STUDY OF THE INTERACTION BETWEEN A HOT GAS JET AND A LIQUID BATH

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Results are presented from an experimental investigation of the interaction between a hot gas jet and a liquid bath with different schemes of organization of the jet.

The efficient use of energy resources is an important problem in modern industry. The use of plasma jets as sources of highly concentrated energy, with a broad range of thermal and chemical potentials, makes it possible to significantly increase the thermal efficiency of processes, intensify heat and mass transfer in a system, and increase useable output. The advantages of plasma technology become evident in realizing high-temperature gas–liquid processes connected with the thermomechanical processing of a molten bath. Plasma application here is currently based on the use of the products of combustion of a hydrocarbon fuel as the energy carrier, which means that the heat utilization factor is low. Blowing equipment based on electric-arc gas heaters, in contrast to fuel combustion chambers, makes it possible to obtain hot gas flows with independently specified thermal and chemical potentials in accordance with the requirements of a specific industrial process.

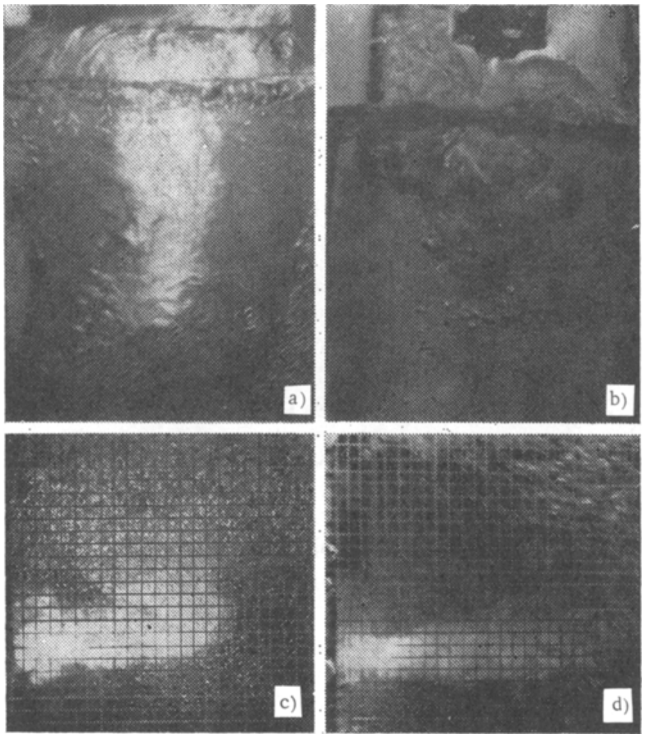

Fig. 1. Photographs of the discharge of a high-temperature jet of nitrogen into water with top and bottom blowing: *a*) $Fr_0 = 438$, $T_0 = 5320$ °K, $H/d_0 = 0$, $d_0 = 6 \cdot 10^{-3}$ m; b) 850, 3580, 5, $4 \cdot 10^{-3}$; c) 650, 5790, 32, $4.3 \cdot 10^{-3}$; d) 5120, 5720, 32, $3 \cdot 10^{-3}$.

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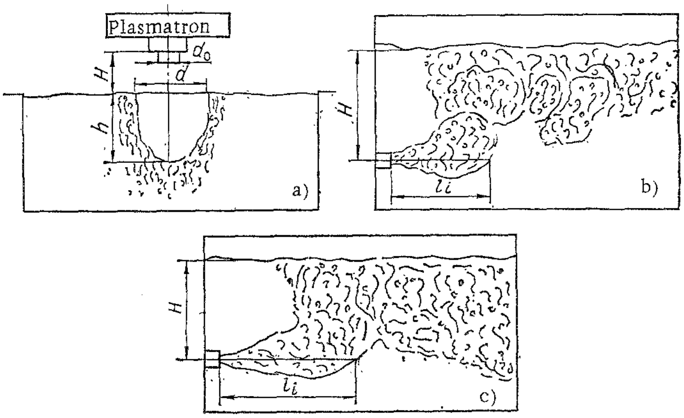

Fig. 2. Schemes of measurement of the geometric characteristics: a) top blow; b) lateral blow (transitional regime); c) bottom blow (regime of developed jet discharge, $Fr_0 >$ 3000).

