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GAS MIRROR

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A gas mirror is an optical gas device deflecting a light beam and consisting of a flat plate on which a stable controllable distribution of the refractive index is created by a certain means. Working capacities of such devices are estimated and their experimental studies are carried out. Limiting geometric and optical characteristics of the gas mirrors are determined.

Investigation of the thermal boundary layer on vertical and sloped flat surfaces with free and mixed convection is the objective of many papers and monographs, for example [1-3]. Recently some interest has been shown on the optical properties of the thermal boundary layer, which can affect the quality of image of optical instruments. In [4] it has been shown that optical inhomogeneities in the thermal boundary layer can deflect light rays through angles of up to 10 min. A light beam passing through this inhomogeneity will be deflected through a certain angle depending on the angle of incidence and the level of inhomogeneity, which is similar in action to a plane mirror with controllable characteristics.

If the inhomogeneity of the refractive index is caused by temperature inhomogeneity, this mirror will be called "thermal." In the case of inhomogeneity caused by inhomogeneous concentration, the mirror will be called a "concentration" mirror.

A "Thermal" Mirror Based on Free Convection. Depending on the slope of the plate to the horizon and the amount of the heat supplied, a temperature distribution field [1] of certain form and, consequently, a refractive index field appear in the thermal boundary layer. Since the temperature is maximum and the refractive index minimum are at the surface of the plate, the light beams will be deflected from the heated surface. In [4] two limiting cases of propagation of the beam are considered:

1) beams reach the surface of the plate (the angles of incidence are close to 90°);

2) beams touch the surface of the plate. It is shown that the critical angle of incidence separating these two cases is independent of the specific form of the distribution of the refractive index $n(x)$ and is determined only by its minimum $n(T_{\omega})$ and maximum $n(T_{\infty})$ values. The work of a "thermal" mirror is clear from Fig. 1, where the angle of deflection is determined by the expression

$$\varepsilon \simeq \frac{n_0 - 1}{n_0} \frac{1}{T_0} \int_0^L \frac{\partial T}{\partial y} dL , \tag{1}$$

where L is the path length of the beam in inhomogeneous medium; n_0 is the refractive index of the medium at the point where the beam enters the boundary layer. Stable angles of deflection of up to 5 min have been obtained experimentally for this mirror.

A "Thermal" Mirror Based on Mixed Convection. The stability of work of a "thermal" mirror based on free convection can be increased by stabilization of the temperature field above the plate using a forced flow along the plate. In this case another temperature field different from the self-similar one appears along the heated plate. The ratio of the effects of free convective and forced flows is characteried by the parameter $\mathrm{Gr}_x/\mathrm{Re}_x^2$. At a low Grashoff number (Gr), the forced convection prevails, while at high values natural convection is predominant. The shape of the temperature field for the various cases of forced flow effects on a free convective flow is presented in Fig. 2, where the dimensionless coordinate is $\eta = 0.5y/x(\mathrm{Re}_x)^{1/2}$ and Re_x is the local Reynolds number. The vertical

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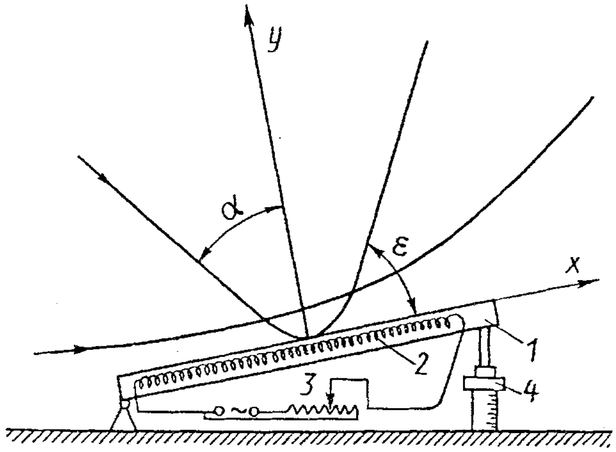

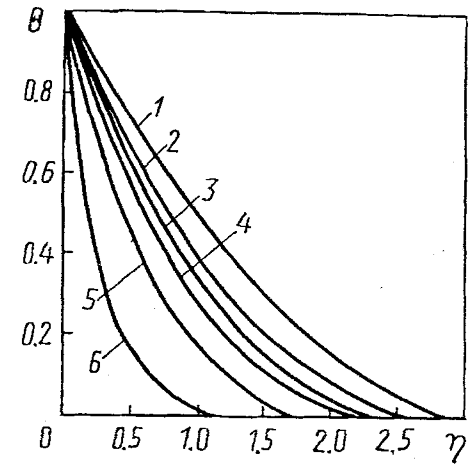

Fig. 1. Schematic diagram of a "thermal" mirror: 1) flat surface; 2) heater; 3) autotransformer; 4) micrometer.

Fig. 2. Temperature profiles in the boundary layer for the case of mixed convection: 1) $Gr_x/Re_x^2 = -0.05$; 2) -0.5; 3) 0; 4) 1; 5) 10; 6) 100.

