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EFFECT OF A DISPERSED COMPONENT ON THE NATURE OF HEAT EXCHANGE DURING FLOW OF A HETEROGENEOUS JET AROUND A BARRIER

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Flow in a turbulent nonisothermal heterogeneous jet is characterized by considerable velocity [1, 2] and temperature disequilibrium [3] ($u_s \neq u$ and $T_s \neq T$, where u_s, T_s and u, T are velocity and temperature of dispersed and gas components). As was shown in [4], an impurity is not passive, and it leads to suppression of jet turbulence (a result of interphase exchange by pulse and heat). Nonetheless, during reaction of a heterogeneous jet with a barrier orientated along the normal to the running flow, a significant increase is observed in heat emission characteristics in the vicinity of the point of deceleration [5] (for a single-phase jet an increase in heat exchange is typical with an increase in the intensity of turbulence [6]). The intensity of the change in heat emission in this case is a result of velocity and temperature disequilibrium for flow in jets, and it depends on a number of factors (temperature, concentration, phase condition of the dispersed impurity, etc.) and on the nature of the reaction of the dispersed component with the barrier surface [7]. There are numerous experimental data devoted to this. Apart from work in [5, 7], attention is drawn to [8] where an increase is also noted in the heat flow (by a factor of 1.4) at the deceleration point for a plane cylindrical end and a hemisphere. The aim of the present work is a study of the effect of a dispersed component on heat exchange with jet flow around a barrier.

1. Experimental Procedure and Processing of Data. The study was carried out in an experimental unit consisting of an electrothermal source, a coordinated barrier device, a protective flap ahead of it with a mechanism for retension in the upper position, and also an automatic system for switching on the apparatus and switching off the source of supply.

High temperature jets were created by means of an electric arc heater with a partially fixed arc length. Use was made of a nozzle of the following geometry: outlet section diameter $d_a = 9 \cdot 10^{-3}$ m, critical cross-section diameter $d_* = (5.5\text{-}6) \cdot 10^{-3}$ m. Introduction of a dispersed impurity into the jet was accomplished in the discharge space directly beyond the critical cross section. In order to feed particles use was made of a powder doser of the vibration type.

Convective heat flow during operation of the jet on a plane boundless barrier located perpendicular to the running flow, was determined by the exponential method [9] for measuring

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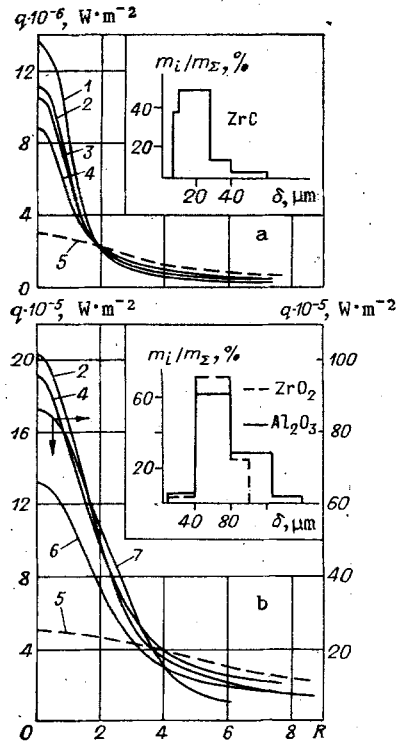

Fig. 1

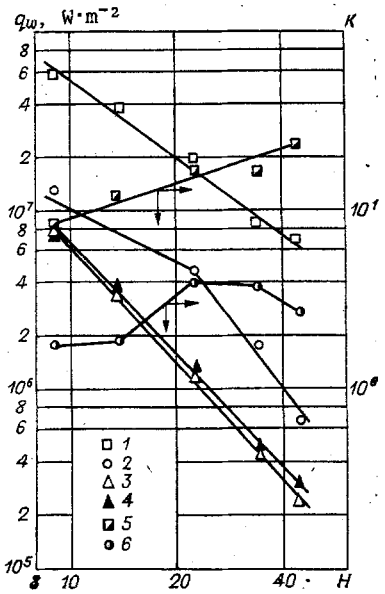

Fig. 2

the temperature of heat flow sensors with time, in the form of copper cubic calorimeters with a fin length of $3 \cdot 10^{-3}$ m insulated from each other by mica to whose inner surface Chromel–Copel thermocouples were attached. Twenty calorimeters were fixed into one series on a copper plate $3 \cdot 10^{-3}$ m thick fastened to a thermal insulating substrate. The optimum height of a calorimeter was selected by reference to the magnitude of the prescribed heat flow, and the minimum range for heating time after which there is equality for the increase in temperature with time at both surfaces of a calorimeter (plate), and also the maximum time range of the linear section for the copper sensor [9].