The realization of gas–liquid processes using plasma technology involves the localized action, on the melt, of high-enthalpy gas jets blown onto the surface or into the body of the melt. The interaction of plasma flows with a melt has been the subject of investigation in works devoted to the development of plasma technology [1, 2], although the dynamic effect on the melt of gas heated in a refining plasmatron is very slight. The circulation of the melt is determined by the electromagnetic field of the arc discharge [2]. The gas-melt phase boundary is undeveloped in this case, which means that mass transfer takes place slowly. The contact area can be increased and the effects of pulsative transport can be enhanced by increasing the dynamic effect of the plasma jet on the melt.

A large number of works have experimentally studied different aspects of transport phenomena in the interaction of high-velocity gas jets with a liquid, the main goal of these researches having been to establish a correlation between the parameters of the blow and the characteristics of the blowing zone. The studies have been conducted under isothermal or slightly nonisothermal conditions with heating of the gas and with the blowing of jets of cold gas onto melts. The character of dispersion of hot (plasma) jets, under nonisothermal conditions, is quite different from the laws for isothermal conditions, so that the above results may not apply to the interaction of a plasma jet with a liquid both under pronounced nonisothermal conditions. The features of heat transfer in such systems remain nearly unexplored in both the theoretical and empirical senses.

Heat transfer from a hot argon jet to a water bath was studied in [5]. The authors investigated a variant of organization of the process which used extended top nozzles at gas exit velocities $\leq$ 120 m/sec and gas exit temperatures $\leq$ 3000°K. An attempt was made to describe the effects of the interaction within the framework of boundary-layer theory, which limits the possibility of application of the results for analyzing features of the discharge of high-velocity ($\sim 10^3$ m/sec) submerged plasma jets into a liquid, accompanied by the mutual mixing of the phases as the gas jet is broken down into individual bubbles under conditions of turbulent pulsative transport (Fig. 1).

The goal of the present work is to experimentally study heat transfer from a plasma jet to a liquid both end characteristics of propagation of the jet in the liquid with different schemes of organization of the blow (top, lateral, and bottom blowing) for a broad range of gas mean-mass exit velocities (150-3000 m/sec) and temperatures $(1.7\text{-}6.5)\cdot 10^3$°K. The tests were performed on a unit consisting of an electric-arc gas heater with vortical stabilization of the discharge, with a nominal power of 20 kW. The unit had baths of different geometries (cylindrical bath with a diameter of 0.17 m and a height of 0.19 m and a bath of rectangular cross section with sides $0.3 \times 0.16 \times 0.35$ m). The interaction of plasma jets with a liquid bath was studied in nitrogen (helium)–water (glycerine) systems differing significantly in their physical properties. The heat-transfer studies were conducted with the water flowing through the bath, and the measurements were based on the calorimetric method. The characteristics of the blow were calculated for equilibrium mean-mass parameters of the gas flow at the outlet of the plasmatron nozzle. The characteristic dimensions of the interaction zone were determined on the basis of quantitative analysis of photographs (Fig. 2).

Top Blow. The macroscopic picture of the process of interaction of the liquid with a plasma jet flowing normal to the bath surface corresponds to that described in the studies conducted under isothermal conditions

