EVALUATIONS OF SUPERSONIC HIGH-TEMPERATURE AIR FLOWS PARAMETERS

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Arc-heater facilities are the most effective mean for ground testing of hypersonic flight vehicles heat protection materials (HPM) as being capable to generate a long-term exposure of low-temperature air plasma on a HPM sample.

The arc-heater facilities complex of TsNIIMash was founded in fifties of the last century for experimental investigations of ablative HPM destined for vehicles of ballistic and gliding reentry [1-3]. The complex includes four arc-jet facilities with demountable main elements (heaters, nozzles, diffusers) providing a wide spectrum of testing environments. Special high-voltage substation feeds the heaters up to 50 MW. Line-type arc-heaters of 1,5 MW power consumption, 10MW coaxial heaters and four-electrodes 40MW heaters are today in use. Powerful heaters permit to operate not only with high energy flows but also with large-size test pieces (from 20 to 70 mm in diameter), considerably greater than a composite material structure sell size.

An aerodynamic heating of a body in a high-temperature flow is defined by the enthalpy difference across the boundary layer and by heat transfer factor which depends mainly on the pressure on the body surface and the body size as

$$\left(\alpha/\mathrm{Cp}\right)_0 \sim \sqrt{\frac{P0'}{R}} \qquad (1)$$

where R – the bluntness radius.

So, a total enthalpy, as a rule total enthalpy of a flow centerline $I_0(0)$, and a total pressure behind normal shock P_0' are the main flow parameters that define heat transfer and hence ablation velocity of a HPM test piece. Correspondently, an accuracy of the HPM ablation parameters determination depends substantially on these flow parameters evaluation accuracy. The P_0' experimental measurement presents normally no difficulties, whereas determination of arc heated flow enthalpy is a great problem because of reference quantities absence.

The following techniques are mostly used in arc-heater facilities practice of the enthalpy determination [3-6].

1. **Energy balance method**. The electric power W consumed by a heater with efficiency factor η goes to heating a flow with mass rate G up to I_{0av} enthalpy:

$$W \cdot \eta = G \cdot I_0\mathrm{av}\,. \qquad (2)$$

In principle equation (2) is useful to make an estimate of the maximum possible value of the flow average enthalpy. The mass-average enthalpy determination accuracy can be raised by measurement of a heat accepted by water-cooling system.

2. **Flow rate (**sonic section flow) **method**. Mass flow rate through a supersonic nozzle throat depends only on the flow stagnation parameters in the heater chamber ahead of the throat:

$$G = A(P_0, T_0) \cdot \frac{P_0 \cdot F^*}{\sqrt{T_0}}. \qquad (3)$$

For ideal gas the factor A equals to $\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left(\frac{m\gamma}{R}\right)^{0.5}$.

Here γ, m, R, F* are correspondingly adiabatic factor, molecular weight, universal gas constant and throat area.

3. Heat transfer (or calorimetric) methods. Heat flux to the stagnation point of a blunt axisymmetric body is to be measured. At known pressure P_0' the total enthalpy at the flow centerline $I_0(0)$ (or at any stream tube) can be evaluated. These methods are mostly used in arc-jet facilities practice since it is the flow centerline but not the mass average enthalpy value that defines heat transfer to a tested body surface.

3.1 **Unsteady-state technique** of heat flux determination is based on measurement of temperature rise rate of a small insulated calorimetric body (as a rule, copper slug):

$$q_w = C \cdot \rho \cdot \delta \cdot \frac{\partial T}{\partial \tau}, \quad (5)$$

where C, ρ, δ are the calorimeter heat capacity, density and thickness correspondently,
$\frac{\partial T}{\partial \tau}$ – temperature rise rate.

This technique application for high energy flows needs a fast system for a model input-output as a duration of the calorimeter stay in the flow is limited by the insulation destruction temperature.

3.2. **Stationary technique** is used for measurements of heat fluxes as high that no material can withstand them accounting for input-output mechanism possibilities. Stationary calorimeters are made as a thin-wall water cooled shell and the coolant heating gives total heat to the shell outer surface:

$$Q_\Sigma = C \cdot \rho \cdot \Delta T \cdot G\ . \quad (6)$$

There C, ρ, ΔT and G are the coolant heat capacity, density, temperature rise and mass flow rate.

