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CONTACT METHODS FOR DIAGNOSTICS OF THERMAL PLASMA

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Abstract - In this paper principle of measurement, together with illustrative examples of possible applications, are presented for the following contact methods: 1) enthalpy (calorimetric) probe, 2) flying Pitot-probe, 3) flying thermocouple. Calorimetric or enthalpy probe is, in fact, water cooled Pitot-probe for direct measurement of stagnation pressure and stagnation enthalpy. Dynamic method of flying Pitot-probe enables a brief collecting of experimental data and implies good dynamic characteristics of pneumatic part of measuring system. Measuring of plasma flow temperature by flying or dynamic thermocouple, consists of two or more passings with sensitive element of thermocouple along the diameter of the flow. Besides the detailed description of each method, some experimental results are presented for air-nitrogen plasma jet at the exit of the experimental plasma torch.

1. INTRODUCTION

Term of thermal or dense plasma is relied with partially dissociated or ionized gas, but not so rarefied that radiation processes of energy transfer becomes dominant compared to particles collision processes. Term of thermal plasma is closely connected with the condition of local thermodynamic equilibrium (LTE) which implies unique value of temperature for every particle at one single point. Greater deviations from equilibrium plasma should be expected at lower pressures (<0.1 bar).

Experimental investigation of flow parameters for dense or thermal plasma (high temperature 5000-15000 K, multiphase flow, chemical reactions) is very complex problem. For diagnostics of typical plasma flows, plenty of contact and optical methods are presently in use.

Temperatures of 5000 K and more exceed melting point of all technical materials, so some special constructions had to be developed to enable application of contact methods. Contact methods are based on small dimension probes: a) cooled for static (point by point) measurements and b) uncooled for dynamic measurements. Although contact methods induce some flow disturbance and usually gives lower accuracy (typical range (5-10%) compared with optical methods, they are widely used in thermal plasma diagnostics because:

- they are based on cheap commercial sensors and instruments,
- they can be quickly installed, and easily and inexpensively used,
- they can measure a whole profile or even a flow field in a short period of time (for dynamic methods typical scanning period is of the order 1 sec).

Paper presents development and application possibilities for: 1) miniature calorimetric or enthalpy probe, 2) dynamic method of flying Pitot-probe and...
3) dynamic method of flying thermocouple.

2. ENTHALPY (CALORIMETRIC) PROBE

For measuring the distribution of pressure and enthalpy in thermal plasma flows ($T < 15000 \text{ K}$), enthalpy probe is widely spread experimental method /1,2,3,4/. This method enables measuring the local values of stagnation pressure and enthalpy in flow field with high gradients of thermodynamic and flow parameters. Special advantage of this method is high quenching velocity of "gas-sample" which enables a simulation of freezing device i.e. examination of possible products of chemical reaction. For this reason enthalpy probe is widely used in plasma chemistry and material processing.

Method is based on two measurements in each measuring point: with and without aspiration of "gas-sample" through the central channel of diameter $d_1$ (figure 1). In regime without aspiration, stagnation pressure and "tara" heat flux ($Q_b$) from plasma through outer probe surface to coolant water are measured ($Q_b=m c_p \Delta T_b$; $m$-mass flow rate, $c_p$-specific heat capacity and $T_b$-temperature rise of coolant water). In regime with aspiration, heat flux to coolant water is equal to the sum of heat flux through the outer probe surface ($Q_a$) and heat flux from "gas-sample" ($m c_p \Delta T_a=Q_a+G (h_i-h_o)$; $h_i$ and $h_o$ are stagnation enthalpy of the "gas sample" at the inlet and outlet of the probe. If aspiration is isokinetics i.e. if mass flow rate of gas sample $G$, is equal (or less) to the free stream mass flow rate ($G \leq \rho W \pi/4$; $W$ and $\rho$ are free stream velocity and dencity of the gas at the inlet of the probe), heat fluxes to the outer probe surface in two regimes are equal ($Q_a=Q_b$) and obtain formula for measured stagnation enthalpy:

$$h_i = h_o + m c_p (\Delta T_a - \Delta T_b) / G \quad (1)$$

There are few basic requirements which enthalpy probe has to meet in order to qualify it self as a diagnostics tool:

1) The probe has to be rigid and thermally properly protected to survive extremely hostile environment of plasma flows.

2) The probe must be small enough to ensure sufficient spatial resolution and small disturbance of the flow.

