EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN THE REGION OF A STAGNATION POINT

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An investigation has been made of heat transfer to a body from a gas stream in the region of the stagnation point, as a function of enthalpy and stagnation pressure of the gas, and the velocity gradient at the stagnation point. The enthalpy of the gas (nitrogen) was varied from $6.5 \cdot 10^3$ to $115 \cdot 10^3$ kJ/kg, and the pressure from 10.3 to 14.7 N/cm^2. The upper enthalpy limit corresponded to an ionization level of $x_{N+} = 0.43$. The investigation was carried out in a gas jet heated by means of an electric arc.

In the flow of a dissociated and ionized gas over a body, the heat flux from the gas to the wall is made up of the heat flux due to the temperature gradient at the wall and the thermal conductivity of the gas, and additionally of the flux due to the concentration gradient of atoms, ions, and electrons. While the diffusion of atoms relative to molecules in a dissociated gas increases the heat flux by roughly 20% [1], the presence of electrons and ions leads to diffusion of ion-electron pairs (ambipolar diffusion), the intensity of which is greater than the diffusion of atoms.

Depending upon the parameters of the incident gas stream, the boundary layer may be in a state of thermodynamic equilibrium, when the rate of chemical and electronic reactions is much greater than the velocity of motion and diffusion of the gas, or it may be "frozen" (the second extreme case) in the inverse ratio between the velocities. In the second case the heat flux may be increased by the heat of recombination liberated at a catalytic surface.

Another special feature of heat transfer in the presence of dissociation and ionization is due to the specific nature of the dependence of the physical properties of the gas on temperature and pressure at high temperatures. Maxima [2,3] appear in the temperature dependences of the specific heat and thermal conductivity, associated with dissociation and ionization. The dependences of viscosity and density on temperature are also quite complicated [2,27]. These cannot therefore be approximated by simple relations, and especially they cannot be assumed constant, as is done at low temperatures.

The Lewis-Semenov number at temperatures above 10 000° K is 0.6 according to one evaluation, and 1 according to another [1], and even 2 [5], instead of the usual value of 1.4 up to 8000° K. It should be noted that the data of various authors on other properties of nitrogen, for example, on thermal conductivity [3] at high temperatures, also differ appreciably one from another.

The papers of Sibulkin [6], Lees [7], Fay and Riddell [1], and others have dealt with the theoretical investigation of heat transfer to a body from a dissociated gas in the region of the stagnation point. In Fay and Riddell's paper the cases of equilibrium and "frozen" flow were examined, as well as intermediate cases. For the stagnation point, where the basic parameters have a maximum and are assumed independent of the coordinate along the surface (except the velocity, which may be determined by the expression $u = \beta\chi$, the differential equations of the boundary layer were solved numerically, including allowance for the gas being a mixture of components. Numerical solutions were carried out for Pr = 0.71, Le from 1 to 2, and a recombination rate parameter c_1 from 0 to ∞. The analysis embraced the stagnation enthalpy range from 1550 to 24 100 kJ/kg of air in thermodynamic equilibrium, corresponding to velocities from 1770 to 7000 m/sec at heights from 7600 to 37 000 m. The wall temperature was varied from 300° to 3000° K.

The heat flux in a dissociated gas at rest, as was noted above, is determined as follows:

$$q = q_T + q_D = \lambda \operatorname{grad} T + h_A D \rho \operatorname{grad} c_A,$$

or

$$q = \frac{\lambda}{c_p} \operatorname{grad} h \left[1 + (\mathrm{Le} - 1) \frac{h_A \operatorname{grad} c_A}{\operatorname{grad} h} \right].$$

It follows from the last expression that the formula for heat flux must contain the enthalpy difference across the boundary layer, the physical parameters of the gas, and the correction for diffusion. In addition, the heat flux in a moving gas depends on the velocity gradient at the stagnation point.