The stationary calorimeter advantage is a possibility of its reuse in a HPM serial tests.

As shown in papers [5, 6], results of the calorimetric techniques in low-density arc-heated flows can be influenced noticeably by low catalytic reactivity of the copper oxide film on the calorimeter surface. Another source of error can be un equilibrium state of the plasma flow.

4. Profile measurement method.

Calorimetric measurement error can be neglected if, at the known mass-average enthalpy I_0 , measurements are made through all the test section diameter and heat flux and pressure profiles are obtained. According to Fay&Riddell [7] the enthalpy correlates with heat flux as

$$I_0(r) \sim (q_w(r))^{1.14}.$$

Let *A* be a quantity proportional to the heat flux, for example $\frac{\partial T}{\partial t}$ for unsteady calorimeter or $\Delta T_w \cdot G_w$ for stationary water-cooled calorimeter. Then, taking for the first approximation

$$I_0(0) \approx I_0 \int_0^R \left(\frac{A(r)}{A(0)}\right)^{1.14} \cdot 2\pi r dr,$$

at the known pressure profile $P_0'(r)$ one can calculate flow parameters at the nozzle exit ρ(r) and *V(*r) and, as the mass average enthalpy equals to

$$I_0 = \frac{\int_0^R I_0(r) \rho V r dr}{R^2 G}, \quad (7)$$

correct I_0(r) values by successive approximations.

5. Optical (spectral) methods. The arc-heaters flows spectral diagnostics would be very useful for the plasma condition determination and estimation of the above methods correctness since all of them are based on the assumption of plasma thermodynamic equilibrium. However, the spectral data interpretation is very complicated and involves also various assumptions and resulting error of the centerline enthalpy evaluation can be very considerable. So, Park in [6] demonstrates experimental results of the flow centerline determination with the use of calorimetric technique and of spectral means. The discrepancy about 30% the author accounts for the calorimeter surface low catalytic activity.

In TsNIIMash arc-jet facilities complex practice, total enthalpy determination technique depends on the heater type. They are sonic flow rate method and water-cooled calorimeter that are mostly in use when series of HPM tests is curried out [3]. The facilities complex gasdynamic design ensures mass flow rate constancy both without and with the arc ignition, so mass-average value of the flow enthalpy is evaluated from the ratio of hater chamber pressure at active arc P_0 to the pressure without the arc P_{cold} [3, 8]

$$I_0 = A(P_0, T_0)\left(\frac{P_0}{P_{0\,хол}}\right)^2\left(\frac{T_{хол}}{273}\right).$$

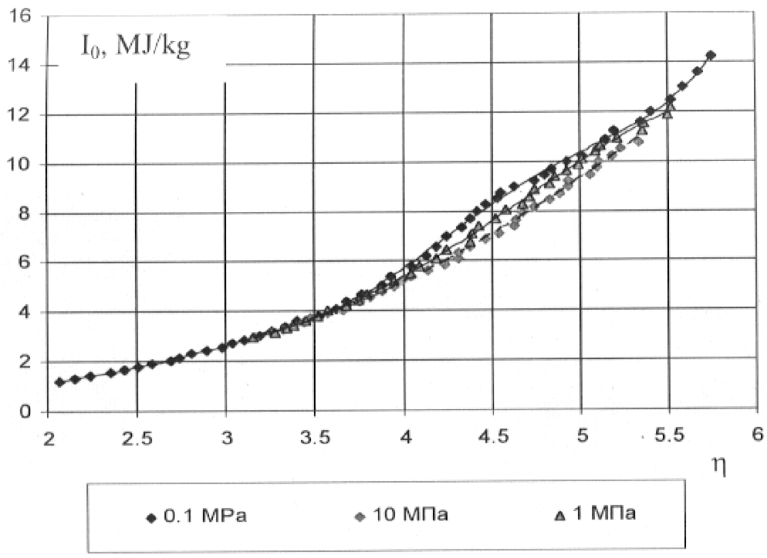

Fig. 1. Flow mass-average dependence on parameter η

Figure 1 demonstrates mass-average total enthalpy dependence on parameter

$$\eta = \frac{P_0}{P_{0хол}}\sqrt{\frac{T_{хол}}{273}}$$

for P_0 values from 0.1 to 10 MPa and the temperature range from 1100 K to 6000 K.

