Int. J. Heat Mass Transfer. Vol. 10, pp. 1361–1371. Pergamon Press Ltd. 1967. Printed in Great Britain

EXPERIMENTAL STUDY OF STAGNATION POINT HEAT TRANSFER OF A SOLID IN HIGH-ENTHALPY GAS FLOW

A. V. LUIKOV, V. L. SERGEEV and A. G. SHASHKOV
Heat and Mass Transfer Institute, B.S.S.R. Academy of Sciences, Minsk, U.S.S.R.

(*Received* 21 *March* 1966)

Аннотация—Исследован теплообмен тела с потоком высокоэнтальпийного газа в области точки торможения. Верхний предел энтальпии соответствует степени ионизации газа (азота), равной 40%. Исследование проведено в струе газа, нагреваемого с помощью электродугового подогревателя.

NOMENCLATURE

G,	weight of calorimeter element;
δ,	thickness of calorimeter element [mm];
α_R,	proportionality factor in equation relating resistance of metal plate with temperature;
t_m,	fusion point of material [degC];
$x_{\lim}$,	minimum length of rod [mm];
$\delta_{\lim}$,	limit thickness of calorimeter element;
f,	area of gauge heat-transfer surface;
G_g,	mass flow rate of gas;
h_2,	gas enthalpy at the exit from enthalpy gauge;
$\overline{H}$,	mean mass enthalpy of gas at anode exit;
$\overline{W}$,	mean mass velocity of jet at anode exit;
u,	velocity along end face radius of gauge;
$h_0 . 4{\cdot}19$,	stagnation enthalpy [kJ/kg];
$P_s = (P_0 + 1)\,9{\cdot}81$,	stagnation pressure [N/cm^2];
d_{hfg},	diameter of heat flux gauge;
d_{an},	diameter of hole in anode;
d_{dg},	diameter of pressure distribution gauge;
q,	specific heat flux [kW/cm^2];
Δt_{dc},	temperature rise of water in discharge chamber;
R_r,	rheostat resistance in arc circuit;
Δ_{tg},	temperature rise of water in heat flux gauge.

INTRODUCTION

THE RESULTS of papers [1–6] devoted to experimental studies of the stagnation point heat transfer of a solid in a high-enthalpy gas flow do not agree.

In the present paper an attempt is made to analyse certain available methods of measurements and the results obtained by these methods and to compare them with the data reported by the present authors.

The aim of the experimental study of stagnation-point heat transfer involves measurements of the surface heat flux, enthalpy and velocity gradients at the stagnation point as well as the surface temperature.

HEAT FLUX MEASUREMENTS

1. *Exponential* (*calorimetric method* [7–12])

When the heated element is small or made of a heat-conducting material, or heat-transfer coefficients are low, the heat flux may be deduced from the rate of temperature change at any point of the element.

The conditions just mentioned correspond to small Biot numbers $Bi = \alpha\delta/\lambda$ for a system under consideration, and in this situation temperature at all the points of the element which is usually a fragment of an infinite plate, are virtually the same at the same time moment.

The heat quantity transferred to such a body for the time $\mathrm{d}\tau$ is equal to the change of the enthalpy element of:

$$Q\,\mathrm{d}\tau = GC_p\,\mathrm{d}T \qquad \text{or} \qquad q = \delta\rho C_p\,\mathrm{d}T/\mathrm{d}\tau. \tag{1}$$

The temperature change of a metallic element in time may be expressed in terms of the change of the parameters of electric current passed through the element. If the current is maintained constant, the temperature change may be related to the change of the voltage by the following expression:

$$\frac{\mathrm{d}T}{\mathrm{d}\tau} = \frac{1}{\alpha_R R_0 I}\cdot\frac{\mathrm{d}U}{\mathrm{d}\tau}.$$

Thus, the expression for the heat flux becomes of the form

$$q = \frac{1}{IR_0}\left(\frac{\rho C_p \delta}{\alpha_R}\right)\frac{\mathrm{d}U}{\mathrm{d}\tau}. \tag{2}$$

The experimental method depends on the choice of either expression as the basis for calculations.

Small metallic cylinders and hollow metallic cylinders with flat, spherical and ellipsoidal end faces and thin walls were used as models for the determination of heat fluxes in the case of expression (1) [8–12]. Thin walls allow measurement of the heat flux distribution over the surface within a single run, if no effect of adjacent regions on heat propagation is assumed. For reduction of the error in the determination of heat fluxes caused by heat flows in the wall along the generating line of the model, a semi-spheric copper model consisting of individual elements (rings) was used in [10]. The gaps between the rings were filled with heat-insulating putty. During the experiments, the time change of the temperature of segments or individual sectors of the model were recorded by thermocouples and special recorders. The slope of the curves $t_w = f(\tau)$ at the initial time moment was used for the calculation of q, since the rate of temperature change of different sections was different which gave rise to the increase of heat flow between them.

When expression (2) is used for the determination of heat flux, the gauge consisted of a platinum plate in contact with the model made of Pyrex [11]. The plate was connected to four leads: two for the current and two for the measurement of voltage. In this case the record of the voltage change across the plate allowed the determination of the average heat flux to the plate. The plate thickness was of the same order as the diffusion length $l = \sqrt{(a\tau)}$ which represented the depth in a material into which heat flux penetrated in time τ which equalled the test time. Since a number of assumptions have been made, the method involves certain errors.