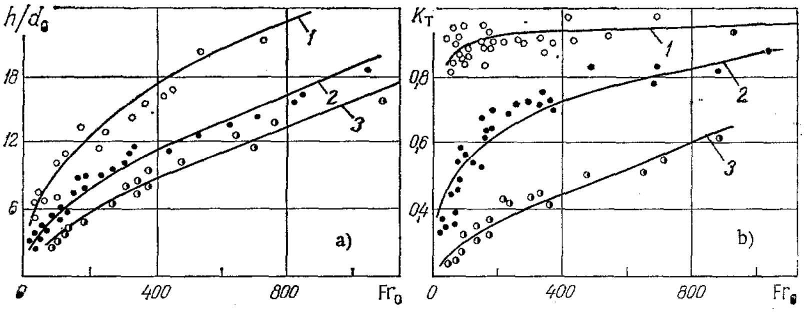

Fig. 3. Dependence of the dimensionless depth of the crater (a) and the heat-transfer function (b) with top blowing of a high-velocity gas jet onto the liquid on the Froude criterion for different distances of the plasmatron nozzle from the bath surface (the points denote experimental values, while the curves denote calculation by Eq. (1) (a) and Eq. (3) (b): 1) $H/d_0 = 0$; 2) 5; 3) 13; b – 1) $H/d_0 = 0$; 2) 7.5; 3) 13.

[3]. The structure of the interaction zone is determined by the flow of momentum of the incident jet at the level of the liquid.

An increase in the Fr_0 number increases the transience of the gas–liquid boundary, and this is accompanied by comminution of the gas flow into individual bubbles. During the investigation of the process in a circulating system, with the fixed temperature of the liquid at the bath outlet not exceeding 310°K, we prevented boiling in the volume and the distortion of the interaction zone that would have accompanied it.

The dimensions of the zone of interaction between the high-velocity plasma jet and the surface of the liquid are determined by the modified Froude number (Fr_0) (Fig. 3a). The viscosity of the liquid does not, within the range investigated, affect the characteristic dimensions of the interaction zone. However, during blowing with a high velocity, we did notice pronounced gas saturation of the bath volume with small gas bubbles about 10^{-3} mm in diameter. These bubbles were capable of staying in the bath for a long period of time. This fact may have a significant effect on mass transfer processes in similar systems.

Statistical analysis of the experimental data gave us theoretical relations for determining the mean dimensionless depth of penetration of the plasma jet into the liquid (h/d_0) and the diameter of the interaction zone (d/d_0):

$$\frac{h}{d_0} = A\,\mathrm{Fr}_0^{m+a\frac{H}{d_0}}\left(1+\frac{H}{d_0}\right)^{n+b\,\mathrm{Fr}_0}, \tag{1}$$

where $A = 1.2$; $m = 0.44$; $a = -1.7\cdot10^{-2}$; $n = -0.26$; $b = 1.3\cdot10^{-4}$;

$$\frac{d}{d_0} = \mathrm{Fr}_0^m\left(\frac{H}{d_0}+1\right)^n, \tag{2}$$

where $m = 0.33$ and $n = 0.08$. The mean relative deviation of the test data from the theoretical values obtained with Eqs. (1) and (2) is 7%.

Comparison of Eq. (1) with the equation $h/d_0 = Fr_0^{0.5}$ [3] for isothermal conditions with the nozzle edge located at the bath level ($H/d_0 = 0$) shows that, for a broad range of blowing regimes, the depth of penetration of the jet does not differ much from the value corresponding to isothermal conditions.

The diameter of the interaction zone is larger when the bath is blown under isothermal conditions than when it is blown by the plasma jet, a fact which is explained by the decisive effect of the reflected gas flow on the cross-sectional dimensions of the crater. Upon interaction with the liquid, the reflected jet undergoes rapid cooling, leading to a reduction in its dynamic characteristics.

The results of experimental studies of heat transfer in a plasma-jet – liquid-bath system are represented by an integral characteristic of the process – the heat-transfer function (K_t), defined as the ratio of the heat taken up by the liquid, without consideration of energy expenditures on evaporation, to the available

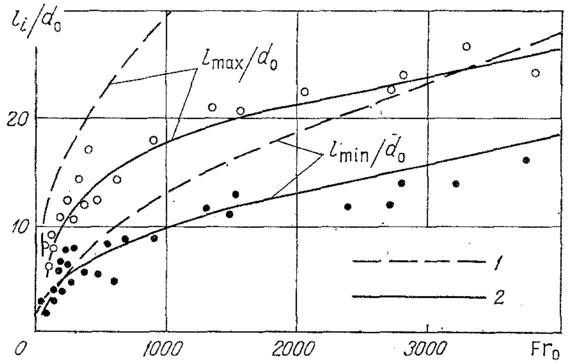

Fig. 4. Dependence of depth of penetration of high-temperature and isothermal gas jets in a liquid on the Froude criterion with lateral blowing: 1) isothermal jets (the equations [5] $l_{min}/d_0 = 0.27\ Fr_0^{0.56}$, $l_{max}/d_0 = 1.85\ Fr_0^{0.4}$); 2) high-temperature jets (Eqs. (5), (6)).