The 10 MW coaxial type heater is the only one type of the tree types of arc heaters used in the complex, that produces, due to radial position of the arc, the flows so even that the enthalpy mass-average value can be considered as the centerline one. The flows investigations were fulfilled both by water-cooled calorimeter placed at various distances from the axis and by unsteady quick-response calorimeter slowly moved across the flow. The unsteady calorimeter was made as a thin copper plate with thermocouple at its bottom center. The thermocouple and the motion transducer signals were registered and processed by PC. The investigations revealed that the flow enthalpy profile unevenness does not exceed 4% and pressure unevenness is less than 2%.

The main problem in flow enthalpy evaluation is connected as a rule with heaters of a linear type where axis values of flow enthalpy can many times exceed mass-average values and pressure varies across the flow noticeably [8].

Because of the flows core high enthalpy, this type of arc heaters is mostly in use for HPM studies. Our arc-jet facilities complex includes two 1,5 MW heaters of linear type (so called “plasmatron”), its flow core can be heated up to 35 - 40 MJ/kg. The “plasmatron” scheme is given in Fig. 2. Figure 3 presents a scheme of water-cooled hemispherical probe that is designed for hear flux and pressure simultaneous measurement giving a possibility of enthalpy determination.

Photo of the probe in the facility test chamber is given in Fig. 4.

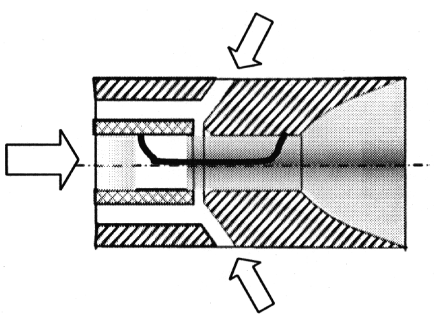
Fig. 2. Scheme of 1,5 MW arc heater

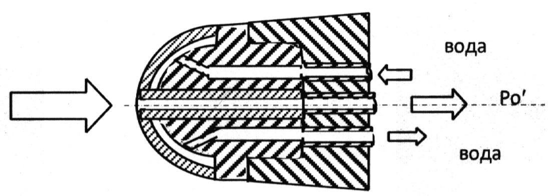

Fig. 3. Scheme of thermal probe

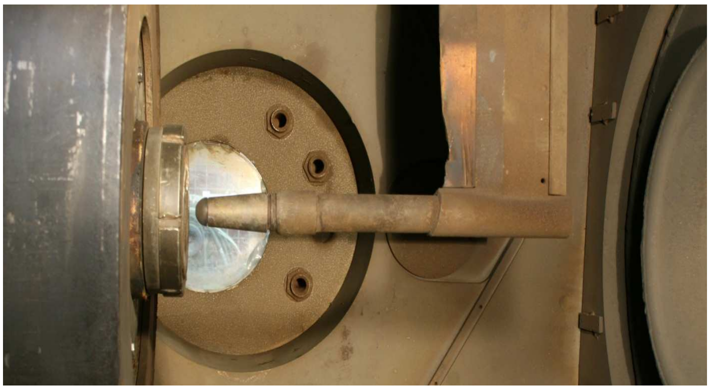

Fig. 4. Thermal probe in the facility working chamber

Hemispherical shape of the probe bluntness permits to use a well-known distributions of pressure and heat flux along a sphere generatrix. The heat flux variation at uniform hypersonic overflowing is described as [9]

$$q_w(\theta) = q_w(0)\left(0{,}55 + 0{,}45\cos(2\theta)\right), \quad (8)$$

and the total amount of heat to the probe surface equals to

$$Q_{\Sigma} = \int_0^{\frac{\pi}{2}} q_w(\theta)\, 2\pi R^2 \sin(\theta) d\theta = 0{,}8\, \pi R^2 q_w(0).$$

Hence, $q_w(0)$ can be found.

Heat exchange factor is calculated by a well-known Fay&Riddell equation [7] where velocity gradient in the stagnation point of sphere with radius R equals to

$$\left(\frac{\partial U}{\partial x}\right)_0 \approx \frac{1}{R}\sqrt{\frac{2.34P_o'}{\rho_\delta}} \,.$$

At given values P_0' and $q_w(0)$, total enthalpy $I_0(0)$ value and other flow parameters can be calculated by iteration procedure [8].