In all cases when this method is used, one-dimensional heat propagation in the calorimeter element should be provided. This is achieved by using metallic elements of small thickness as well as by thermal insulation of sides of the element.

When the gauge is placed on an insulating pad a fraction of heat from the gauge will be transferred to this pad. Heat losses through the leads are also possible.

If ionization of the gas interacting with the gauge is high enough, errors may occur because of the short circuit of the gauge in the case when heat flux is determined from the change of electrical resistance of the plate. This effect was found in the shock tube with the values of the stagnation enthalpy h/RT_0 of an order of 900 and it was eliminated by a silica insulation of thickness 6×10^{-4} cm [13]. In this reference it is stated that a large error may be made due to an inaccurate estimation of the time of the steady-state gas flow, the whole test time being 15–25 μsec.

The use of a metal plate for the measurement of the heat flux to a model of an insulator may entail a change of heat-transfer coefficients and, thus to a certain error in the results. Simplicity of measurements and the possibility of measuring the heat flux distribution over the surface within a single run affords a useful feature of the exponential method.

As stated in literature [7, 8] expression (1) for heat flux is valid for $Bi < 0\cdot01$–$0\cdot02$ when temperatures at all points of a calorimetric element are virtually the same. In effect, this condition is not necessary when expression (1) is used since apart from its validity only equality of temperature gradients at both plate surfaces is necessary when the temperature of the rear surface is to be measured.

The heat flux and the condition of equality of the temperature gradients may be found without the above constrain from the solution of the heat-conduction equation for an infinite plate of which one surface is heated (with constant heat flux) and the other surface is insulated [14]:

$$t = \frac{q_0\tau}{\rho C_p\delta} + \frac{q_0\delta}{\lambda}\left\{\frac{3x^2 - \delta^2}{6\delta^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left[-\frac{an^2\pi^2\tau}{\delta^2}\right]\cos\frac{n\pi x}{\delta}\right\}.$$

The analysis of the solution has shown [15] that the satisfaction of the inequality $Fo \geqslant 0\cdot35$ is equivalent to the condition of validity of expression (1) and equality of the gradients within 1 per cent. The condition of equality of temperatures at all points of the plate is equivalent to the constrain $Fo \geqslant 33$ within 1 per cent. Comparison of the above given inequalities reveals that the condition obtained extends the validity of the calorimetric method.

If the heat losses in the insulator layer are neglected or absent, the analysis of the presented solution allows to obtain the optimal thickness of the calorimeter element (plate).

For the calculation of the heat flux by the method considered a linear portion of the time–temperature curve at constant heat flux is used. The lower boundary of this portion is determined by the condition $Fo = 0\cdot35$ and the upper corresponds to the moment when the temperature of the frontal surface reaches a certain limiting value for the present material.

The maximum time of the linear portion corresponds to the optimal thickness.

The optimal thickness and the time interval of the maximum linear portion are respectively [16]:

$$\delta_{\text{opt}} = 0\cdot73\,\lambda t_m/q \qquad (3)$$

$$\Delta\tau_{\max} = 366\,\lambda^2 t_m^2/aq^2. \qquad (4)$$

Introduction of expressions (3) and (4) in design calculations of a gauge is especially important with high heat fluxes for which the time of the linear portion is short (4).

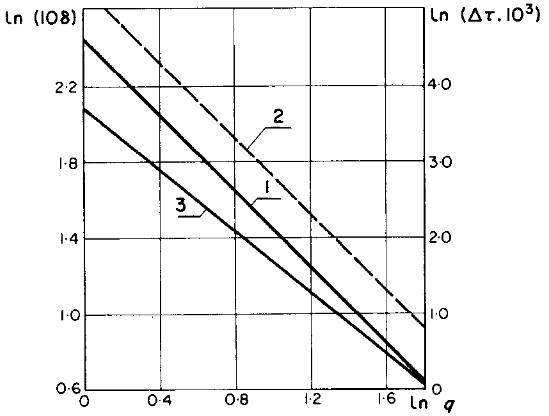

FIG. 1. Plot of copper calorimeter element thickness (1: δ_{opt}, 2: δ_{lim}) and maximum time of linear portion 3 vs. heat flux ($\bar{\lambda} = 0\cdot348$ kW/m deg; $\bar{a} = 0\cdot35\ \text{m}^2/\text{h}$; $t_m = 1000°\text{C}$).

As it is shown in paper [16], the ratio $\Delta\tau/\Delta\tau_{\max}$ which is equal to unity when $\delta/\delta_{\text{opt}} = 1$, approaches zero when the plate thickness differs by 45 per cent from the optimum value. The results of the optimum thickness calculation for a copper calorimeter are presented in Fig. 1.

