A STUDY OF HEAT TRANSFER AND PLASMA CONDENSATION IN CYLINDRICAL AND CONICAL CHANNELS

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Results are shown of an experimental study concerning the heat and mass transfer during the flow of plasma of alkali metals through cylindrical and conical channels.

In many engineering applications one encounters the problem of heat and mass transfer from a plasma jet to channel walls of diverse geometry. The results of a study concerning the flow of nonequilibrium plasma with condensation have been reported earlier in [1]. The purpose of this later study was to further explore the problem of condensate and thermal flux distributions in a plasma stream with a high condensation rate.

The plasma source in this experiment was a coaxial plasmatron operating at a power up to 100 kW. Lithium was used as the active substance. According to spectroscopic and superhigh-frequency measurements, the discharge velocity corresponded to a Mach number M = 3-10 at a temperature T = 5000°K (T_e = 10,000°K)* and a mass flow rate $m = (2-3) \cdot 10^{-5}$ kg/sec at the exit. The apparatus is shown schematically in Fig. 1.

The plasmatron was placed horizontally on the lid of a vacuum chamber. A dc generator served as the voltage supply, through a loading rheostat. The active substance (lithium), in the liquid state, was fed into the discharge zone of the plasmatron from a displacer at a prescribed flow rate. For the purpose of checking the given flow rate, the feed system was weighed before and after a test. The vacuum system ensured a rarefaction down to $5 \cdot 10^{-5}$ torr at a leakage rate of 30 μl Hg/sec. A preliminary rarefaction (of the order of 10^{-2} torr) in the vacuum chamber was produced by means of model VN-6G prevacuum pumps. A vacuum of $5 \cdot 10^{-5}$ torr was achieved by the operation of models BN-4500 and VA-8-7 high-vacuum aggregates.

For the study of heat and mass transfer in the vacuum chamber, a channel model was mounted on a special coordinate mechanism with which it could be inserted into the stream after the plasmatron has stabilized in the operating mode.

The coordinate mechanism made it possible to vary the distance between the throat section of the nozzle (plasmatron anode) and the channel entrance from 10 to 100 mm. For our study of heat and mass transfer we used channels of various shapes and dimensions, as shown in Fig. 2 and in Table 1. In the exit segment was provided an annular slot with an inlet section of 0.2×0.3 mm^2, for draining uncondensed gases from the channel. The temperature of a channel wall was measured with Chromel–Alumel thermocouples and then recorded on a model OT-24 oscillograph. A model ISP-51 spectrograph was used for recording the spectrum.

The tests were performed in the following sequence. At a given fixed power input to the plasmatron and a given flow rate of active substance, a channel was inserted into the stream for a definite period of time. The chamber was then dehermetized, the channel was withdrawn, and the amount of condensate was

*These spectroscopic and superhigh-frequency measurements were performed by V. G. Mikhalev and Yu. P. Shurov.

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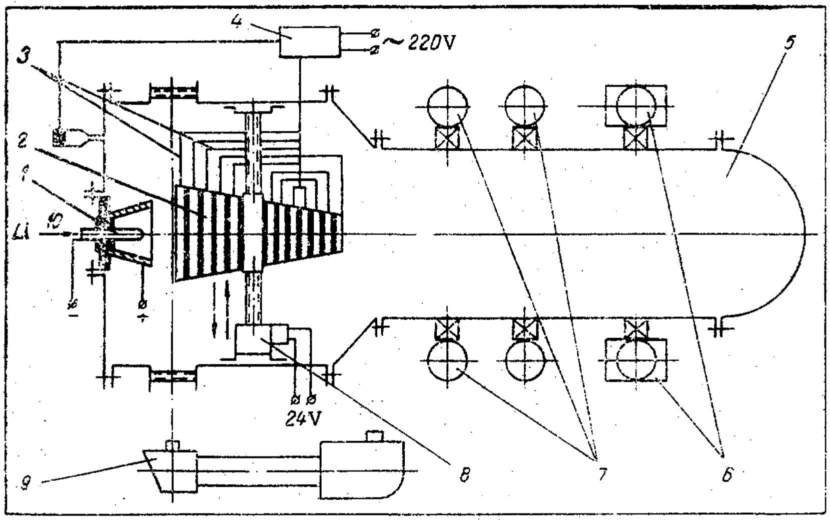

Fig. 1. Schematic diagram of the test apparatus: 1) plasmatron; 2) channel; 3) thermocouples; 4) oscillograph; 5) vacuum chamber; 6) model VN-6G prevacuum pumps; 7) models BN-4500 and VA-8-7 pumps; 8) coordinate mechanism; 9) spectrograph; 10) feed of active substance.

determined by titrating at the probe surface (in channels *a* and b or at channel segments (channel c). With channels *a* and b, the thermal power of the jet and the condensate profile along the channel were measured with special probes made of stainless steel or copper. These probes comprised circular disks, 0.65 cm^2 in area and 1-2 mm thick, with welded-on thermocouples, and spaced along the channel generatrix 40-70 mm apart, attached to a special device for opening and closing them during a test. The temperature of the channel walls was held constant at a 100-150°C level by means of water cooling.