With the aim of the probe measurement accuracy assessment, several tests were curried out with the use of the 10 MW heater which, as it was said above, produces rather even flows. To obtain measurable heat flux to the probe, the nozzle 300 mm in diameter that is commonly in use in HPM tests was replaced by the nozzle of less Mach number. It permitted to rise P_0' values up to 0,85 MPa and correspondently heat fluxes to the probe also increased.

The tests results gave measured values of P_0' 3-5% less than calculated ones and of the enthalpy – up to 5,5% higher. Taking into account that computing error of the both enthalpy evaluation procedures (sonic flow method and calorimetric method) can be estimated as 3%, the probe enthalpy measurement total error can be assessed as not exceeding 10%.

As it was said above, the flow unevenness is the specific feature of a linear-type heaters, so the problem arises of equations (8) and (9) adaptability for the probe in the “plasmatron” flows. To estimate the flow core diameter within which the flow parameters can be considered as uniform, an experimental investigation was fulfilled to determine total enthalpy and pressure profiles of the “plasmatron” flows with the use of a 10 mm diameter probe. In practice, there are two variants of the “plasmatron” assemblage with supersonic nozzles and hence two stable test regimes that are in use for a HPM production tests. One of the variants is specified by the flow pressure P_0'~0,3 MPa and $I_0(0)$~ (8-12) MJ/kg, another one has P_0'~0,03 MPa and $I_0(0)$~ (20-40) MJ/kg, heat fluxes to the 12.5 mm probe are from 20 to 35 MW/m^2.

The experimental results are presented in Fig. 5 as $P'_0(r)/P_0'(0)$ and $I_0(r)/I_0(0)$ radial distributions for the both of the “plasmatron” regimes. The probe heating data were processed in accordance with equations (8) and (9), that is at every position of the probe the flow was treated as a locally uniform one.

The data shows that diameters of the flows core where the flow can be considered as uniform are about 40 mm at P_0'~0,3 MPa regime and about 10 mm at P_0'~0,03 MPa.

The probe size, shape and surface condition can play a large role in the enthalpy evaluation. The calorimeter surface state can reduce the total heat consumption due to oxide film having low

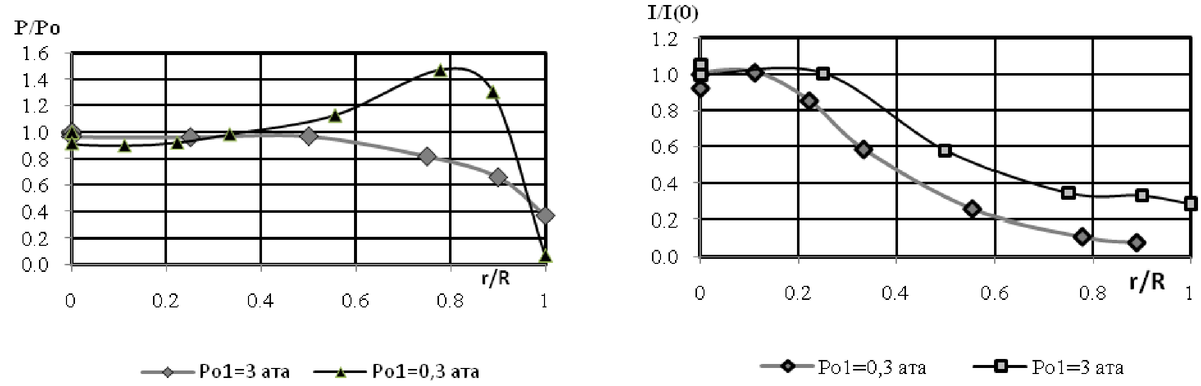

Fig. 5. Pressure and enthalpy profiles of the "plasmotron" flows

catalitical activity [5, 6] as well as can increase it due to the surface roughness [10].

Calculations of thermodynamically unequilibrium air plasma flows fulfilled for the most of the arc-jet facilities regimes revealed that at all levels of pressure realized by the "plasmotron", the air in boundary layer is practically equilibrium and influence of the calorimeter surface catalytic activity can be neglected. The surface roughness effect is also neglectible due to low Reynolds numbers.