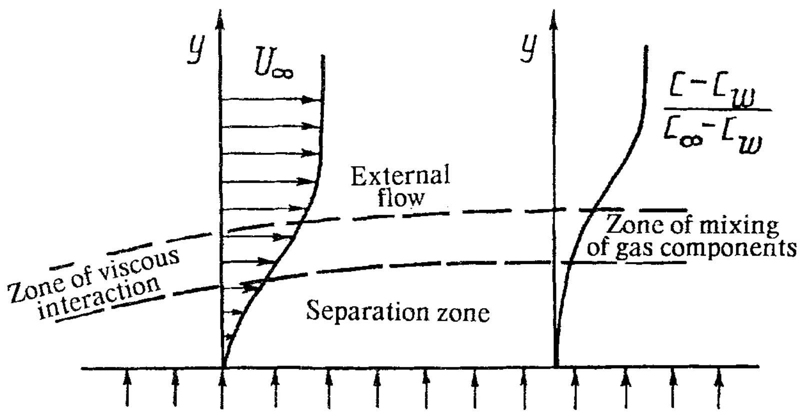

Fig. 3. A gasdynamic model of a "concentration" mirror.

axis is the dimensionless temperature $\Theta = T - T_\infty/T_\omega - T_\infty$. When the free convective and forced flows have the same directions, $Gr_x/Re_x^2 > 0$; when the directions are opposite, $Gr_x/Re_x^2 < 0$.

As can be seen from Fig. 2, changes in Gr_x/Re_x^2 cause changes in the temperature field and as this parameter increases, the function $\Theta = f(\eta)$ becomes stronger, which suggests growth of the temperature gradient. The angle of deflection of the light beam ε directed along the "thermal" mirror is determined from an expression similar to Eq. (1). Growth of the temperature gradient across the boundary layer causes an increase in the angle of "reflection" of the light beams from the thermal mirror. The most stable angles of deflection of the laser beam from an LG-38 reached $20'$ at a velocity of the longitudinal air flow $v_{av} = 0.5$ m/sec, which is four times higher than the maximum angle of deflection of the "thermal" mirror based on free convective flow.

A "Concentration" Mirror. The design of a "concentration" mirror is a combination of a "thermal" mirror with forced convective flow above the substrate (without a heater) made of a porous material through which a gas with a refractive index lower than that of the gas medium, for example, helium, can be injected. In this case a boundary layer with a concentration gradient and, consequently, density and refractivity gradients appears on the "reflecting" surface of the substrate. The gas medium near the substrate has a minimum refractive index. The incident light beam will be deflected towards a larger refractive index, as if it were reflected from the substrate. The value of the angle of "reflection" is controlled by both the amount of the gas injected through the porous substrate and the velocity of the gas flow along the substrate.

In order to study the specific dependence of the angle of deflection of a light beam on the parameters of the device, we will consider the physical picture of a laminar gas flow above a porous flat substrate with injection

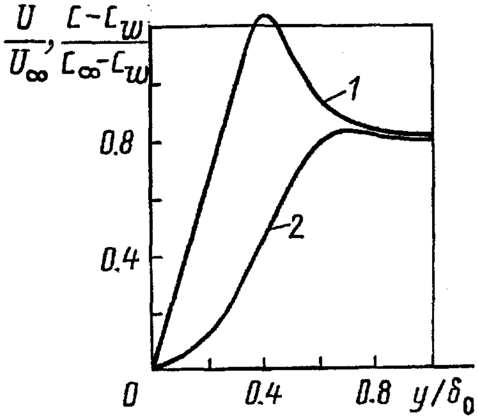

Fig. 4. Profiles of velocity (1) and mass concentration of helium (2) in the boundary layer.

of a foreign gas. It is known that a laminar flow on a permeable plate persist over a substantial length in a wide range of intensities of injection, including separation of the shear part of the boundary layer from the surface. The situation is shown in Fig. 3, where intense injection ($F = \rho_w v_w \sqrt{\mathrm{Re}_x}/\rho_\infty v_\infty$, where ρ_∞, v_∞ are the density and velocity of the injected gas, respectively; ρ_∞, v_∞ are the density and velocity of the flow not disturbed by the presence of the plate; $\mathrm{Re}_x = v_\infty x/\nu$ is the local Reynolds number) gives rise to a zone of 100% concentration of injected gas, and the boundary layer mixed with the injected gas is separated from the plate. In this case the coordinate y_0 of initiation of the beam should be shifted upwards by the dimension of the separation zone but the optical characteristics of the mirror are not affected at all by these conditions of the flow since the angle of deflection of the beam only depends on the selected pair of gases (blown above and injected through the plate). Therefore the minimum flow rate of injected gas can be determined from the condition that the dimension of the separation zone, for example, for a selected laminar gas flow injected at the velocity U_∞, tends to zero. The velocity U_w of injection of the gas determined at this moment is the desired velocity at a minimum flow rate of injected gas. The plot in Fig. 4 is an interesting case where a light gas (helium) (flow rate $F = 0.0067$) is injected through a porous plate with a laminar flow around it ($U_\infty = 6$ m/sec). Here the mass concentrations $C - C_w/C_\infty - C_w$ and the velocity profile U/U_∞ are the ordinate and y/δ_0, where δ_0 is the thickness of the hydrodynamic boundary layer ($\delta_0 = 5\sqrt{\nu x/U_\infty}$), is the abscissa. In Fig. 4 one can see the similarity of the profiles in the shifted mixing zone and their merging on the external boundary of the flow, which is due to the low molecular weight of helium. It can also be concluded that the gradient of the relative mass concentration of the injected gas and, consequently, the gradient of the refractive index are constant within 80% of the thickness of the concentration boundary layer.