The dependence of heat flux on the numerous parameters, describing the results of the numerical calculations to an accuracy of 2%, was obtained by Fay and Riddell in the form

$$q = 0.763\,\mathrm{Pr}^{-0.6} (\rho\mu)_w^{0.1} \cdot (\rho\mu)_{es}^{0.4} \left[1 + (\mathrm{Le}^n - 1) \frac{h_D}{h_{es}} \right] (h_{es} - h_w) \sqrt{\left(\frac{du}{dx} \right)_{es}} \quad (1)$$

or

$$\frac{\mathrm{Nu}}{\sqrt{\mathrm{Re}}} = 0.763\,\mathrm{Pr}^{0.4} \left(\frac{\rho_{es}\mu_{es}}{\rho_w\mu_w} \right)^{0.4} \left[1 + (\mathrm{Le}^n - 1) \frac{h_D}{h_{es}} \right]. \quad (1a)$$

The Le number exponent was 0.52 for equilibrium flow and 0.63 for "frozen" flow.

Formula (1) differs from the results of Sibulkin and Lees by the factor $\left(\frac{\rho_w \mu_w}{\rho_{es}\mu_{es}}\right)^{0,1}\left[1+(\mathrm{Le}^n-1)\frac{h_D}{h_{es}}\right]$, which increases the heat flux by 20%. Rose and Stark [8] measured the heat flux in a shock tube by a calorimeter method, using platinum film gages, and by the change in surface temperature, and found that their results agreed with calculations according to the Fay and Riddell formula, if it was assumed that Pr = 0.71 and Le = 1.4. In their investigation, Fay and Riddell did not examine the influence of ionization of the gas on heat transfer. A number of papers [4, 5, 9–16] have been devoted to this question.

According to the calculations of Adams [5], the thermal conductivity of the gas increases by a factor of 5 when ionization sets in, because of the large mobility of the electrons. The viscosity is also changed. It is assumed that the ion-electron pairs diffuse twice as fast as the atoms and molecules. The Le number is assumed to be 2. Hence Adams estimated the increase in heat flux due to ionization. The calculations showed that it did not exceed 30% for values of velocity up to 13 km/sec.

In [9] five methods of calculating heat transfer at a stagnation point with reference to a partially ionized gas are compared. Of these the methods of Adams and Cohen were developed to take account of ionization, while the others are an extrapolation of the methods of Fay and Riddell, and of Scala, and of the determinant enthalpy method. It was shown in the paper that the results of calculations by the Fay and Riddell method and by the determinant enthalpy method are in good agreement with results obtained by Cohen's method, allowing for ionization, and that therefore the Fay and Riddell method may be applied right up to a velocity of 12 km/sec. It should be noted that, generally speaking, the difference between the results of calculations by the various methods reaches 40%.

A recent paper which makes a theoretical investigation of heat transfer to a body from a partially ionized gas in the stagnation-point region is that of Fay and Kemp [4]. In this paper the gas is assumed to be a two-component one as regards diffusion. One component consists of the molecules, the other of atoms, ions, and electrons. In addition, the concept of "frozen" specific heat and thermal conductivity is used. As in the previous Fay and Riddell paper, an equilibrium and a "frozen" boundary layer is examined, while the air is assumed to consist of "air" atoms, molecules, and ions.

The equations were solved numerically for nitrogen, and the results are shown in Fig. 5 (curves 2 and 3). The authors observed an appreciable difference between heat transfer in equilibrium and frozen boundary layers when v > 9 km/sec. The values of the quantity $\mathrm{Nu}/\sqrt{\mathrm{Re}}$ obtained are close to the Pallone and Van Tassel calculation results, and diverge by a factor of approximately 2 at a velocity of 12 km/sec from the calculation of Scala and Warren [9,4] (Fig. 5, curve 4). The authors attribute this discrepancy to a difference in the values of the transfer coefficients used. As was remarked in [4], according to Adams's evaluation, the quantity $\mathrm{Nu}/\sqrt{\mathrm{Re}}$ is equal to 0.4 for the velocity range 9–14 km/sec. This value is close to that calculated by Fay and Kemp for a "frozen" boundary layer.

The theories of Fay and Kemp, Pallone and Van Tassel, and Scala and Warren have been confirmed by measurements of heat flux in shock tubes [4, 11, 12]. It is shown in [13] that the divergence of the experimental results may possibly be explained by the influence of the electrons in the boundary layer not being in equilibrium, by the state of the surface, and by the kind of sensor material.