The problems mentioned above arise when low density flows are under consideration. High pressure of arc heated flow stagnation produces problems of the measurements technical realization.

So, a HPM ablation investigations at a turbulent heat transfer regime are curried out in U-15T-2 facility equipped with the 4-electrodes heater of 40 MW power consumption [1-3, 11]. In the test section near the nozzle exit there is P_0'~ 2,3 MPa, mass average flow temperature is about 4500 K. Heat flux to the 12.5 mm probe, taking into account the flow enthalpy unevenness, is about 80 MW/m^2 and existing mechanism of the probe input/output with water cooling equipment could not withstand it. The probe radius upsizing could reduce the heat flux to measureable levels, but would increase the flow total force on the probe. So, an aerodynamic force on 70 mm (in diameter) object is about 0,5 ton, that also does not permit the input/output mechanism reliable operation.

Taking into account that each arc-heater generates flows with intrinsic ratio of the centerline to average enthalpy values and relative flow parameters profiles are practically the same for any operation regime, the calorimetric tests were conducted for the facility assemblage with another nozzle of greater Much number resulting in far less P_0' value. Unsteady quick-response calorimeter made as a thin (1 mm) copper plate equipped with thermocouple in its center was moved acroos the flow and the calorimeter temperature T(t) and its holder movement X(t) were recorded by PC. The experiments gave that flow core enthalpy exceeds mass-average value 1,65 times: $I_0(0)/I_{0av}\approx 1,65$. The experimental distributions of measured heat flux and evaluated enthalpy are presented in Fig. 6 [11]. The assumption that this value is valid for the standard P_0'~ 2,3 MPa flows was confirmed by the following experiments. Supposing that the flow core total enthalpy keeps the same far downstream, the enthalpy probe was located at about 1 m distance from the nozzle exit. The tests with cold air curtain of 6 kg/s mass flow rate blowing up through a gap around the noz-

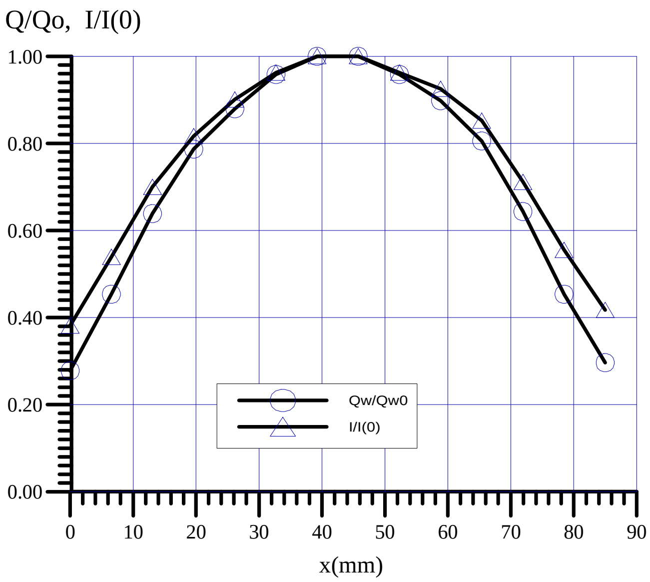

Fig. 6. Heat flux and total enthalpy variations across test section of U-15T-2

zle exit resulted in measure enthalpy ratio $I_0(0)/I_{0av} \approx 1,4 - 1,7$ (measured P_0' was about 0,15 MPa) whereas without the air curtain the measured enthalpy values corresponded to the mass-average ones. So, the strong coaxial blowing up prevents the jet mixing and the flow core keeps its enthalpy.

In conclusion, it must be noted the following. As a rule, HPM tests in arc-jet facilities are comparative and intended for the best technology choice or for verification of the material party ablation properties. Moreover, since various arc-jet facilities have various levels of flow pulsations, acoustic noises and contaminations (mainly copper), so only the data can be compared which are obtained in the same facility at the same regime of its operation. The measurement techniques and data processing must also be the same.

Continual widening of arc-jet investigations area with the growing importance of a methodological approaches demands more and more efforts on the flows diagnostics involving the plasma thermodynamic state evaluations.

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