We will calculate the dimension of the separation zone δ and the thickness of the hydrodynamic boundary layer δ_0. According to [5]

$$\delta = 0.6\left(\frac{D}{\nu}\right)^{1/3}\delta_0\,,$$

where D is the interdiffusion coefficient (for the helium-air pair $D = 0.689$ cm^2/sec).

The dimension of the mixing zone is determined by the thickness of the hydrodynamic boundary layer. If it is assumed that in the cross-section $x = 10$ cm from the point of injection at $U_\infty = 4$ m/sec, a separation zone is formed, we obtain ($\nu = 0.152\cdot 10^{-4}$ cm^2/sec)

$$\delta_0 = 0.3\ \text{cm}\,;\quad \delta = 0.29\ \text{cm}\,.$$

The critical angle of incidence for this mirror can be found from the formula [4]

$$\arcsin \alpha_{cr} = \frac{n_{\text{helium}}}{n_{\text{air}}}\,,\quad \alpha_{cr} = 88.69^\circ\,.$$

The maximum angle "covered" by the mirror operating by a purely optical gas mechanism (for the selected air-helium pair) is $\varepsilon = 90^\circ - 88.69^\circ = 1^\circ 19'$. In addition, we will estimate the velocity of injection of the working

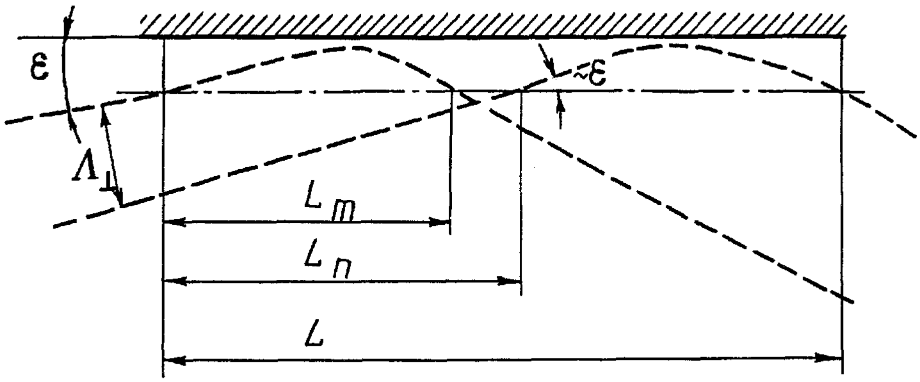

Fig. 5. Diagram illustrating the determination of the minimum length of a gas mirror.

gases, which is necessary for the operation of a "concentration" mirror. According to experimental data [6], a zone with 100% concentration of the injected gas is developed on the wall and, consequently, the boundary layer is separated at $F_w/2 = 0.765$ in the cross-section $x = 15.2$ mm from the start of injection ($Re_x = 4 \cdot 10^3$), i.e., these parameters are the upper limit for operation of the "concentration" mirror.

With the determined ε, for a preset width of the aperture of the beam $\Lambda_\perp$, it is possible to calculate the minimum length of the mirror that caw reflect a beam of preset width incident on it at an angle ε to its surface.

It is clear from Fig. 5 that just as in an ordinary solid-state mirror, the length L cannot be shorter than

$$L_n = \frac{\Lambda_\perp}{\sin \varepsilon} \simeq \frac{\Lambda_\perp}{\varepsilon}.$$

However, for the case of aerothermal mirrors this length should be increased by L_m, which is covered by the beam from the point of its entrance to the boundary layer to the point of its exit. It is clear from Fig. 5 that L_m can be estimated simply as $L_m \simeq 2\delta/\sin \varepsilon = 2\delta/\varepsilon$. Therefore, the total length of the mirror for the beam with the aperture $\Lambda_\perp$ is

$$L = L_n + L_m = \frac{\Lambda_\perp + 2\delta}{\varepsilon}.$$

For the beam with dimension $\Lambda_\perp = 5$ cm the minimum length of the substrate of the "concentration" mirror considered is $L = 243$ cm.

NOTATION

n, refractive index; ε, angle of deflection of the light beam; U, flow velocity; T, temperature; C, gas concentration; Gr, Re, Grashoff and Reynolds numbers. Subscripts: ω and ∞, parameters on the wall and in the environment, respectively; av, average flow velocity.

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