The theoretical limit of validity of the calorimetric method is the case when fusion of the material commences before the linear portion of the curve. The condition which describes this case is of the form

$$(\delta q)_{\lim} = t_m \lambda / 0{\cdot}683.$$

2. *Brogan's method of heat flux determination* [17]

In this method the solution of the heat-conduction equation is used for the case of a semi-infinite body with constant surface heat flux [14]

$$t(x, \tau) = \frac{2q_0}{\lambda}(\sqrt{a\tau}).\, i\operatorname{erfc}\frac{x}{2(\sqrt{a\tau})}. \tag{5}$$

In time τ_1 from the commencement of heating, the surface temperature reaches the fusion point t_m. Substitution of these values into the solution of the heat-conduction equation gives the predicted formula for heat flux

$$q = \tfrac{1}{2}\sqrt{(\pi \rho C_p \lambda / \tau_1)}\,.\, t_m.$$

For measuring the heat flux by this method it is sufficient to fix the heating time of a sample before fusion commences, which, however, involves certain difficulties because the time interval before fusion commences may be a fraction of a second. If we take a rather long metal rod thermally insulated on the side surface as a model of a semi-infinite body, the difference between the real model and predicted system will be a source of errors in the results.

If the minimum length of the rod $x_{\lim}$ is defined as a distance from the heated end face to the cross section where the temperature difference during the time τ_1 is not above 1 per cent in the case of a copper rod, then from expression (5) we obtain

$$x_{\lim} \cdot q = 170.$$

The decrease of the minimum length of the rod with increasing heat flux may be attributed to the reduction of the time necessary for heating the front face of the rod to the point of fusion.

3. *Method of a cooled calorimeter* [18]

The heat flux to the cooled calorimeter is defined by the flow rate G_b and temperature rise Δt_g of the cooling water.

Thus,

$$q = G_b . \Delta t_g C_p / f. \tag{6}$$

At variance with the earlier methods, in this case the steady-state temperature distribution sets in in the heated wall of a gauge. Expression (6) shows that in the determination of the heat flux the dependence of the thermal properties of the heated element on the temperature is not included and measurements of the time-dependent wall temperature are not necessary. The errors caused by the transient nature of the process are also eliminated. On the other hand, in the latter case the errors due to subsidiary heat fluxes may be essential.

The necessity for the steady-state heat transfer through the cooled wall restricts the maximum values of heat fluxes to be measured by a cooled calorimeter by the limiting fluxes for the cooled metallic wall (Fig. 2).

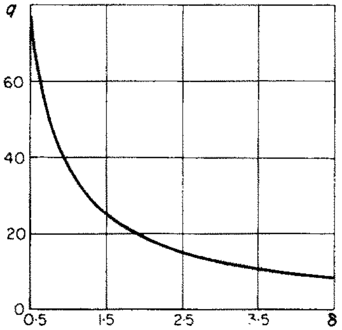

FIG. 2. Plot of limited heat fluxes for cooled copper calorimeter vs. wall thickness.

Besides the above methods a number of different methods reported may be mentioned. Some are discussed in [28]. They are: determination of heat fluxes from the surface temperature [11, 19–21], the surface-point method [8, 12], the method elaborated by Stokes, Knipe and Streng [22, 23], the capacity method [24], the method of determination of heat flux by the change of the colour of the die [25], the regular regime method [8, 26], measurement of heat fluxes by infrared gauges [27].

Since the present device for gas heating allowed a high-temperature steady-state gas flow to be obtained for a long time, a steady-state method of a cooled calorimeter was used for the measurement of the heat fluxes. The results were verified by the simplest and widely used methods: the exponential method and Brogan's method.

MEASUREMENT OF GAS PARAMETERS

For the determination of the stagnation gas enthalpy, the calorimetric method [29], the energy-balance method [31] and results of spectroscopic temperature measurements of a gas flow [30, 31] were used.

We shall describe the calorimetric method. The heated gas is let through a cooled tube; the gas gives up a fraction of its heat to water and flows to the flowmeter. The temperature rise of the water cooling the gauge is measured, with the valve behind the tube being closed and then with the valve open. In the latter case the gas temperature and flow rate at the outlet from the gauge were measured. The difference of heat-quantities received by water is the heat amount taken from the gas flowing through the probe

$$G_g(h_1 - h_2) = (G_b C_p \Delta t)_{0p} - (G_b C_p \Delta t)_{cl}.$$

This expression allows to obtain the quantity h_1 which is the gas enthalpy at the entrance of the gauge.

A value of the mean mass enthalpy of the gas at the outlet from the heater may be found from the energy balance of the heater.

In the case when uniform parameter distribution across the heated gas jet is provided, this value may be assumed to be equal to the stagnation gas enthalpy.

Spectroscopic methods allow the determination of the temperature in the jet core as well as the temperature distribution along the jet radius. For the determination of the values just said the methods of the relative intensity and temperature determination by broadening of the line H_β are used [30].

Among other methods of temperature (enthalpy) measurement of high-temperature gas flows we may mention the thermodynamic method [32] and the measurement by a two-element gauge [33].

In the case when the front of a body is a section of a sphere of the radius R, the velocity gradient at the stagnation point is

$$\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)_{0e} = \frac{1}{R}\sqrt{[2(P_0 - P_\infty)/\rho_0]}. \qquad (7)$$

As it is shown in [34], at $M < 1$ the experimental values of the velocity gradient differ essentially from those predicted by formula (7).

In the present work stagnation velocity distributions are determined by the Bernoulli's equation using the measured pressure distribution [18]. Velocity gradients are found from the velocity distributions obtained.