The probes were exposed for 20-200 sec. Since they were located sufficiently close to one another, hence it was permissible to regard the channel surface as divided into zones, each with its own probe. It was also assumed that, within any one zone, the condensation rate j ($g/cm^2 \cdot sec$) was constant. The amount of condensate precipitated on the surface of each fictitious zone m_i during the test time could be found from the simple relation

$$m_i = S_i \frac{m_{pi}}{S_{pi}},$$

with S_i denoting the area of a fictitious channel zone; m_{pi} denoting the amount of condensate precipitated on a probe; and S_{pi} denoting the area of a respective probe.

Unlike channels *a* and b, channel c consisted of thermally insulated copper segments. Each segment served as a probe for determining the mass of condensate and the thermal flux from the jet. In such a channel the distribution of condensate and thermal flux could be measured more accurately. The higher accuracy was achieved here by a reduction of heat leakage along the channel.

The thermal flux profile along the channel was in all cases measured by the calorimetric method. In addition, we also measured the angular profiles of thermal flux and condensate mass, using for this an arcuate instrument holder with a radius of 750 mm and carrying 15 probes. These were spaced at equal distances apart, with their surfaces oriented normally to the arc radius, while the vertex of the conical nozzle (anode) was located at the center of that circle. With the aid of the coordinate mechanism, this arcuate probe assembly was inserted into the jet for 10-100 sec. The function and the arrangement of probes was the same here as in the earlier described experiments.

In Fig. 2 are shown the profiles of thermal flux and condensate mass along channels of various shapes and at conventional levels of plasmatron input power. According to the graphs, the profiles of thermal flux and condensate mass along channels are quite similar, regardless of the geometry. Within a segment L/D = 0.5-0.8 both q and m increase up to a certain maximum and then sharply decrease. The locations where q and m are maximum depend on the plasmatron input power and on the distance from the throat section of the nozzle (anode) to the channel entrance. The maxima of q and m shift farther away from the channel

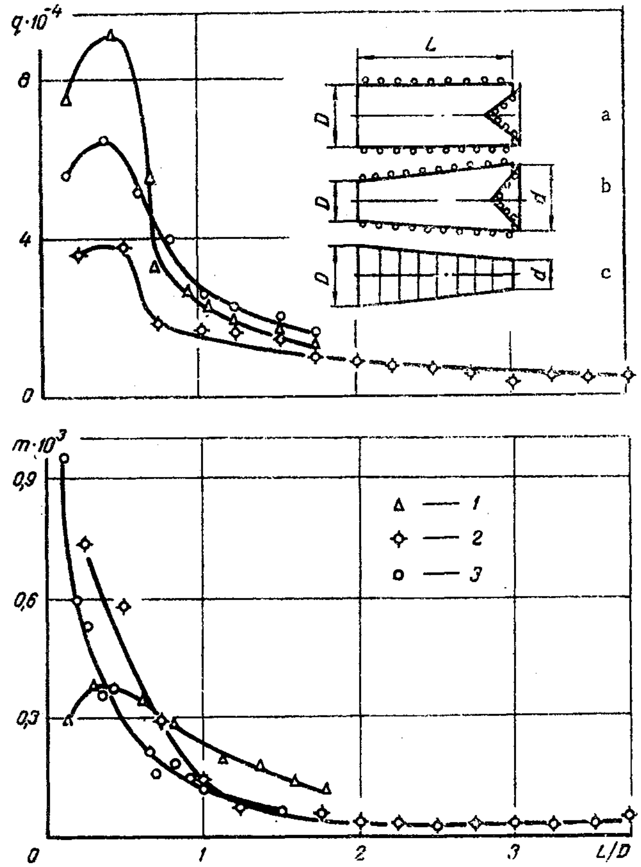

Fig. 2. Longitudinal profiles of thermal flux (q, W /m^2) and condensate mass (m, kg): 1) channel *a* with N = 40 kW; 2) channel c with N = 40 kW; 3) channel b with N = 70 kW.

TABLE 1. Geometrical Dimensions of Channels

Shape of channel	D, mm	d, mm	L, mm	$\frac{L}{D}$	α	S, m^2
Cylinder *a*	500 400 300	— — —	1000 700 600	2,00 1,75 2,00	— — —	1,7 0,88 0,57
Cone b	300	550	620	2,10	12°	0,83
Segmented cone c	400	100	1500	3,75	6°	1,18

entrance, as the power input increases at a constant distance from the nozzle (anode) throat to the channel entrance, or as that distance is decreased at a constant input power.

In several cases the amount of condensate at the channel exit increased somewhat, while the thermal flux did not. Such a divergence between $m = f(l/D)$ and $q = f(l/D)$ profiles at a channel exit can, apparently, be attributed to the reflection of particles at the wall near the exit and to the presence of endface reflectors.

Experimental studies made with channels of various shapes have established that the condensation of a plasma jet is most nearly complete, when the distance from the nozzle (anode) throat to the channel entrance remains within $(0.1 \text{ to } 0.5)d_n$, at a plasmatron input power ranging from 30 to 70 kW and with the channel diameter at the entrance not smaller than $1.5d_n$.