thermal energy of the high-temperature gas jet at the edge of the nozzle of the blowing apparatus. The temperature of the liquid at the outlet from the vessel, measured directly during the experiment, is taken as the determining value in calculating the available thermal energy of the jet. It is not possible to unambiguously determine the temperature of the phase boundary under the transient conditions of the interaction, accompanied by evaporation of the liquid and mutual mixing of the gas and liquid. It has been established that the value of the heat-transfer function in a top-blown system is determined by the value of the modified Froude number, calculated from the parameters of the jet at the edge of the nozzle, and the distance of the nozzle from the surface of the liquid. The following relation was obtained from statistical analysis of empirical results to calculate the heat-transfer function

$$K_t = [1 + A\,Fr_0^{m+aH/d_0}(1 + H/d_0)^{n+bFr_0}]^{-1}, \tag{3}$$

where A = 3.2; m = −0.8; $a = 3.3\cdot10^{-2}$; n = 0.56; $b = -9\cdot10^{-5}$. The mean relative deviation of the experimental data from that caclulated with Eq. (3) is 5%.

Equations (1)-(3) were obtained with the following parameter ranges: w_0 = 150-800 m/sec, $d_0 = (3.6\text{-}8)\cdot10^{-3}$ m. H/d_0 = 0-13, Fr_0 = 20-1500, T_0 = 1700-6300°K.

Within the limits of accuracy of the experiment (the maximum relative deviation of the results calculated with Eq. (3) from the empirical results does not exceed 20%), the thermophysical properties of the gas do not effect the integral characteristic of the heat-transfer process when using plasma jets of helium and nitrogen. The reason for this is evidently as follows: the developed surface of contact between the interacting phases and the high frequency of the pulsations of the boundary have a decisive effect on the heat-transfer rate when a liquid bath is blown with a high-velocity plasma jet; the difference in the value of the heat-transfer function for gases with different thermophysical characteristics may prove to be substantial as the dynamic effect of the jet on the bath decreases ($H/d_0 > 10$; $Fr_0 < 20$).

The value of the heat-transfer function increases significantly as the edge of the plasmatron nozzle approaches the liquid surface and as the intensity of the blow, determined by the Fr_0 criterion (Fig. 3b), increases. Location of the nozzle at the bath level ensures near-maximum heat intake by the bath at $Fr_0 > 200$. In connection with this fact, molten baths may be efficiently thermally processed by using unsubmerged nozzles.

Changes which occurred in the structure of the plasma jet due to the location of water-cooled adapters with $L/d \simeq 12$ behind the plasmatron nozzle did not affect the characteristics of thermal and dynamic interaction of the jet and liquid bath. Thus, the study results can be used to design a broad range of plasma blowing devices.

Lateral Blowing. Two regimes, transitional and jet, were seen to characterize the flow of the gas into the liquid, depending on the dynamic effect of the plasma jet on the bath (the above regime classifications were taken from [4]). The transitional regime corresponded to minimum gas exit velocities in the investigated range ($Fr_0 < 5\cdot10^2$), while jet flow was observed at $Fr_0 > 5\cdot10^2$.

The study results showed that the depth of penetration of the high-velocity gas jet into the liquid with lateral blowing is determined by the value of Fr_0 (as in [4], by the depth of penetration we mean the length of the straight section of the jet (see Fig. 2b and c)). Due to lengthwise pulsations, the depth of penetration of the jet into the liquid during the transitional regime is of a statistical nature. The range of this depth, given a constant blowing regime, may be as great as 50% at the minimum Fr_0 values.