Because of the discrepancy between the different theories, which may be explained by the use of inaccurate the use of a transport coefficients of the gas at high temperatures, by the use of a number of simplifying assumptions, and also by a difference in the experimental results obtained using equipment generally of one type, it is especially necessary to have experimental verification of methods of calculating heat transfer in the presence of ionization.

In the present work measurements of heat flux were made in a stream of nitrogen heated in an electric-arc heater whose features have been described elsewhere [17,18]. The discharge chamber of the electric-arc heater developed by the author for the investigation of heat transfer results from an investigation of discharge chambers of various types [17,18], and in comparison with them it possesses a number of special constructional features permitting stable operation in the range of variation examined—current from 150 to 1300 A and gas flow rate from 2 to 10 g/sec. No appreciable changes in the electrodes were observed after 10 min of continuous operation of the discharge chamber at a current of 600 A and a power of 180 kW.

Treatment of the current-voltage characteristics of the electric-arc heater (Fig. 1 A) by the method suggested in [20], yields an analytical relation for the current-voltage characteristics in the form

$$U = 436G^{0.632}I^{-0.264}.$$

The maximum deviation of the voltage calculated from this formula from the mean curves of Fig. 1A is 10%.

It may be seen from Fig. 1B, that in the range of power investigated, 70-270 kW, the mean mass enthalpy of the gas at the exit from the anode, determined by the heat balance of the discharge chamber, depended linearly on the power, for the various gas flow rates. The coefficients entering into the

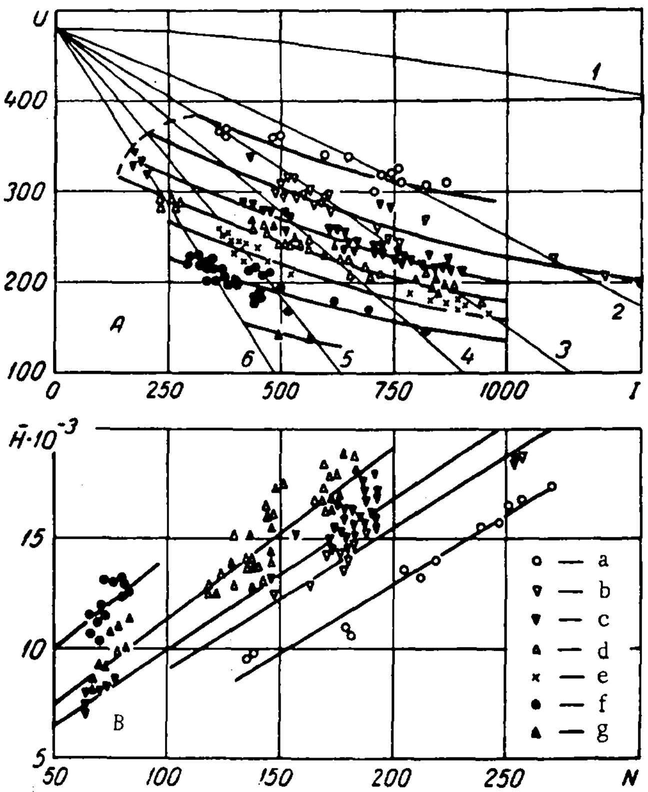

Fig. 1. Characteristics of the electric-arc heater: A) current-voltage characteristics [1) source voltage; 2, 3, 4, 5, 6) available voltage at the arc, with rheostat resistance 0.183, 0.283, 0.379, 0.575, 0.771 ohm]; B) dependence of the mean mass enthalpy of the gas on the power: a) mass flow rate of gas = 10 g/sec; b) 7; c) 6; d) 5; e) 4; f) 3; g) 2.