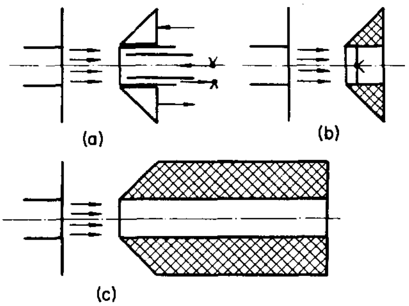

FIG. 3. Schematic diagram of heat flux gauges. (a) cooled calorimenter method; (b) exponential method; (c) Brogan's method.

When the methods of measurement adopted were applied (Fig. 3) special attention was paid to the elimination of the sources of errors and the reduction of errors.

The cooled calorimeter consisted of a hollow copper cylinder with one end closed, the face of the closed end being used as the heat-transfer surface. The end wall thickness was 1–5 mm, the diameter was 5, 10, 15 and 20 mm. Cooling water was fed through a tube fixed at the cylinder axis. The gap between the tube and the cylinder end face was 0·5–1 mm. The water temperature before and after the calorimeter was measured by thermocouples and thermistors checking one another, the readings being recorded by an electronic potentiometer and loop oscillography respectively (Fig. 4).

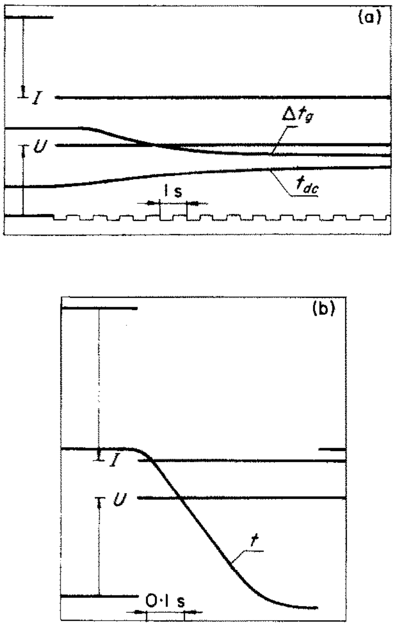

FIG. 4. Oscillograms of measured heat fluxes by (a) the method of cooled calorimeter and (b) exponential method. (a) $I = 740$ Δ, $U = 228$ V, $G_g = 5$g/s, $\Delta\ t_{hfg} = 5{\cdot}5°\mathrm{C}/5{\cdot}8°\mathrm{C}$ by electric potentiometer, $\Delta\ t_{dc} = 22{\cdot}5°\mathrm{C}$ (24·2°C by electric potentiometer). (b) $d_{hfg} = 5$ mm, $I = 750$ A, $U = 228$ V, $G_g = 6$g/s, $\Gamma t/\Delta\tau = 2900°\mathrm{C/s}$, $q = 3$ kWt/cm^2.

Since all the above heat flux expressions are written with the assumption of one-dimensional heat flux, to provide this condition, the side surface of the calorimetric elements were protected from heating by cooled rings shaped as a frustum of a cone. There were no appreciable heat fluxes between the gauge and the cone (as it was established experimentally). This was produced by insulation and appropriate control of the temperature rise of cooling water by changing the mass flow rate of water.

When the first and the second methods were used, the gauges were in the shape of solid copper and aluminium cylinders of the length 0·3–8 mm (in the first case) and 200 mm (in the second case). The sizes and shapes of cylinder ends and protecting rings of the gauges were the same as in tne cooled calorimeters.

For measurement of enthalpy by the calorimetric method a gauge was used which consisted of three coaxial copper tubes, water being pumped through the annular gaps. The gas passage diameter was 1 and 5 mm, the gauge length was 300–500 mm. For the determination of the inlet gas enthalpy, the temperature and mass flow rate of gas at the outlet as well as the flow rate and temperature rise of water were measured.

The results of measurement of enthalpy in the jet core obtained by different methods agree satisfactorily with one another [35].

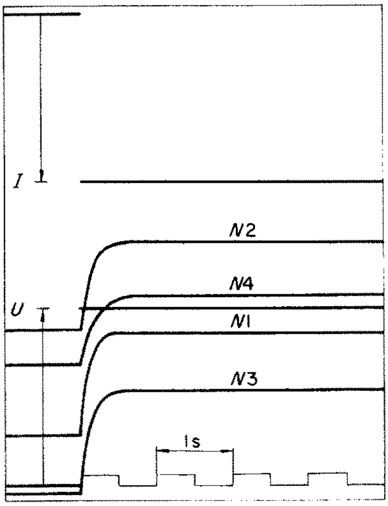

FIG. 5. Oscillogram of pressure distribution $d_{dg} = 18$ mm, $I = 515$ A, $U = 242$ V, $G_g = 5$ g/s. Gauge readings (N/cm^2): No. 1, 0·23; No. 2, 0·92; No. 3, 1·01; No. 4, 0·62.

The enthalpy gauge mounted to a closed channel connecting it with atmosphere allowed measurements of the stagnation pressure.

The pressure distribution gauges consisted of cylinders with flat end faces, and with a number of holes drilled along the axis at different distances from the axis. Their shape and sizes were quite similar to those of the heat flux gauges. Pressure effects were transformed into electrical signals and recorded by a loop oscillograph [Fig. 5].

All the gauges were mounted along the axis of the heated gas jet at a distance of 25 mm from the outlet section of the nozzle.