The following relations were obtained to determine the mean, minimum, and maximum depths of penetration of plasma jets into a liquid (l_i/d_0):

TABLE 1. Results of Experimental Studies of Heat Transfer with Lateral and Bottom Blowing

Lateral blowing				Bottom blowing			
$\frac{H}{d_0}$, mm/mm	Fr_0	T_0, K	K_t	$\frac{H}{d_0}$, mm/mm	Fr_0	T_0, K	K_t
$\frac{40}{8} = 5$	57	6180	0,95	$\frac{140}{6} \simeq 23$	256	6140	0,99
	24	6260	0,96		141	6380	0,96
	84	6200	0,96		210	6250	0,95
	31	6240	0,93		103	6270	0,99
$\frac{40}{6} \simeq 7$	85	4720	0,90	$\frac{104}{6} \simeq 17$	140	6350	0,79
	231	5190	0,86		169	6230	0,94
	292	5180	0,87		256	6150	0,86
	86	3820	0,93		106	6290	0,89
	181	5110	0,86		364	5930	0,93
$\frac{90}{6} = 15$	111	6030	0,96	$\frac{55}{6} \simeq 9$	139	6320	0,70
	144	6010	0,99		110	6370	0,77
	261	5750	0,99		221	6290	0,71
	77	5700	0,99		329	6130	0,70
	152	5800	0,92		411	6080	0,80

$$l_{av}/d_0 = 1.1 Fr_0^{0.38}, \quad (4)$$

$$l_{min}/d_0 = 0.63 Fr_0^{0.4}. \quad (5)$$

$$l_{max}/d_0 = 2.4 Fr_0^{0.3} \quad (6)$$

for the following blowing-parameter ranges: w_0 = 160-3000 m/sec, $d_0 = (3\text{-}8)\cdot 10^{-3}$ m, T_0 = 3500-6400°K, H/d_0 = 5-40, Fr_0 = 20-5300. The mean deviation of the experimental values from the theoretical does not exceed 10%.

The depth of penetration into the liquid is significantly less for a high-temperature jet than under isothermal conditions (Fig. 4), which is explained by the additional dissipation of kinetic energy along the jet as a result of heat transfer to the liquid.

The results of study of heat transfer in a plasma-jet – liquid-bath system with lateral blowing show that nearly complete transfer of the heat to the liquid phase ($K_t \geq 0.95$ with $H/d_0 = 15$ and $Fr_0 > 20$) (see Table 1) is ensured when the nozzle edge is submerged (except for "breakthrough" of the bath [4]).

The value of the heat-transfer function in the "breakthrough" regime is within the range 0.85-0.95 (H/d_0= 7, Fr_0 = 30-300), which shows that the main role in the thermal interaction of the plasma jet and the liquid bath is played by the jet breakdown region, not be the bubble region.

Bottom Blowing. The structure of the gas–liquid system in the case of bottom blowing of the liquid bath with plasma jets is determined by the immersion of the nozzle of the blowing device. At $Fr_0 > 100$ and $H/d_0 \sim 10$, a spouting disperse-gas zone is formed over the bath surface as a result of breakthrough of the liquid by the gas jet. The resulting value of the heat-transfer function for heat transfer to the liquid in the bath and in the spouting layer lies within the range 0.7-0.8 for $H/d_0 \sim 10$ and Fr_0 = 100-400. As H/d_0 increases, the effects of the interaction of the plasma jet directly with the liquid bath become predominant: the heat-transfer function under these conditions approaches the maximum value (see Table 1).

The studies show that the use of high-velocity plasma jets on a liquid bath makes it possible to conduct the process with a high thermal efficiency using different methods of organizing the blow. The results obtained here can be used to design high-temperature apparatus intended for realizing strongly nonisothermal gas–liquid processes.

NOTATION

$Fr_0 = \rho_0 w_0^2/\rho_W d_0 g$, modified Froude criterion; ρ_0, w_0, T_0, mean-mass density, velocity, and temperature of the plasma jet; ρ_W, density of the liquid; d_0, diameter of the nozzle of the blowing equipment; g, acceleration due to gravity; H, height of nozzle above bath; h, d, depth and diameter of crater with top blowing; l_i, depth of penetration of jet into liquid; $K_t = Q_W/(\Delta H_{T_0} - \Delta H_{T_2})$, heat-transfer function; Q_W, heat taken up by liquid bath, without consideration of energy expended on evaporation, referred to the mass of the gas blown; ΔH_{t_0}, ΔH_{t_2}, change in mass enthalpy of gas with heating from 0°K to the temperature of the plasma jet and the temperature of the liquid at the bath outlet, respectively.