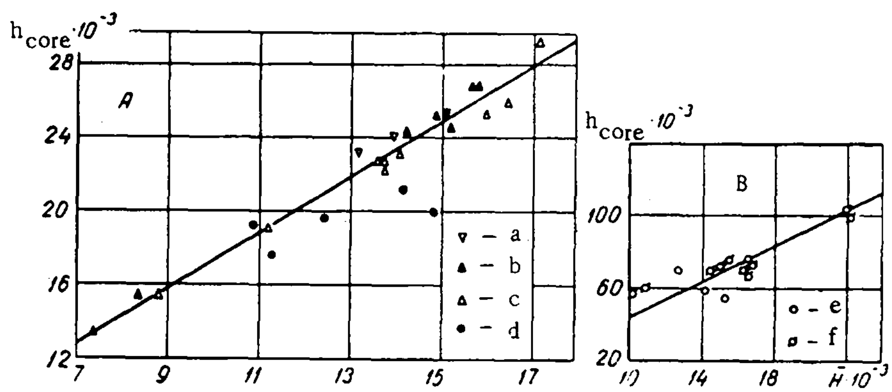

Fig. 2. Dependence of the enthalpy of the gas in the core of the stream on the mean mass enthalpy: A) with gas flow rate of 7, 6, 5, 3 g/sec (points a, b, c, and d, respectively), enthalpy sensor diameter of 5 mm, and depth of cathode "bowl", l_{cat} = 100 mm; B) with gas flow rate from 6 to 10 g/sec and l_{cat} = 50 mm; (e) measurements using an enthalpy sensor; (f) spectroscopic measurements).

linear dependence of enthalpy on power, may be expressed in turn in the form of equations of straight lines depending on the gas flow rate. Thus the expression for the mean mass enthalpy of the gas, in kJ/kg, takes the form

$$\overline{H} = (21.55N - 0.671GH - 166G + 1730)\cdot 4.19.$$

The deviation of values calculated from this formula from the mean lines on Fig. 1B does not exceed 6%. It may be noted that by using this expression and a simple transformation, we can obtain the dependences on N and G of the power going into heating the gas, and the efficiency of the discharge chamber. The expression obtained similarly for the mean mass velocity, whose error does not exceed 4%, has the form

$$\overline{W} = (1.2N + 0.17GN + 55.2G + 48)\,225/d_{an}^2. \tag{2}$$

Using the Bernoulli equation and (2), we may calculate the stagnation pressure, the formula taking the form (N/cm^2)

$$p_{stag} = \left(1 + 0.65\cdot 10^{-2}\frac{G}{d_{an}^2}\overline{W}\right)\cdot 9.81. \tag{3}$$

The measurements have shown that the experimental values of excess pressure in the pressure range examined from 10.3 to 14.7 N/cm^2 at a distance of 25 mm from the exit section of the anode do not differ by more than 12% from values calculated from (3).

In the investigations of heat transfer to a body from a stream of ionized gas, use was made of the special feature of discharge chambers with eddy gas stabilization [21], this being that in the core of the stream the temperature is roughly twice the mean mass temperature, and reaches 15 000°–18 000° K [17,18].

The enthalpy of the gas in the jet core was determined using a stagnation enthalpy sensor according to the method described in [22], and additionally from the temperature measured by spectroscopic methods [18,19]. The enthalpy measurement results for two discharge chambers differing from one another in construction, are shown in Figs. 2A and B. It follows from (1) that, the heat flux is determined in addition to the stagnation enthalpy, by the velocity gradient at the stagnation point.

In the case when the body nose is part of a sphere of radius R, the velocity gradient is [23]

$$\left(\frac{du}{dx}\right)_{es} = \frac{1}{R}\sqrt{2(p_s - p_\infty)/\rho_s}. \tag{4}$$

As was shown in [24], for M < 1, velocity gratients determined experimentally differ from those calculated from (4) by 3–35%. In the present work the velocity gradients were determined using the Bernoulli equation in accordance with measured pressure distributions [25]. The pressure distribution sensors had plane end faces with a number of apertures positioned in different ways on the various sensors, and the heat flux sensors were of the same size and shape. Both cooled copper and uncooled graphite sensors were used in the tests. The measurements show (Fig. 3) that the quantity $k = [(u/\overline{w})/r/r_{pd})]$ does not depend on the gas flow parameters. Thus, for d_{pd} = 5–12 mm, du/dr = (1.86 ± 0.12) $\overline{w}/d_{pd}$, and for d_{pd} = 18–22 mm, du/dr = (1.7 ± 0.2) $\overline{w}/d_{pd}$. This result agrees with the conclusions of [25].

