$$\frac{t_l^{\max} - t_l^{\min}}{\bar{q}_{in} R_L} \lambda_m = B \left(\frac{\lambda_m}{\lambda_g} \right)^{0,66} Re_{i.f.}^{-0,6}. \tag{1}$$

The values of the coefficient B are: for packing I – B = 3.44; II – B = 2.16, and III – B = 2.97. With the porosity taken into account expression (1) will take the form

$$\frac{t_l^{\max} - t_l^{\min}}{\bar{q}_{in} R_L} \lambda_m = (0.64 + 5{,}88\varepsilon) \left(\frac{\lambda_m}{\lambda_g} \right)^{0,66} Re_{i.f.}^{-0,6}.$$

The dependences of the maximum temperature nonuniformity on the calorimeter surface of the first series of different types of packings on the quantity Re_c are presented in Fig. 4. The dependences obtained for an isolated calorimeter in the initial section of the jet are shown by the lines. Analysis of the dependences shows that the maximum temperature nonuniformity on the calorimeter surface in the first series of packings increases as the value of the ratio D_0/D_c decreases and is practically always higher than for an isolated sphere with the identical values of D_0/D_c.

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MECHANISM OF LASER MAINTENANCE OF A DEEP VAPOR CHANNEL WITHIN A LIQUID

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The question of the limiting depth of penetration of a laser beam into a target material is of significant physical interest, as well as being of practical importance, for example, in increasing the efficiency of laser welding. It is known that with decrease in the velocity of beam motion its penetration into the target increases, and it can be assumed that the maximum depth is attained with a nonmoving beam. We note that in experiments with such a beam under certain conditions, a quite stable cavity has been observed, showing relatively small oscillations of its surface [1]. Therefore, it is of interest, as one stage in the investigation of laser welding, to study the model of a stationary vapor channel, formed in a liquid by a nonmoving laser beam. It is natural to commence with the simplest possible models of mechanical and thermal equilibrium of the cavity, not considering plasma phenomena, liquid hydrodynamics, light scattering, etc.

The condition for cavity stability is the equality of the pressures p_1 and p_2 (Fig. 1) at each point of the surface. In the present study it will be assumed that p_1 is composed of the hydrostatic pressure in the liquid, the external pressure p_a, and the pressure due to surface tension forces: $p_1 = d(h - z) + p_a + \sigma k$, while p_2 is composed of the pressure in the vapor p and the recoil pressure produced by mass transfer through the cavity surface. Here d is the specific gravity of the liquid, σ is the surface tension coefficient, k is the channel surface curvature, and h is its depth. In [2, 3] in a similar formulation of the problem it was assumed that $p = \text{const} = p_a$, which eliminated any effect of vapor flow dynamics in the cavity on cavity form.

In a deep and narrow channel, which is characteristic of laser welding techniques, it can be assumed that the gasdynamic quantities figuring in the problem are functions solely of distance from the cavity bottom z,

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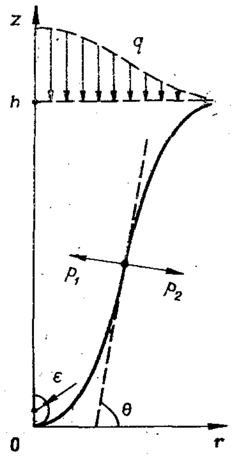

Fig. 1

while heat and mass transfer at the surface can be considered by distributed sources. Therefore for further study of the deep penetration mechanism and investigation of the role of vapor dynamics in cavity formation we will use the equations of quasi-one-dimensional gasdynamics

$$(\rho v r^2)' = (2r/\sin\theta) j_m, \quad [(p + \rho v^2) r^2]' = (2r/\sin\theta) j_p, \quad [\rho v r^2 (e + v^2/2) + p v r^2]' = (2r/\sin\theta) j_e, \quad p = (R/M)\rho T, \quad e = c_p T + \lambda, \tag{1}$$

where r is the cavity radius; ρ, v, T, density, velocity, and temperature of the vapor; j_m, j_p, j_e, mass, momentum, and energy flux densities through the phase surface; M, molar weight of the material; λ, latent heat of evaporation; and e, internal energy of the vapor. The prime denotes the operation d/dz.