3) The probe has to be sensitive to detect enthalpy variations in flow field with high gradients of flow parameters.

Dimensions of i.d. (1.6 mm) and o.d. (3.2 mm) are choosen to satisfy all previously mentioned criterions. Dimensions $\Omega 1.6/\Omega 3.2$ and construction with stainless steel tubes argon welded at the probes tip, enable reliable work of the probe in thermal plasma with enthalpy up to 10 MJ/kg, stagnation heat flux up to 8 MW/m and mass flow rate of coolant water of minimum 10 g/s, and high sensitivity of the probe $S=(\Delta T_a - \Delta T_b) / \Delta T_s < 27\%$. Accuracy of the measurement depends on accuracy of measurements of temperature and mass flow rate of coolant water, and of measurement of mass flow rate of gas through the central channel of the probe, and has been determined approximately at 5% /5/. Under the assumption of LTE One can calculate temperature from measured value of stagnation enthalpy, and velocity from measured value of stagnation pressure. This means that use of enthalpy probe at real experimental situation (free jet, model of plasma reactor) enables one to get distribution of four basic flow parameters. From the expences point of view, this is great advantage in comparison with other experimental methods for plasma flows diagnostics. Figures 5-8 present axial profiles of jet flow field with constant value lines of stagnation enthalpy, stagnation pressure, temperature and velocity obtained from measurement by enthalpy probe for one working regime of the experimental plasma torch.

3. DINAMIC MEASUREMENT OF STAGNATION PRESSURE

Dynamic measurement is based on fast passings with Pitot-probe along the diameter of plasma flow /6,7/. Experimental installation is schematically presented at figure 3. An uncooled Pitot-probe 2, with pressure transducer 3, is fixed directly on pendulum 1. Pendulum oscilates within the plane perpendicular to jet axis. During the rapid probe flight across the jet, pressure signal is recorded in memory of computer. Optical position detector 4 is used to correlate the time dependence of pressure signal with radial coordinate. This method is very useful because of several advantages:
- it is relatively unexpensive and simple method.
- probe can withstand extremely high temperatures.
- a whole pressure profile can be measured in very short period of time.
- uncooled probe with small dimensions can be used with minimal flow disturbances.

Main problem of the method is phase and amplitude distortion of inlet signal in acoustic part of measuring system, figure 3, which consists of the Pitot probe tube, volume $V_1$, and the chamber above the transducer membrane, volume $V_2$.

Basic differential equations governing transient one-dimensional adiabatic flow of compressible fluid with friction induced by unit step pressure function at the inlet of the Pitot probe ($\tau \leq 0$, $p=p_0$, $u=0$; $\tau > 0$, $p=p_0+p_m$) are:

\[
\frac{\partial u}{\partial x} = \frac{1}{\rho C_s^2} \frac{\partial p}{\partial \tau} \quad (2) \quad \text{and} \quad \frac{\partial p}{\partial x} = - \rho \frac{\partial u}{\partial \tau} - R_u \quad (3)
\]

where $x$ is distance from inlet, $u$ is velocity, $p$ is pressure, $R_u$ is friction resistance, $\rho$ is density, and $C_s$ is speed of sound. Laplace transform of the above equations gives differential equation which governs dynamic behavior of the pneumatic system in complex (frequency) domain. Transfer function $\phi(s)$ of the pneumatic system is a ratio of the solutions of this differential equation at the boundaries of the system i.e. presents the ratio between inlet signal, $P(x=0, s)$, and its response in volume $V_2$, $P(x=l_1, s)$, in complex area:

\[
\phi(s) = \frac{P(x=0, s)}{P(x=l_1, s)} = \frac{\cosh \left[ L \sqrt{(R+S_p)/\rho} \right] + V \sqrt{(R+S_p)/\rho} \sinh \left[ L \sqrt{(R+S_p)/\rho} \right]}{\sqrt{(R+S_p)/\rho} \sqrt{L} \sqrt{(R+S_p)/\rho}} \quad (4)
\]

where $s$ is Laplace transform variable, $R=32 \mu/k_T^2$ (derived for laminar flow from Hagen-Poiseuille law), $L=l_1/c$, $V=V_2/V_1$ (Fig.4). Transfer function can serve as a base for selection of the pressure transducer and design of Pitot tube with good dynamic characteristics. Main demands for this purpose are following:

- volume $V_2$ above the transducer membrane has to be minimized,
- length of Pitot-probe tube has to be as short as possible, having in mind that such an optimal length can still protect transducer against high thermal stresses,
- an optimal internal diameter of the Pitot-probe tube has to be chosen in a way to meet a local measurement requirements and to give a good dynamic characteristic of the measuring system at the same time.