Gas (nitrogen) was heated by an electrical arc heater. The discharge chamber of the heater consisted of three units. A hollow copper cylinder closed from one end served as a cathode. The wall thickness of the cylinder was 5 mm. The cylinder was cooled by water pumped through a gap of 1 mm. The length of the cylinder was 50–100 mm, and the internal diameter was 15–20 mm. The anode was a hollow copper cylinder of which the internal diameter was 10, 15, 20 and 30 mm. The gap between the electrodes through which gas was fed was equal to 1–4 mm. The gas was supplied through two tangential holes in the ring insulating the electrodes.

The parameters of a direct current source were $U = 500$ V, $I = 1500$ A. The water supply system provided water flow rate of 3 kg/s with the pressure head 40–100 atm. Nitrogen from the gas container was fed into the discharge chamber. To provide steady arc burning, a wire rheostat was included into a power circuit, the resistance varying from 0·1 to 1·2 Ω.

For the determination of the operating conditions of the discharge chamber, which provided the required parameters of a heated gas flow, the voltage–current characteristics and the relations between the gas flow parameters at the anode outlet and the electrical parameters, the electrode dimensions and the gas flow rate were obtained [35].

The electrical arc heater allowed a heated gas jet with a mean mass enthalpy of 6300–35000 kJ/kg and the velocity of 300–1400 m/s. The enthalpy in the jet core was up to 104000 kJ/kg. The admixture of the electrode materials in the gas was below 0·1 per cent.

EXPERIMENTAL RESULTS

The measurements have shown [35] that the quantity $(k = u/\overline{W})/(r/r_{dg})$, which describes the velocity gradient at the stagnation point, is independent of the gas flow parameters and changes slightly with the gauge diameter d_{dg}.

For

$$d_{dg} = 5\text{–}12\,\text{mm}\;\frac{du}{dr} = (1\cdot86 \pm 0\cdot12)\frac{\overline{W}}{d_{dg}}$$

and for

$$d_{dg} = 18\text{–}22\,\text{mm}\;\frac{du}{dr} = (1\cdot70 \pm 0\cdot20)\frac{\overline{W}}{d_{dg}}.$$

These results agree with the conclusions of [18] if the gauge diameter used in the work is taken into account.

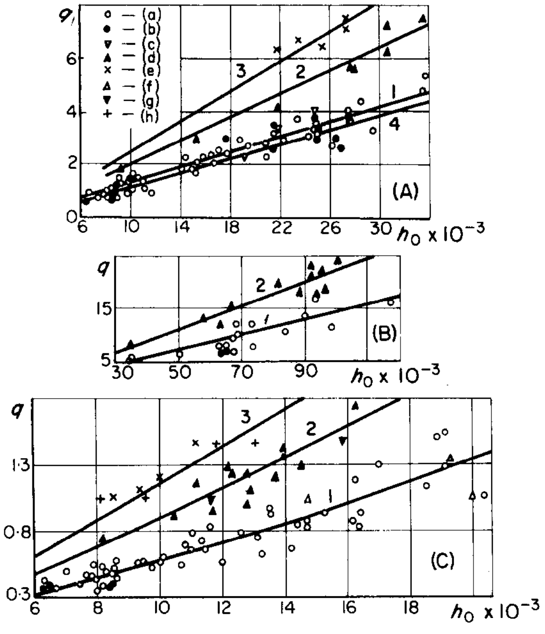

FIG. 6. Heat flux vs. gas parameters. (A, B) diameter of heat flux gauge of 5 mm (C) 20 mm; 1,2,3: predicted at t_w = 100°C, Pr = 0·71, Le = 1·4, 4: predicted at 1000°C; (a, d, e) experimental data obtained by a cooled calorimeter; (c) obtained by Brogan's method; (b) measured by exponential method; (f, g, h) data of [18]. Pressure is equal to 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 analysis of the relations of specific heat flux (Figs. 6 and 7) and gas parameters at the stagnation point shows satisfactory agreement between the results of measurements obtained by different methods. Heat fluxes change with stagnation enthalpy according to the law close to a linear one. Heat fluxes increase with the stagnation pressure and velocity gradient and depend slightly on the temperature of the heated surface of the gauge when this temperature is raised to 1000°C. The last conclusion is made because the heat fluxes measured by three different methods (cooled and non-cooled gauges the surface temperature of which was different) agree well.

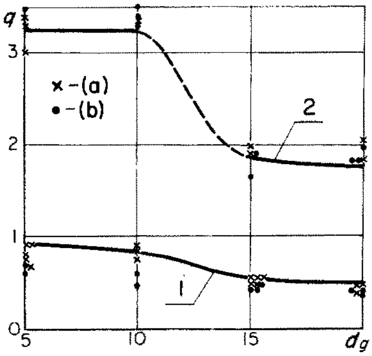

FIG. 7. Plot of heat flux vs. diameter of heat flux gauge. (1) with mixing chamber; $d_{mc} = 20$ mm; $\overline{H} = 8700$ kJ/kg; $\overline{W} = 270$ m/s; (2) without mixing chamber; $d_{an} = 15$ mm; $\overline{H} = 13400$ kJ/kg, $\overline{W} = 600$ m/s. (a) method of cooled calorimeter; (b) exponential method; (1,2) predicted by formula (8).