LITERATURE CITED

1. Yu. V. Tsvetkov and S. A. Panfilov, Low-Temperature Plasmas in Reduction Processes [in Russian], Nauka, Moscow (1980).
2. A. A. Erokhin, Plasma-Arc Refining of Metals and Alloys [in Russian], Nauka, Moscow (1975).
3. V. I. Yavoiskii, G. A. Dorofeev, and I. L. Pavkh, Theory of Blowing of a Steelmaking Bath [in Russian], Metallurgizdat, Moscow (1974).
4. I. P. Ginzburg, V. A. Surin, A. A. Bagautdinov, A. S. Grigor'yants, and L. I. Shub, "Study of the discharge of a gas stream from a submerged nozzle into a liquid," Inzh.-Fiz. Zh., 33, No. 2, 213-233 (1977).
5. S. V. Zhurbin, V. P. Motulevich, and E. D. Sergievskii, "Heat transfer in the cooling of plasma jets by a liquid coolant," Eighth All-Union Conference on Low-Temperature-Plasma Generators, Summary of Documents, Vol. 1, ITF (Institute of Thermophysics), Novosibirsk (1980), pp. 114-117.

RELATIVE INCREASE IN HEAT TRANSFER IN VISCOUS-INERTIAL REGIMES OF FLOW OF HELIUM AT SUPERCRITICAL PRESSURE IN A HEATED PIPE

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Results are presented from an experimental study of an increase in heat transfer to a turbulent flow of supercritical helium in a pipe.

It follows from [1, 2] that, given sufficiently high heat fluxes on the wall, the heat-transfer rate in the forced turbulent pipe flow of supercritical helium can increase significantly in the case of heat exchange with constant liquid properties. According to the correlations in [3, 4], based in the region $Nu > Nu_0$ on limited data from [1], this effect is governed by the specific heat ratio $\bar{c}_p/c_{pq}$. No special conditions have been observed for a relative increase in heat transfer in the case of viscous-inertial regimes of flow of supercritical helium. The present work is devoted to experimental investigation of this question.

The experiments were conducted on a crystal-type unit. High-pressure helium traveled from a ramp through a reducer and a control valve into the liquid-nitrogen-filled cryostat. The helium was cooled in the cryostat in two heat exchangers to about 80°K by reflux flow of the helium with the vapors of the boiling nitrogen. The helium was then sent to an adsorber with activated charcoal where it was cleaned and dried. It then traveled along a cryogenic pipeline to a KG 60/300-1 cryostat with liquid helium. Here, it was first gradually cooled to 8-15°K in the main heat exchanger by refluxing with the liquid helium. Then it was cooled to 5-6°K in an intermediate heat exchanger by outgoing vapors from boiling helium. Finally, it was cooled in a liquid heat exchanger to 4.2°K. The supercooled helium entered a vertical section located in a vacuum chamber submerged in liquid helium. The reverse helium flow, after throttling and heating, was passed through a metering section with a ring and then directed into a gas holder.

The working section was a stainless steel pipe 1.8 mm in diameter, 510 mm in length, and 0.1 mm in wall thickness. It had a heated section 400 mm (222 diameters) long which preceded the 78-mm-long unheated hydrodynamic stabilization section. The walls of the pipe were heated by the passage of a direct electrical current through them from niobium stannide leads. The wall temperature was measured at 15 stations along the working section with TSG-2 germanium resistance thermometers installed 25 mm (about 14 diameters) apart in holders made of electrolytic copper. The holders were secured tightly against the heated pipe through a lavsan film 10 μm thick. The mean-mass temperature of the helium at the inlet and outlet of the working section was measured with similar thermometers installed in mixing chambers. The temperature of the outer

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