Temperature measurement for the calorimeter body T was carried out as follows. After bringing the nozzle into the regime the protective flap was released ahead of the barrier and a record was made of T and τ. After passage of a prescribed operating time τ the supply was switched off and the recording was stopped.

During operation of a heterogeneous jet on the barrier there was some particle adhesion. Due to the low thermal conductivity of the particles used in the experiment, a thin layer of deposited material served as a heat screen for heat flow q arriving at the barrier. In this case the correctness of measurements was monitored from the deviation from curves $T = f(\tau)$ from a linear relationship, since in the absence of a dispersed component readings from all of the calorimeters had a strictly linear dependence on time (linearity for the input signal, as was shown previously, was provided by selecting the optimum height of the heat flow sensor). The time of jet operation on the barrier was selected so that particles did not affect measurements of the heat flow (in order to determine its value use was made of the linear section of T on τ). Under experimental conditions τ was varied from 0.5 to 5 sec. The error in determining q did not exceed 10%.

Energy parameters of the heater, power input P, losss in electrodes Q, average mass enthalpy and temperature of the nozzle edge (without taking account of the dispersed component) h_a and T_a, were determined by the procedure in [9].

The experimental study was carried out in the following range of parameter variation: arc current I_g = 400 A; mass consumption of gas (nitrogen) through the nozzle $G_\Sigma = (1.14\text{-}3) \cdot 10^{-3}$ kg/sec; mass consumption of zirconium oxide ZrO_2 particles $G_s = (1.1\text{-}5) \cdot 10^{-3}$ kg/sec, zirconium carbide ZrC $G_s = 3.7 \cdot 10^{-3}$ kg/sec, aluminum oxide Al_2O_3 $G_s = 1.55 \cdot 10^{-3}$, $3.5 \cdot 10^{-3}$ kg/sec; initial mass consumption concentrations $\varkappa_a = G_s/G_\Sigma = 0.41\text{-}1.85$, 1.23, 1.36, 1.3; distance from the nozzle edge to the barrier $H = H/r_a = 98.9\text{-}44.5$. The powder particles used are a polydispersed mechanical mixture with the size fraction indicated in Fig. 1, where m_i is mass of the i-th fraction, m_Σ is total mass of particles of all fractions.

TABLE 1

Jet flow conditions	$\varkappa_a$	$P \cdot 10^{-3}$, W	$(P-Q) \cdot 10^{-3}$, W
$h_a = 9{,}44 \cdot 10^6$ J/kg	0	33.4	25.5
$T_a = 5660$°K			
ZrO_2			
$G_\Sigma = 2{,}7 \cdot 10^{-3}$ kg/sec	0.41	33.6	25.7
$d_* = 5{,}5 \cdot 10^{-3}$ m	0.89	34.2	26.3
	1.30	34.2	26.3
	1.85	34.4	26.5
$h_a = 8{,}83 \cdot 10^6$ J/kg	0	34.4	26.5
$T_a = 5520$°K			
ZrC			
$G_\Sigma = 3 \cdot 10^{-3}$ kg/sec	1.23	37.1	29.2
$d_* = 5{,}5 \cdot 10^{-3}$ m			
$h_a = 15{,}5 \cdot 10^6$ J/kg	0	25.6	17.7
$T_a = 6350$°K			
Al_2O_3			
$G_\Sigma = 1{,}14 \cdot 10^{-3}$ kg/sec	1.36	27.0	19.1
$d_* = 6 \cdot 10^{-3}$ m			
$h_a = 9{,}5 \cdot 10^6$ J/kg	0	33.6	25.7
$T_a = 5680$°K			
Al_2O_3			
$G_\Sigma = 2{,}7 \cdot 10^{-3}$ kg/sec	1.3	34.8	26.9
$d_* = 6 \cdot 10^{-3}$ m			

2. Results of the Study and Discussion. Given in Table 1 is a summary of nozzle energy parameters with different values of initial consumption mass concentration. Analysis of data in Table 1 indicates that the loss in power in electrodes does not depend on $\varkappa_a$ and it equals losses with absence of dispersed component in the jet. With an increase in $\varkappa_a$ there is some increase in arc voltage accompanied by an increase in P. Thus, introduction into the nozzle of impurity has almost no effect on the heater energy parameters.