In cylindrical or conical channels, almost the entire jet energy is released within a distance equal to two to three diameters of the entrance section, where also the entire active substance condenses. The condensation rate is highest at the surface of convergent cones, however, which has been explained in [1] by the hydrodynamic characteristics of plasma flow in such channels.

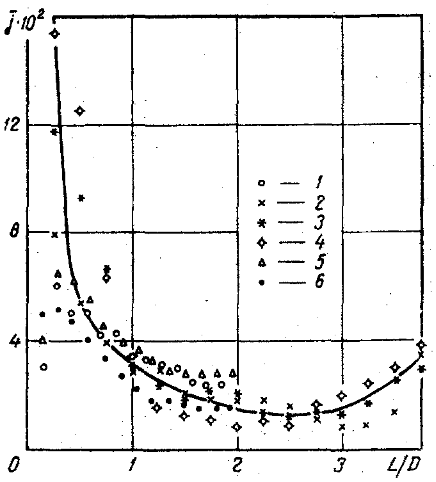

Fig. 3

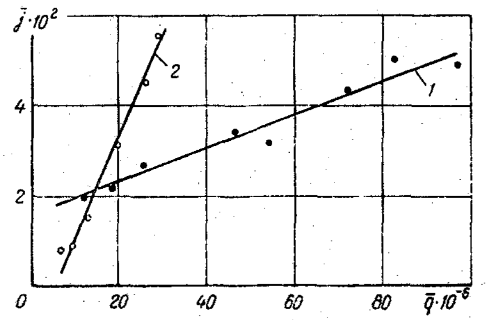

Fig. 4

Fig. 3. Profile of condensate density in a channel: 1) channel b with N = 70 kW; 2) channel c with N = 35 kW; 3) channel c with N = 38 kW; 4) channel c with N = 40 kW; 5) channel *a* with N = 40 kW; 6) channel *a* with N = 30 kW.

Fig. 4. Relation between condensation density and thermal flux: 1) channel *a* with N = 40 kW; 2) channel b with N = 70 kW.

A peculiar aspect of analyzing the process of plasma condensation in a channel in these experiments is that, because of the difficulties in making measurements, the criterial numbers characterizing the process in a jet cannot be used. This makes it necessary to evaluate the test data here by a method other than those of similar thermotechnical experiments in gases and liquids to which Nu, Re, Pr, and other numbers are applicable. It is well recognized that a correct use of these numbers requires the sectional profiles of basic parameters in the channel (density temperature, velocity) to be known.

Another peculiar aspect of analyzing the test data of these experiments is that the values of parameters are averaged over the measurement time, while the processes are often transient. Such a situation leads to certain errors. In order to reduce these errors, the exposure time of the probes in our experiment had to be shortened. In the course of measurements, many data have been collected which indicate an appreciable effect of the system geometry on the plasma condensation. The governing parameters include the integral plasmatron characteristics: the flow rate, the power, and certain quantities determining the processes in a channel (T_W, q, and j). A dimensional analysis of the quantities governing the mass-transfer processes has yielded a large number of dimensional simplexes and complexes. It is to be noted that, because of the difficulties in making measurements, it has not been possible to consider the influence of all these groups. The following expressions relate geometrical ratios to two dimensionless parameters:

$$\bar{j} = \frac{jd^2}{m}\,; \quad \bar{q} = \frac{qd^2}{mV^2}\,.$$

The first of them $\bar{j}$ is proportional to the ratio of condensation rate to jet flow intensity at the nozzle (anode) throat; $\bar{q}$ represents the fraction of jet energy dissipated in the channel wall. Obviously, these parameters do not constitute a complete set, if only because they do not contain the thermophysical properties of the active substance and because the expansion process depends in a peculiar manner on the plasmatron parameters.

The $\bar{j} = f(L/D)$ profile is shown in Fig. 3 for conical and cylindrical channels. According to the graph, these profiles follow a similar trend and diverge only slightly for different channel shapes, different distances from the nozzle (anode) throat to the channel entrance, and different levels of input power.

The relation between mass transfer and energy is shown in Fig. 4. The $\bar{j} = f(\bar{q})$ curve comes close enough to a straight line, for either a cylindrical or a conical channel. When the plasmatron draws heavy power ($\bar{q} > 15 \cdot 10^6$ W/m^2), then, with the same thermal flux, the plasma condensation process can be designed more efficiently on the surface of conical channels.

NOTATION

D, d are the diameters, m;
$\dot{m}$ is the flow rate of the active substance, kg/sec;
j is the condensation rate, $kg/m^2 \cdot sec$;
L is the channel length, m;
q is the thermal flux density, W/m^2;
S is the surface area, m^2;
T is the temperature, °K;
v is the flow velocity at the nozzle (anode) throat section, m/sec.

Subscripts

p denotes the probe;
n denotes the nozzle (anode) throat section;
e denotes the electrons;
i denotes a fictitious channel zone or segment;
w denotes the channel wall.

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