The experimental curve plotted in Figs. 6 and 7 may be described by a single formula of the following form:

$$q = (2 \times 10^{-3}(\sqrt{p_0})h_0 + 0{\cdot}57 \times 10^{-3}\, h_0 - 0{\cdot}84\,(\sqrt{p_0}) - 0{\cdot}22) \cdot 1/(\sqrt{0{\cdot}6 d_{hfg}^{-0{\cdot}33}}). \quad (8)$$

The values of heat fluxes predicted by formula (8) differ by no more than 2 per cent from the ordinates of the averaged lines drawn through the experimental data.

The estimated data have shown that the contribution of gas radiation is about 3 per cent of the measured heat fluxes which fact allows us to assume pure convective heat fluxes.

The measurements carried out show (Fig. 8) that heat fluxes decrease rapidly with the distance L from the outlet section. The quantity $q_4/q_{4=25}$ is independent of the operating regime

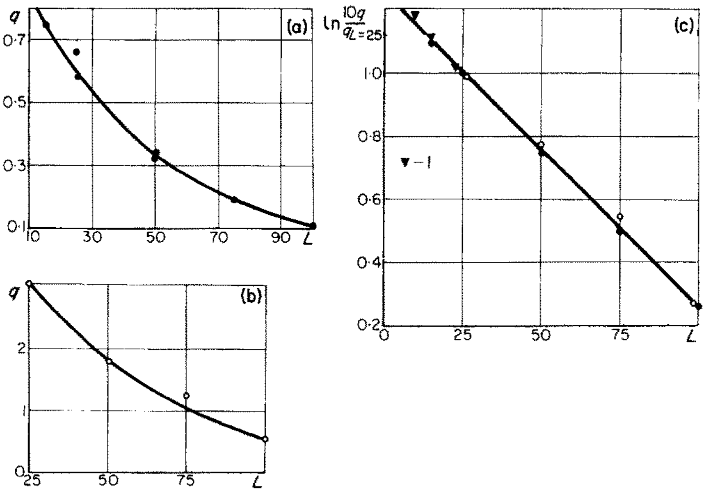

FIG. 8. Plot of heat flux vs. distance from the outlet cross-section of nozzle to gauge. (a) $d_{hfg} = 20$ mm, $d_{mc} = 20$ mm, $G_g = 6$ g/s, $R_r = 0{\cdot}3\ \Omega$; (b) $d_{hfg} = 10$ mm, $d_{an} = 20$ mm, $G_g = 6$ g/s, $R_r = 0{\cdot}4\ \Omega$; (c) correlating expression of heat flux in terms of L. (1) data of [23].

of the electric arc heater and the presence or absence of a mixing chamber. The shape of the curve may be attributed to the general law for these cases of interaction of the heated gas jet with the surrounding medium which governs the rate of decrease of the parameters along the jet.

The equation relating the heat flux and L is of the following form

$$q_L = q_{L=25} \exp(0{\cdot}55 - 2{\cdot}2 \times 10^{-2} L). \quad (9)$$

The quantity $q_{L=25}$ is determined from formula (8). The validity of formula (9) is confirmed by the measurements of other workers (Fig. 8).

The error of the measured values of heat fluxes is the sum of the errors due to the methods of measurement and deviations of the instruments and it is equal to ±15 per cent in the case of the exponential method and ±20 per cent when the method of a cooled calorimeter is used. The error in the determination of the stagnation enthalpy and pressure is within 10–12 per cent. The errors of the values obtained do not exceed those of the values measured in shock tubes.

Thus, formula (8) and (9) allow the calculation of the heat flux field in the heated gas jet.

The comparison of the present results with available reported experimental data obtained in shock tubes and electric arc heaters [2, 3, 5, 6, 18, 27] is of interest.

It is known from the literature that the predicted values of the heat fluxes of Fay and Kemp, Pallone and Van Tassel and also those of Skala which essentially differ from the former (to 200 per cent), are confirmed by measurements of heat fluxes in shock tubes [1].

In [3] the experimental results are presented which show that deviation in experimental data may be attributed to the material of the gauge and the state of the boundary layer. The experiments of [4] in which the gauges of platinum, gold and nickel were used, do not reveal the appreciable effect of the material on the results. The same conclusion was made by the authors of work [27] who used a new method of measurement of heat fluxes. The experiments described in the above works were carried out in shock tubes. The authors of [2, 3, 4] applied the calorimetric method and also measured the heat fluxes according to the change of the surface temperature. Reference [3] contains also the heat flux values obtained by Brogan's method on aluminium models.

Deviation of experimental points reaches 20 per cent in [3] and 27 per cent in [4], the material of the gauges being the same.

The results of [1–6] show that the material may affect the results because of its catalytic properties and the surface state but this effect is probably within the experimental error.