We assume that light absorption, evaporation, and condensation take place solely on the surface. If the surface temperature at a given point is equal to T_S, then for the mass flux j_m we may use Knudsen's well-known expression

$$j_m = j_+ - j_- = \sqrt{\frac{M}{2\pi R}} \left(p_S / \sqrt{T_S} - p / \sqrt{T} \right), \tag{2}$$

where p_S is the saturated vapor pressure at the surface temperature T_S, j_+ and j_- are the flux densities directed into and out of the cavity, respectively. The flux j_+ moves with a thermal velocity $v_+ = \sqrt{8RT_S/\pi M}$, directed along the normal to the surface. Since in Eq. (1) we have only axial projections of the velocities, then

$$j_p = j_+ v_+ \cos\theta - \gamma v j_- + p \cos\theta. \tag{3}$$

The coefficient γ considers in some effective manner the fact that the flux j_- carries off molecules from a relatively thin boundary layer of vapor flowing at a velocity which in general is less than the vapor velocity v on the flow axis. We note that j_m, j_p, and j_e are defined by the kinetics of the processes of material evaporation and condensation on the phase boundary. Unfortunately the kinetics of the phase transition are difficult to reconcile with the one-dimensional nature of the problem, forcing the use of artificial procedures (for example, the introduction of γ). The energy flux density has the form

$$j_e = j_+ \left(v_+^2/2 + c_p T + \lambda \right) - j_- \left(v_-^2/2 + c_p T + \lambda \right), \tag{4}$$

where $v_- = \sqrt{8RT/\pi M}$ is the thermal velocity of molecules in the vapor.

As has already been noted, in the given model the laser beam is considered only as an intense source of heat, which is liberated in a thin surface layer. In a long narrow cavity it can be assumed that removal of heat into the liquid occurs in a radial direction, and we may approximate the thermal flux value by a difference relationship $\varkappa (T_S - T_\infty)/r$, where T_∞ is the liquid temperature far from the vapor channel. Let the laser beam have a Gaussian power density distribution, and the entire incident energy be completely absorbed. Then the surface temperature T_S can be determined from the thermal balance equation

$$q \exp[-(r/r_0)] \cos\theta = \varkappa (T_S - T_\infty)/r + j_e. \tag{5}$$

We complete our system of equations with the condition for surface equilibrium

$$d(h - z) + \sigma k + p_a = j_+ v_+ + j_- v_-, \tag{6}$$

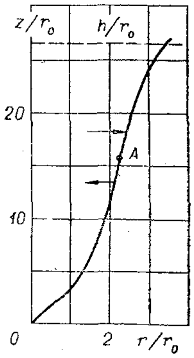

Fig. 2

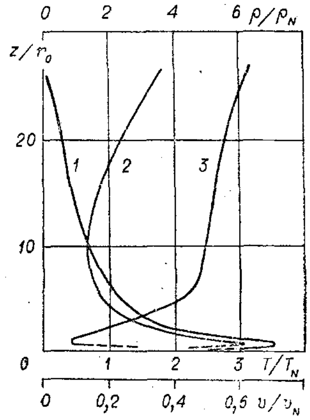

Fig. 3

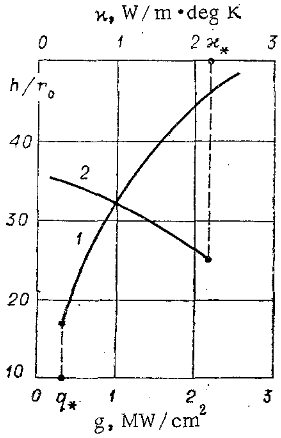

Fig. 4

where $k = \sin\theta/r + (\sin\theta)'/r'$, and the right side is the total pressure from the vapor side on the liquid.

In order to completely define the boundary problem it is necessary to specify boundary values for the variables. On the bottom of the cavity these values are related to each other by the conservation laws:

$$q = \rho_0 v_0 \lambda + \varkappa (T_{s0} - T_\infty)/\varepsilon, \tag{7}$$
$$\frac{R}{M}\rho_0 T_0 + \rho_0 v_0^2 = p_a + dh + \frac{2\sigma}{\varepsilon},$$
$$\rho_0 v_0 = j_+(T_{s0}) - j_-(T_0), \quad p_s(T_0) = p(T_0, \rho_0),$$

where ε is the radius of curvature of the surface at the bottom. As in [4], it is assumed here that the vapor in a very narrow layer at the surface enters the saturated state, corresponding to a temperature T_0. In the infrasonic flow regime system (7) is completed by a condition at the channel input

$$p(h) = p_a. \tag{8}$$

With supersonic flow this condition is replaced by the condition $r'(h) \geq A$, where A is a sufficiently large number.