Presented in Fig. 1 are some results for heat flow distribution over the barrier surface along radius $R = r/r_a$ with operation on it of heterogeneous jets containing dispersed additive ZrO_2, Al_2O_3, and ZrC, for H = 13.3 (Fig. 1a, jet with ZrO_2 particles) and 33.3 (Fig. 1b, curve 4 for ZrO_2, curve 6 for Al_2O_3, curve 7 for ZrC) for the flow conditions indicated in Table 1. Positions 1-7 correspond to $\varkappa_a = 1.23$, 1.3, 1.85, 1.3, 0.89, 0.41, 0. Here and subsequently all of the linear dimensions are related to the radius of the nozzle edge r_a. As follows from the data, distribution of q along the radius is nonuniform in character, and this nonuniformity is greater, the closer the barrier is located to the nozzle edge. The nature of change in q along the barrier decreases uniformly with a maximum at the deceleration point, and it relates to the nature of change of q for a single-phase gas jet ($\varkappa_a = 0$).

Presence in the jet of a dispersed component sharply increases heat flow in the vicinity of the deceleration point even with a small ($\varkappa_a = 0.41$) initial consumption mass concentration of the additive (curve 4 in Fig. 1a, b). Results were obtained in [5, 8] which conformed qualitatively with the present study. It was noted in [5] that there is an increase in transfer coefficient even with low values of concentration: $\varkappa_a = 0.11$ (it is lower by a factor of 1.75 for reaction of an isothermal turbulent jet of nitrogen with $T_a = 293$°K supporting a dispersed admixture of graphite $d_p = 10 \cdot 10^{-6}$ m with a plane perpendicular barrier heated by an electric current with distance H = 8). A further increase in $\varkappa_a$ leads to an increase in heat flow at the deceleration point. However, this increase is not linear (with an increase in $\varkappa_a$) and with $\varkappa_a > 1$ it slows down.

With an increase in distance from the deceleration point in the radial direction the heat flow from a single-phase jet (curve 5) exceeds that from a two-phase jet (curves 1-4, 6, 7). This nature of change in heat flow along a barrier at the periphery conforms qualitatively with data in [5], and it is observed for all distances realized in the experiment.

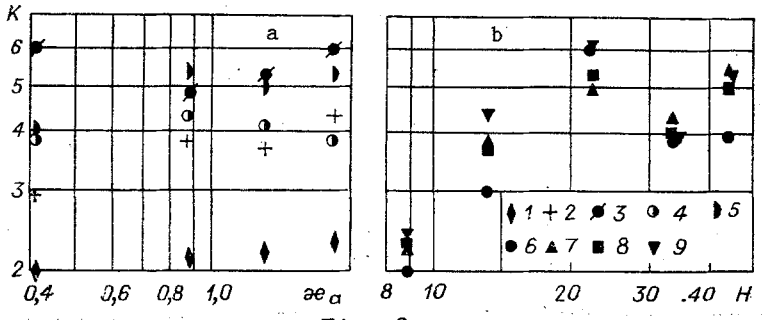

Fig. 3

TABLE 2

Component	ρ_p, kg/m³	T_{pm}, K	$\varkappa_a$	T_w, K	$q_w \cdot 10^{-5}$, W/m²
Al_2O_3	3980	2273	1,3	2500—2000	13.2
ZrO_2	5560	3048	1,3	3200—2900	20.3
ZrC	6700	3803	1,23	4000—3650	86.0

It should be noted that an increase in heat flow (under stable uniform flow conditions) depends to a considerable extent on the nature of the admixture material introduced into the jet. Heat flow at the deceleration point q_w from a jet with ZrO_2 particles is greater than q_w for Al_2O_3 particles, and q_w for a jet with ZrC particles is greater than q_w for ZrO_2 particles (Fig. 1b, curves 2, 6, 7), i.e., with unchanged nozzle power for $\varkappa_a$ and H = const the thermal flow into the barrier is greater, the higher the dispersed component temperature (Table 2). In an experiment the dispersed component temperature was determined directly from the change in surface temperature T_w for flat specimens by a FÉP-4M pyrometer and it was close to the melting temperature T_{pm} for the designated materials (see Table 2, where for T_w the temperature range is indicated for the range of distance for H from 8.9 to 33.3).