For the heat flux measurements, three methods [26] were used: The cooled calorimeter method, the exponential (calorimetric) method, and the Brogan method.

In the first case the heat flux was determined as the ratio of the heat going to heat a known amount of cooling water in unit time, to the area of the heated sensor surface. In the second case the heat flux was determined from the change of heat content of a copper cylinder

$$q = \delta\rho\, c_p \frac{dT}{d\tau}.$$

And in the third case, from the time to start of melting of copper and aluminum cylinders, insulated from the side surface

$$q = \frac{\sqrt{\pi}}{2}\sqrt{\frac{\rho c_p \lambda}{\tau_1}}\, t_m. \tag{5}$$

The diameters of the heat flux sensors for all the methods varied from 5 to 20 mm. The thicknesses of the cylindrical specimens in the second method lay in the range 8 to 0.5 mm, depending on the values of the heat flux and sensor diameter. The length of the cylinders in the third method was 200 mm, which, combined with the insulation of the side surface, allowed the model to be the semi-infinite body for which (5) was written. The heat flux sensors, and also the sensors mentioned above, were mounted at a distance of 25 mm from the exit section of the discharge chamber. Most of the sensors were protected on their side surface by a cooled guard ring in the form of a truncated cone and a metal tube.

The results of the heat flux measurements are shown in Fig. 4 as a function of stagnation enthalpy and pressure, for heat flux sensor diameters (which determine the value of the velocity gradient) of 5 and 20 mm. The maximum measured value of heat flux was 25 kW/cm^2 for a value of enthalpy corresponding to a temperature of 14 000° K. An estimate of the fraction of gas radiation in the heat flux, without making allowance for absorption, gives a value of 3%.

It may be seen from the graphs that the measured values of heat flux agree with those calculated over the whole range of parameters of the gas, assuming the following values of the quantities: Pr = 0.71, Le = 1.4, t_{st} = 100° C. This result confirms the conclusion reached in [8] and based on comparison with other theories that it is possible to apply

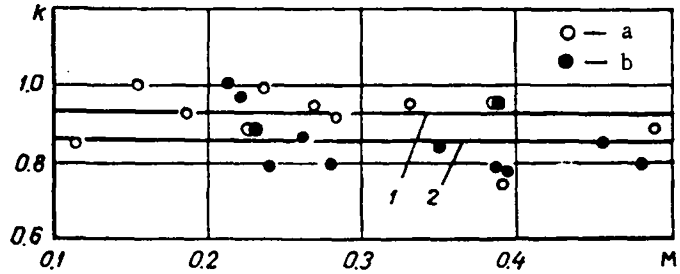

Fig. 3. Dependence of coefficient $k = [(u/\bar{w})/r/r_{pd})]$ on M: 1) and a) d_{pd} = 5–12 mm; 2) and b) 18–22 mm.