The boundary problem defined by Eqs. (1)-(8) was solved numerically with a BÉSM-6 computer for a number of materials over a wide range of external medium and laser beam parameters. Calculations showed that direct substitution of parameters characteristic of laser welding processes produced an unsatisfactory result. The vapor flow condenses so intensely, even near the bottom, that its velocity falls to zero at a depth much less than r_0, i.e., one of the original assumptions is not fulfilled ($h \gg r_0$). It was found that the model is not contradictory for fused dielectrics at external pressures which ensure an infrasonic flow regime within the channel. Figure 2 presents the cavity form characteristic of this case, while Fig. 3 shows the distribution of gasdynamic parameters over cavity depth (1, vapor velocity; 2, vapor density; 3, temperature; $\rho_N = 0.45$ kg/m³, $v_N = 480$ m/sec; $T_N = 1070$°K). The parameters used for the calculations were the following:

$$q = 0.24\ \mathrm{MW/cm^2},\quad r_0 = 1\ \mathrm{nm},\quad p_a = 1.0\ \mathrm{MPa},$$
$$\lambda = 1.9\ \mathrm{kJ/g},\quad \varkappa = 2\ \mathrm{W/(m\cdot deg\ K)},\quad \gamma = 0.01.$$

We note that in a significant portion of the channel (above point A in Fig. 2) thermal balance is maintained by vapor condensation on the walls. In constrast to [2, 3], where due to the impossibility of vapor consenation $r(h) \approx r_0$ always, here the cavity radius at the input is determined by flow dynamics and can be greater than the beam radius. Flow breaking and pressure growth are explained both by geometric expansion of the channel and mass removal from the flow.

A sharp change in the gasdynamic quantities near the bottom is characteristic. This is a consequence of the difficulties of reconciling all variable boundary values within the framework of a one-dimensional model for a region where the flow is significantly two-dimensional. It is this character of the flow within this region which determines the presence of critical parameters in the given model. Figure 4 presents the calculated dependence of cavity depth in the infrasonic flow regime upon power density (curve 1) and thermal conductivity of the target material (curve 2). Also shown are the critical values found for q and $\varkappa$. At $q < q_*$ and $\varkappa > \varkappa_*$ within the framework of the model used it was not possible to find solutions describing a stationary deep cavern. We stress that the existence of solutions described such a cavity in the infrasonic regime is determined by the vapor flow near the bottom of the cavity. However, if such a solution does exist, the details of the flow in this region will prove to have a weak effect on the main vapor flow characteristics far from the bottom, as has been confirmed by calculation.

Numerical study of the model in the supersonic vapor flow regime revealed that no set of external parameters could be found which would provide a cavity with $h/r_0 > 1$. General analysis of the results for both supersonic and infrasonic regimes indicated the great sensitivity of the entire gasdynamic picture to the method of defining surface temperature T_S, which will require more accurate calculation of heat transfer from the surface.

The numerical studies of the proposed model performed, which considered vapor gasdynamics in the quasi-one-dimensional approximation as well as heat loss into the liquid, revealed the following. The model predicts daggerlike melting for materials with sufficiently low thermal conductivity and external pressures ensuring slow escape of the vapor from the cavity. Within the cavity significant regions may exist where equilibrium is maintained not by evaporation, as in [2, 3], but by condensation of vapor on the wall. The channel width is then greater than the diameter of the light beam, and the greater part of the beam energy remains in the liquid. To describe deep penetration of a laser beam into metals, it is obviously necessary to consider the multipath character of vapor flow in the cavity, i.e., to solve the two-dimensional problem.

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PARAMETRIC STUDY OF HYPERSONIC BODY SHAPES

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Although the problem of the design of axisymmetric bodies for minimum drag is practically solved, the optimization of three-dimensional aerodynamic shapes still requires detailed analysis. Many years of experience on the design of optimal spatial configurations using some exact solutions [1-5] and approximate specification of aerodynamic load on the body surface [5-12] revealed the need for systemization of experimental results. The first numerical computations of the flow around linear forms [12] only emphasized the need for conducting parametric experiments on detailed flow characteristics around three-dimensional bodies. The effect of aspect ratio and midsection of a star-shaped body with sharp and blunt leading edges on its drag is considered here as a supplement to the computed results [11, 15] and experimental data [16]. It is shown experimeantally that, as revealed by numerical optimization [11, 15], there is a strong dependence of relative drag reduction of stars on their aspect ratio. It is also shown that even for asymmetric star-shaped bodies [17] the critical parameter is the ratio of the circle inscribed at the midsection and the circle circumscribed near it. Slightly blunt leading edges have practically no effect on the general nature of the relations. Besides, a comparison is made, on the basis of approximations, with experimental and exact computational results [18].

1. One of the features of star-shaped configurations is that among their many types there are some for which it is possible to obtain an exact solution for the inviscid flow field, taking into consideration all complex

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