Provided in Fig. 2 is the change in heat flow at the deceleration point in relation to distance from the nozzle edge to the barrier H for heterogeneous jets containing admixture of ZrC (1 — $\varkappa_a$ = 1.23) and Al_2O_3 (2 — $\varkappa_a$ = 1.36). It follows from Fig. 2 that for $\varkappa_a$ = const, as also in the case of single-phase reaction (3, 4 — $\varkappa_a$ = 0), heat flow q_w increases with approach of the barrier towards the nozzle edge. In addition, at all distances H the q_w from a two-phase jet is markedly greater than from a single-phase jet.

The increase noted in heat exchange in a barrier with introduction into the jet of dispersed admixture may be characterized by a coefficient of increase in heat exchange for the deceleration point represented by the ratio of heat flow from the jet with a dispersed component q_w to heat flow q_{w0} from a jet of pure gas with H = const: $K = q_w/q_{w0}$ (Fig. 2, 5 — ZrC, $\varkappa_a$ = 1.23, 6 — Al_2O_3, $\varkappa_a$ = 1.36; Fig. 3a, b — ZrO_2, $\varkappa_a$ = 0.41-1.85). Positions 1-5 in Fig. 3a relate to H = 8.9, 13.3, 22.2, 33.3, 44.5, and 6-9 in Fig. 3b relate to $\varkappa_a$ = 0.41, 0.89, 1.3, 1.85. As follows from the data presented, with H = const (Fig. 3a) for a jet containing a dispersed admixture of ZrO_2, with an increase in initial consumed mass concentration there is a uniform increase in coefficient K up to a value $\varkappa_a \simeq 1$. With a further increase in $\varkappa_a$ ($1 < \varkappa_a \leqslant 1.85$) K is almost constant. On the other hand, for $\varkappa_a$ = const (Fig. 3b) with an increase the distance of the nozzle edge from the barrier K increases, and with H ≈ 22.2 it reaches its maximum value of ~4-6 for a jet containing an admixture of Al_2O_3 and ZnO_2, respectively. A further increase in H leads to a reduction in coefficient K or to constancy of it for certain values of $\varkappa_a$. The reduction in K with H > 22.2 is connected to a considerable extent with a drop in temperature of the dispersed component, which also leads in turn to a reduction in the proportion of heat flow entering the barrier from the dispersed phase. A reduction in dispersed component temperature is confirmed by T_w measurements (with H > 22.2, T_w falls; see Table 2).

For reacting jets containing an admixture of ZrC (Fig. 2, 5, $\varkappa_a$ = 1.23 = const) a uniform increase in K is observed with an increase in H. The maximum increase in heat exchange (by a factor of ~25) in this case occurs with H = 44.5. Considerable values of coefficients for the increase are caused to a certain degree by an increase in temperature for the gas component due to combustion of zirconium carbide particles observed in an experiment with distances H > 9. In addition, the increase in temperature of the gas component in the range

of distances H = 10-20 according to data in [3] (high-temperature jet of argon supporting a titanium admixture) may be two- or threefold (compared with a single-phase jet). Combustion of a dispersed admixture is possible due to intense injection of air into the jet from the furnace space. Calculations carried out by the procedure in [10] indicate that with H = 10 for the current experimental conditions the content of air in the axis of a single-phase jet of variable composition reaches 75-80%.

Thus, presence in a high-temperature jet of a dispersed component markedly increases heat exchange in the vicinity of the deceleration point even with small values of initial mass consumption concentration of admixture. In addition, the coefficient for the increase in heat exchange for the deceleration point may reach considerable values and it depends (within the limits of the studies carried out) on $\varkappa_a$, the nature of the material particles, and distance of the nozzle edge from the barrier.

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