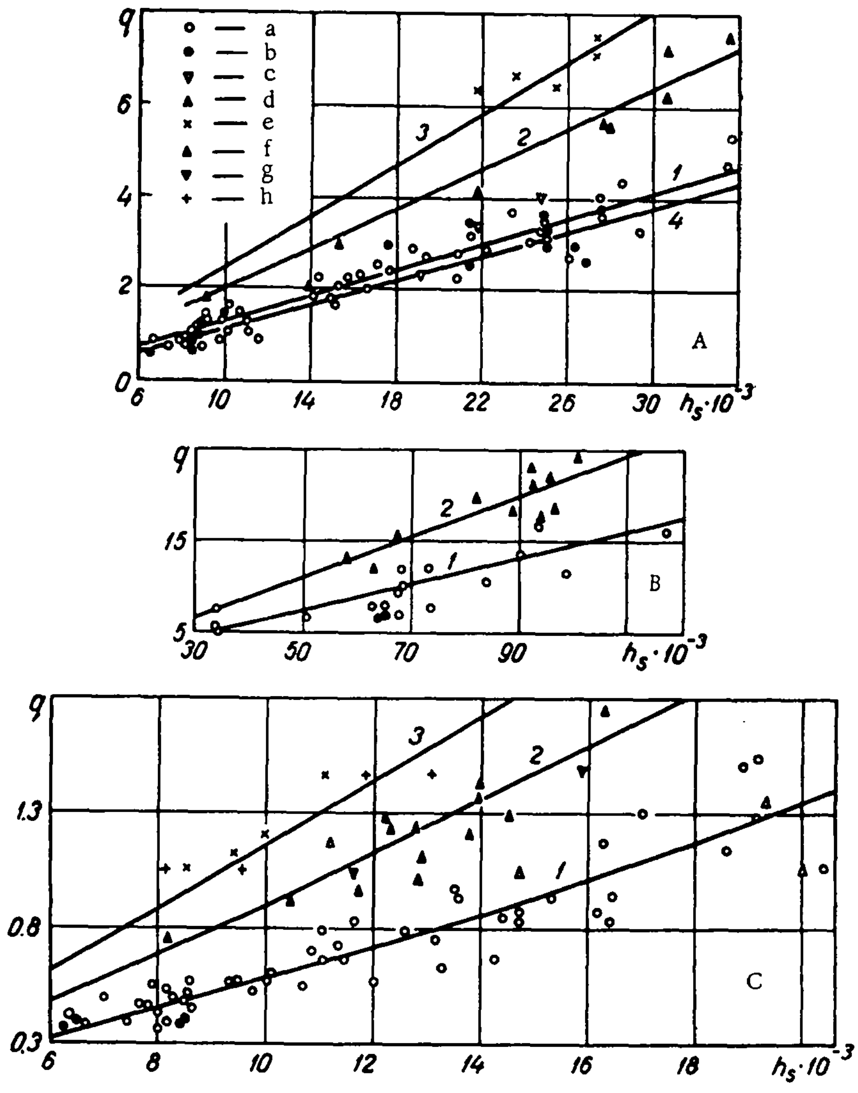

Fig. 4. Dependence of heat flux on parameters of the gas: A, B) with heat flux sensor diameter 5 mm; c) 20 mm; 1, 2, 3) calculation with t_{st} = 100° C, Pr = 0.71, Le = 1.4; 4) calculation with t_{st} = 1000° C; a, d, e) experimental data obtained by the cooled calorimeter method; b) by the exponential method; c) from the time to begin melting; f, g, h) data from [25]. The pressure was 9.81–10.81 N/cm² for 1, 4, a, b, c, f; 12.3 ± 1 for 2, d, g; 14.7 ± 1 for 3, e, h.

the Fay and Riddell equation to calculating heat transfer in an ionized gas. The calculations made in [10] have also shown that the results of extrapolating the Fay and Riddell theory differ by no more than 15% from the results of theory which takes account of ionization.

For the purpose of comparison with the theories of Fay and Kemp and Scala and Warren, which give substantially different values of the heat flux, the experimental results are presented in the form of the dependence of the heat transfer parameter $Nu/\sqrt{Re}$ on the simulated velocity $v=\sqrt{2gh_s}$ (Fig. 5). Comparison shows that the mean line drawn through the experimental data agrees with the relation calculated from the Fay and Riddell formula for velocities up to 8 km/sec, and does not differ from it by more than 5% at higher velocities. The calculations of Fay and Kemp for an ionized frozen gas differ from the experimental relation by no more than 11% in the velocity range from 10 to 15 km/sec.

The scatter of the experimental points was 20%. The results of Fay and Kemp's calculations for equilibrium nitrogen fall noticeably below the experimental relation. The evaluation of the simulated altitudes according to data for air give values in our case in the range 30–60 km, while the altitudes corresponding to velocities > 9 km/sec lie in the frozen flow region, according to Fay's calculations [4].

