'}\right)^{\frac{\gamma-1}{\gamma}},$$

where the primes denote parameters of the gas behind the normal shock wave. This estimate yields a value $T_1 \approx 800$ K. With further motion, the gas in the far wake cools through thermal-conduction processes to the ambient gas temperature, and combustion in the far wake thus occurs as the gas cools from 800 to 450 K. The heating of the gas due to chemical reactions may be ignored, since the heat release during combustion over the characteristic time of motion $\tau = 3\cdot10^{-5}$ sec is small: $q\tau_1/\tau_g \ll c_pT_1$ (where q is the reaction heat per unit mass of mixture, and c_p is the heat capacity of the gas).

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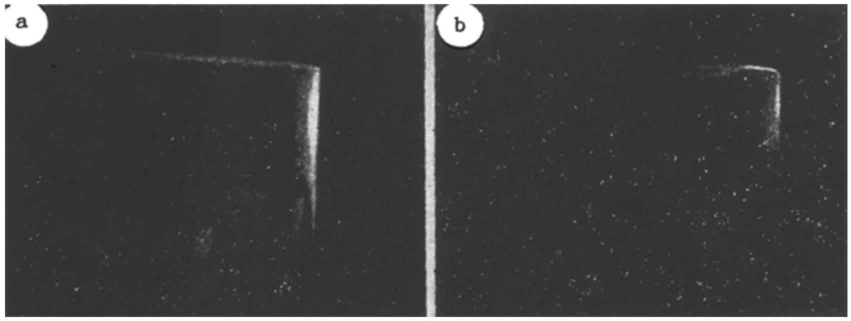

Fig. 1

Fig. 2

The combustion of magnesium vapor in the wake is illustrated in Fig. 1a. Figure 2 shows an example of a visualization in which a flow containing magnesium vapor impinges on a plate positioned at the angle of attack. The flow streamline containing the vapors passes through various disturbed flow zones. In particular, the flow region formed upon interaction of the shock wave in front of the plate with the disturbed flow zone in the wake behind the tube is visualized.

If the gas heater is switched off after the tube heats to the T_{boil} of magnesium, then the vapor continues to enter the cold incident flow ($T \approx 80$ K) as a result of the tube's thermal lag. Here two separate luminous streamlines are observed (apparently tip vortices), which flow from the butt end of the tube (see Fig. 1b).

The equations that describe the processes of the change in the vapor concentration n and the concentration n* of the excited molecules in the wake have the form

$$\operatorname{div}(n^* \vec{v} - D \operatorname{grad} n^*) = -\frac{n^*}{\tau_{rad}} - \frac{n^*}{\tau_q} + k_r n^2 N,$$

$$\operatorname{div}(n\vec{v} - D \operatorname{grad} n) = -k_r n^2 N.$$

Here τ_{rad} and τ_q are the lifetimes of excited molecules with respect to the radiation and quenching processes, respectively, and D is the diffusion coefficient. The hierarchy of the characteristic times of the processes in the wake is such that the divergent term may be ignored in the first equation, and the terms that describe diffusion in the longitudinal direction (along the flow streamline) $[D(\partial n/\partial x)]$ and the combustion process may be ignored in the second equation. In this case, assuming the concentration profile $n = n_0 \exp(-r^2/b^2)$ to be Gaussian and $k_r \approx$ const and $n \ll N$, we obtain $n_0(x) \sim b^{-2}(x)$, $n^* \sim b^{-4}(x)$, $b(x) \sim \sqrt{Dx/v}$. Experiments in a "hot" flow with $x \gg b$ qualitatively confirm the dependence of the radiation intensity ($I \sim n^*$) on the apparent diameter ($I \sim b^{-4}$), which justifies assumptions regarding the burning velocity $\sim k_r n^2 N$ for k_r = const. At the same time, in a cold flow this relationship is broken: the luminous wake extinguishes more quickly than it can expand; obviously, at temperatures $T \approx 100$ K the quantity k_r tails off sharply. (If the quenched wake is directed toward the shock zone of the gas, the streamline once again boils up intensively just in front of the plate, where the temperature increases to 300 K and the density rises, i.e., extinction of the wake is not related to the completion of the process of oxidation of magnesium atoms.)

Upon intersection of the shock wave, n^* changes along the flow line as

$$v\frac{dn^*}{dx}=\frac{n^*}{\tau^*}+k_r n^2 N,$$

where $\tau^* = (\tau_{rad}^{-1} + \tau_q^{-1})^{-1}$ is the characteristic relaxation time of n^*. An estimate based on the rate of change of the radiation upon passage through the shock wave gives $\tau^* < 10^{-6}$ sec. Outside the shock region, all gasdynamic scales L are such that $v\tau/L \ll 1$, and in the absence of diffusion processes the radiation intensity $I \sim k_r n^2 N$ will be determined by the gas density (in particular, when $\tau_{rad} \ll \tau_q$, $I \sim N^3$, and when $\tau_{rad} \gg \tau_q$, $I \sim N^2$). Thus, the change in luminosity can be used to estimate the gas density. On the other hand, the change in $k_r\tau$ can be estimated from the relative change in N and I upon passage through the shock.

The whirl rate of the flow due to rotation of the arc in the heater also can be determined from the deflection of the luminous wake in the plane perpendicular to the tube. The maximum values of the circumferential velocity determined in this manner are 4-6% of the longitudinal velocity. It should also be noted that the main difficulty in using this method is the need to minimize the disturbances introduced into the flow by the tube.

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NONSTATIONARY EFFECTS ACCOMPANYING BURNDOWN OF SYMMETRIC ELEMENTS

V. A. Arkhipov, V. N. Vilyunov, and Vl. F. Trofimov

The study of effects associated with the burndown of samples is one method for studying nonstationary combustion of condensed substances (C-substances). The source of the perturbation of the stationary combustion, in this case, is deformation of the Mikhel'son temperature profile in the sample as the sample burns down [1]. Extinguishment of the samples on a heat-removing metallic substrate (combustion zone freezing method) [2, 3] and bilateral burndown of flat plates [4-8] and cylindrical and spherical elements [8] provide information about the mechanisms of nonstationary combustion under conditions including the effect of external factors that are not directly related with the mechanism of combustion (the gas—dynamic flow field, external physicochemical actions, destruction of the samples, multidimensional nature of the problem, etc.). The question of burndown of symmetric elements is also of practical interest for predicting the characteristics of transient processes in regulated gas generators with a multilayered charge of condensed matter [9]. In particular, it is shown [6] that under certain conditions a jump in the pressure accompanying burndown of a plate in a semiclosed volume can exceed the stationary pressure level by more than a factor of two.

Existing results on nonstationary burndown of symmetric elements have been obtained, as a rule, based on the theory of Ya. B. Zel'dovich [4] by the method of integral relations or numerical calculation of the problem. Some effects associated with the nonstationary nature of the combustion of symmetric elements (plates and samples with a cylindrical channel filled with a viscous liquid) were observed experimentally in [8]. In this paper we shall analyze the results of an experimental investigation of nonstationary burndown of plane-parallel

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