For direct comparison of the measured heat fluxes obtained in shock tubes with those of the present authors the latter data, was plotted as the group $q(\sqrt{R/P_0})$ vs. the enthalpy difference $(h_0 - h_w)$ (Fig. 9). The simulated nozzle radius (virtually the gauge noses were flat) which enters into the group is defined by the following expression [18]:

$$R = \left[\sqrt{\frac{2(P_0 - P_\infty)}{\rho_0}}\right] \Big/ \left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)_{oe}.$$

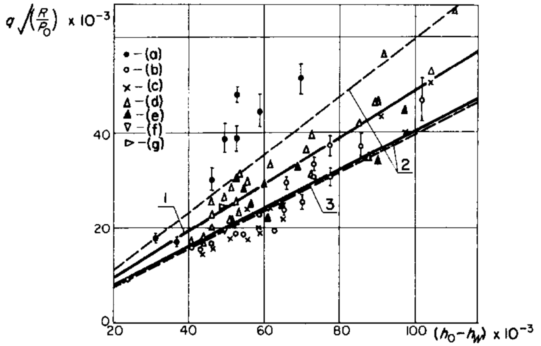

FIG. 9. Comparison of measured heat fluxes. (1) experimental relation of the present work; (2) deviation ±20 per cent; (3) experimental relation of work [6]; (a) data of work [2]; (b) reference [3]; (c) reference [5]; (d, e, f, g) reference [27]; (d) aluminium as gauge material; (e) gold; (f) nichrome; (g) carbon.

Curve 1 in Fig. 9 is the experimental one correlated by expression (8); curve 2 is correlated by the expression of [6] which is of the form

$$q\sqrt{\left(\frac{R}{P_0}\right)} = 0{\cdot}127\,(h_0 - h_w). \qquad (10)$$

The deviation of the values of the group found experimentally from those predicted by equation (10) is 20 per cent.

Figure 9 reveals that with large values of the enthalpy, the results obtained in shock tubes [3, 5] agree with the predicted relation obtained in the present work within the experimental error. For lower enthalpies the measured values do not agree.

The values measured in a shock tube by infrared gauges [27] agree with the results of the present work within the whole range of parameters.

Warren's experimental results [2] as well as the values predicted by Scala and which agree with them, differ considerably from those obtained in shock tubes by other workers and from the present experimental relation.

The experimental relation obtained by the present authors which expresses the heat flux dependence on gas parameters agrees (Fig. 6) with the results measured in an air plasma jet in [18] by the method of a cooled calorimeter over a rather narrow range of parameters. The range of the gas enthalpy was 8400–16 700 kJ/kg.

The heat fluxes are predicted (Fig. 6) by Fay and Riddel's formula [36] which is confirmed by experiments in a shock tube in the range of the stagnation enthalpy up to 2400 kJ/kg using the present experimental relations for the enthalpy in a jet core and for stagnation velocity gradient.

The plots reveal that the measured values of the heat fluxes agree with the predicted results within the range of gas parameters of interest with the following assumed quantities: $Pr = 0{\cdot}71$; $Le = 1{\cdot}4$; $t_w = 100°C$.

This result confirms the conclusion on the possibility of using Fay and Riddel's correlation to the heat-transfer predictions in an ionized gas, which is made in [37] from the comparison with other theoretical predictions.

REFERENCES

1. J. A. Fay and N. H. Kemp, Theory of stagnation point heat transfer in a partially ionized diatomic gas, *AIAA Jl* **1**, 2741–2751 (1963).
2. S. M. Scala and W. R. Warren, Hypervelocity stagnation point heat transfer, *ARS Jl* **32** (1), 101–102 (1962).
3. J. S. Cruczczynski and W. R. Warren Jr., Experimental heat-transfer studies of hypervelocity flight in planetary atmospheres, *AIAA Jl* **2** (9), 1542–1550 (1964).
4. D. J. Collins and J. M. Spiegel, Effect of gauge material on convective heat transfer, *AIAA Jl* **2** (4), 777–778 (1964).
5. P. H. Rose and J. O. Stankevics, Stagnation point heat-transfer measurements in partially ionized air, *AIAA Jl* **1** (12), 2752–2763 (1963).
6. R. M. Nerem and G. H. Stigford, Radiative and convective heating during hypervelocity re-entry, *AIAA Jl* **2** (6), 1156–1158 (1964).
7. E. V. Kudryavtsev, *Application of Transient Regimes Research of Aircraft Engines Heat Transfer*. Oborongiz, Moscow (1958).
8. E. V. Kudryavtsev, K. N. Chakalev and N. V. Shumakov, *Unsteady Heat Transfer*. Izd. Akad. Nauk SSSR, Moscow (1961).
9. Yu. N. Petrov and M. G. Morozov, Measurement of heat fluxes by the exponential method, in *Physical Gas Dynamics, Heat Transfer and Thermodynamics of High Temperature Gases*, pp. 300–303. Izd. Akad. Nauk SSSR, Moscow (1962).
10. J. Korobkin and K. Gruenwald, *J. Aeronaut. Sci.* **24** (3), 188–194 (1957).
11. P. H. Rose, Development of the calorimeter heat transfer gauge for use in shock tubes. *Rev. Scient. Instrum.* **29** (7), 557–564 (1958).
12. O. N. Kastelin and L. N. Bronskii, Heating of a blunt nose of a body in supersonic flow, in *Physical Gas Dynamics, Heat Transfer and Thermodynamics of High Temperature Gases*, pp. 233–238. Izd. Akad. Nauk SSSR, Moscow (1962).
13. E. Offenhartz, H. Weisblatt and R. F. Flagg, Stagnation point heat transfer measurements at super satellite speeds, *Jl. R Aeronaut. Soc.* **66** (1), 53–53 (1962).
14. A. V. Luikov, *Heat Conduction Theory*. GITTL, Moscow (1952).
15. V. L. Sergeev, On exponential method of heat flux measurement, in *Transient Heat and Mass Transfer Studies*. Izd. Akad. Nauk SSSR, Minsk (1966).
16. R. H. Kirchhoff, Calorimetric heating-rate probe for maximum response-time interval, *AIAA Jl* **2** (5), 233–234 (1964).
17. T. R. Brogan, The electric arc wind tunnel—a tool for atmospheric re-entry research, *ARS Jl* **29** (9), 648–653 (1959).