It should be noted also that the lower values of the heat transfer factor obtained in [4] may be explained by the reduced value of the Le number (Fig. 5, curve 5), the authors having assumed a value of 0.6. Calculations according to data from [2,3,27], allowing only for atom-molecule diffusion, give Le number of approximately 0.7 in the temperature range 9000°–14 000° K. The presence of electrons and ions intensifies the diffusion process and must lead to an increase in value of the Le number by twice, as assumed, for example, by the authors of [5,28]. Thus, a possible value of the Le number in this temperature region is 1–1.4.

The experimental relation obtained (Fig.5) in the velocity range 3–15 km/sec may be approximated by the straight line

$$Nu/\sqrt{Re} = 0.582 - 1.46\cdot 10^{-2}v.$$

The dependences of heat flux on gas parameters, shown in Fig. 4, may be described by a single equation of the following type:

$$q = (2\cdot 10^{-3}\sqrt{\bar{p}_s}h_s + 0.571\cdot 10^{-3}h_s - 0.84\sqrt{\bar{p}_s} - 0.217)1/\sqrt{0.604d_{hf} - 0.33}. \quad (6)$$

The stagnation enthalpy is equal to the mean mass enthalpy for the ratio of sensor diameter to mixing chamber exit aperture diameter, d_{hf}/d_{mc}, in the range 1.43–0.75 for d_{mc} = 15–20 mm. For the ratio of sensor diameter to anode diameter (without the mixing chamber), d_{hf}/d_{an} in the range 0.25–0.67 with d_{an} = 15–20 mm, the stagnation enthalpy is determined with the aid of the relations of Fig. 2A and B.

The heat flux values calculated from (6) differ from the ordinates of the mean lines drawn through the experimental data by no more than 2% (Fig. 4).

The measurements show that the heat flux decreases exponentially with increase in distance from the exit section of the discharge chamber, and that in the range of L values from 15 to 100 mm, it is determined by the expression

$$q_L = q_{L=25}\exp(0.55 - 2.2\cdot 10^{-2}L). \quad (7)$$

The value of $q_{L=25}$ is determined from (6).

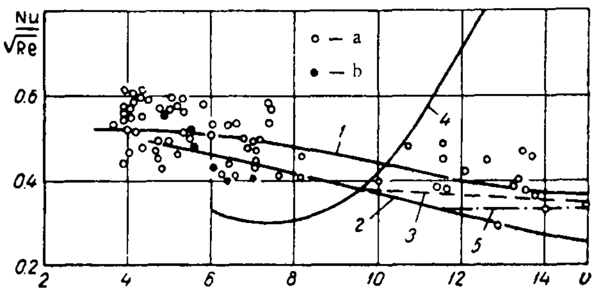

Fig. 5. Dependence of the heat transfer factor $Nu/\sqrt{Re}$ on simulated velocity v, km/sec; 1, 5) calculation from the Fay and Ridell formula [1], with t_{st} = 100° C and Le of 1.4 and 0.7, respectively; 2, 3) calculation of Fay and Kemp [4] with t_{st} = 25° C, Le = 0.6p_{stag} = 9.81 N/cm² [2) for equilibrium, 3) for frozen nitrogen]; 4) according to the theory of Scala and Warren [11]; a) experimental results of the author; b) experimental results of John and Bade [25] for air with p_{stag} = 10.4–12.8 N/cm².

NOTATION

h_A) dissociation energy; c_A) weight fraction of atoms; $h_D = h_A c_A$; $Nu = q\,Prx/\mu_w \times (h_{es} - h_w)$; $Re = \rho_w u_{es} x/\mu_w$; $Le = D\rho c_p/\lambda$; U) voltage over the arc; I) current; N) power; G) gas flow rate in g/sec; $\bar{W} = 4G/\rho\pi d_{ar}^2$) mean mass velocity; d_{an}) diameter of anode exit section; $\bar{\rho}$) gas density, determined from the mean mass temperature; r_{pd}) radius of pressure-distribution sensor; δ) cylinder height; τ_1) time to start of melting; t_m) melting temperature; q) heat flux, kW/cm²; $p_{stag} = (p_s + 1)\times 9.81$) stagnation pressure, N/cm²; $h_s \times 4.19$) stagnation enthalpy, kJ/kg; L) distance from the exit section of the discharge chamber to the sensor, mm.

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