18. R. R. John and W. L. Bade, Testing of reinforced plastics under simulated re-entry conditions, Symposium on thermal ablation, Third Pacific Area National Meeting ASTM. San Francisco, Calif., October 14–15 (1959).
19. Yu. A. Polyakov and E. A. Mit'kina, Method of heat-transfer study in a short gas dynamic process, in *Heat and Mass Transfer*, Vol. 3, pp. 506–513. Gosenergoizdat. (1963).
20. Yu. A. Polyakov and E. A. Mit'kina, Thin-film resistance thermometer, *Pribory Tekh. Eksp.* (4), 140–143 (1961).
21. G. S. Ambrok, Calibration of heat flux gauge, *Izmeritel'naya Tekhn.* (11), 21–23 (1963).
22. C. S. Stokes, W. W. Knipe and L. A. Streng, Heat-transfer rates of an argon plasma jet, *J. Electrochem. Soc.* **107** (1), 35–38 (1960).
23. N. N. Rykalin, I. D. Kulagin and A. V. Nikolaev, Thermal properties of plasma het interaction with heated body, *Avtom. Svarka* (6), 3–13 (1963).
24. N. A. Anfimov and A. P. Shevtsov, Capacity method of transient instantaneous heat flux measurement, *Izv. Akad. Nauk SSSR, OTN, Mekh. I Mashin* (4), 163–165 (1960).
25. R. J. Sartell and G. C. Lorenz, A new technique for measurement of aerodynamic heating distributions on models of hypersonic vehicles, in *Proceedings of the* 1964 *Heat Transfer and Fluid Mechanics Institute*, pp. 130–146. Berkeley, Calif. (1964).
26. A. P. Pershin, Experimental study of thermal efficiency of gas jets of thermal drilling, *Izv. VUZ, Gorn. Zh.* (6), 74–76 (1960).
27. P. H. Rose and J. O. A. Stankevics, Heat-transfer measurements in partially ionized air, *AJAA Jl* **3** (9), 71–82 (1965).
28. V. L. Sergeev, Measurement of high heat fluxes, *Inzh.-Fiz. Zh.* **9** (4), 427–432 (1965).
29. J. Grey, P. F. Jacobs and M. P. Sherman, Calorimetric probe for the measurement of extremely high temperature, *Rev. Scient. Instrum.* **33** (7), 738–741 (1962).
30. E. V. Garkavyi, Temperature measurement of arc jet, *Inzh.-Fiz. Zh.* **6** (2), 20–24 (1963).
31. V. L. Sergeev, V. P. Trofimov, F. B. Yurevich and O. I. Yas'ko, some results of investigation of arc heater performance with gas stabilization of discharge, *Inzh.-Fiz. Zh.* **6** (1), 14–18 (1963).
32. K. A. Chukaev, Thermodynamic method of mean mass temperature determination in gas jets, *Izm. Tekhn.* (5), 37–40 (1958).
33. W. H. Giedt and J. T. Chambers, A duel-element transducer for measuring high gas-stream temperatures, *J. Heat Transfer* **87** (3) (1965).
34. W. L. Bade, Stagnation-point heat transfer in a high-temperature inert gas, *Physics Fluids* **5** (2), 150–154 (1962).
35. V. L. Sergeev, Experimental study of stagnation-point heat transfer, *Inzh.-Fiz. Zh.* **9** (5), 657–666 (1965).
36. J. A. Fay and F. R. Riddel, Theory of stagnation point heat transfer in dissociated air, *J. Aeronaut Sci.* **25** (2), 73–85 (1958).
37. S. Schreier, A comparison of five methods of calculating aerodynamic stagnation-point heat transfer at velocities of 25000–40000 ft/s, *J. Appl. Mech.* **30** (3), 124–130 (1963).

Abstract—In the paper heat transfer is studied in the stagnation region between a solid and high-enthalpy gas flow. The upper limit of the enthalpy corresponds to the gas (nitrogen) ionization of 40 per cent. The study is carried out in a gas jet heated by an electric arc heater.

Résumé—On étudie ici le transport de chaleur à partir d'un solide dans un écoulement gazeux à enthalpie élevée dans la région du point d'arrêt. La limite supérieure de l'enthalpie correspond à l'ionisation du gaz (azote) de 40 pour cent. On a conduit l'étude dans un jet gazeux chauffé par un arc électrique.

Zusammenfassung– Für den Staupunktbereich wird der Wärmeübergang zwischen einem Festkörper und einem Gasstrom hoher Enthalpie untersucht. Die obere Grenze der Enthalpie entspricht einer Gasionisation (Stickstoff) von 40%. Die Untersuchung ist in einem Gasstrahl durchgeführt, der durch einen elektrischen Lichtbogen aufgeheizt wurde.