Beside errors characteristic for static Pitot-probe measurements, accuracy of this method depends on dynamic characteristics of the measuring system. With careful sizing of the probe and by correct choice of pressure transducer, relative error can be decreased to 5% for diagnostics of plasma flows which has been experimentally proved by calibration measurements [7]. Example of this method performances is shown at figure 9 which presents isobars in axial cross section of the jet.

4. DYNAMIC THERMOCOUPLE METHOD

Essence of this method is to make a rapid passing with the junction of the thermocouple through the cross-section of plasma jet and to record its temperature change. Radial profile of jet temperature can be calculated by processing of continuous temperature recordings from two or more passings (figure 2b). In the first passing start temperature of thermocouple is equal to room temperature but in the second thermocouple is heated to temperature 400-500°C. If we neglect radiation of the tip, we can assume that convective heat flux $q(r_1)$ at any observed point (point $A$, figure 2a) can be obtained by differentiating of recorded temperature signal $T_S(r)$ of spheric thermocouple (with radius $R$).

\[
q(r_1) = 0.33 \rho C_p \left( \frac{dT_S}{d\tau} \right)_A \quad (5)
\]

where $\rho$ is density of thermocouple material and $C_p$ is its specific heat capacity. Under the assumption that convective heat transfer coefficients from plasma to thermocouple tip, at the same observed point $A$, but in different passings, $\alpha'(r_1)$ and $\alpha''(r_1)$, are equal, we obtain:
from this equation we finally obtain expression for calculating the temperature of the plasma jet at observed point A.

\[ T(r_1) = \frac{q'(r_1) - q''(r_1)}{q'(r_1) - q''(r_1)} \]

Basic parameter which defines possibilities of this method, is velocity of thermocouple passing through the plasma jet. There are two opposite demands for this velocity:
- it has to be high enough to avoid the melting of thermocouple,
- it has to be small enough to limit the initial irregular regime of heating the thermocouple, to small region of the jet (1/20 of jet diameter) /8/.

Temperature probe is schematically presented at figure 2b. K type thermocouple (chromel-alumel) has been used due to its linear characteristics. Thermocouple tip was spheric, with 0.95 mm in diameter.

Demand for equality of convective heat transfer coefficients \( a'(r) \) and \( a''(r) \) is hard to be fulfilled in practice. Certain difference between temperature of the film, surrounding spheric thermocouple tip, in two passings can cause difference in heat transfer coefficients of few percentages. Ratio between these coefficients \( K = a'(r)/a''(r) \) can be experimentally determined from three or more passings along the same diameter of the jet. Value of \( K \) should be controlled and certain corrections in calculation procedure should be involved each time when \( K \) is greater than 1.02. This value of \( K \) involves systematic error in calculation by expression (7) of about 8% in the direction of increasing the temperature. On the other hand calculation (7) is carried out under the assumption of idealized heat transfer regime from jet to thermocouple. Radiation of thermocouple junction is neglected as well as conduction losses in its wires. This causes systematic error less than 7.5% in the direction of decreasing the calculated temperature. Systematic errors mentioned are opposite in sign and they are balancing each other to certain amount.

While differentiating temperature signals and calculating heat flux by expression (5), adjacent error occurs, which can be decreased by using equipment for automatic data collecting with high frequency. Sumar error of the method does not exceed 10%, and having in mind simplicity and expeditevity of measuring procedure, we can conclude that this method can be readily used when high accuracy of measurement is not an imperative. Figure 10 presents three radial temperature profiles for one working regime of experimental plasma torch obtained by processing of continious temperature recordings for several passings per cross-section.

5. CONCLUSION

General adventage of methods described is their simple construction and, according to that, their relatively low cost, compared to different contactless methods. Parallel use of these methods enables complete diagnostics of plasma flow field, with getting all significant flow parameters, for relatively short time. Accuracy of these methods is of the order 5 to 10%, and from experimental investigation of plasma flows point of view, is completely satisfactory. During the developing process of certain plasma technology, when global diagnostics of temperature and flow fields are of prior interest, these methods are of great importance. When main task of measurement is to collect experimental data for mathematical modelling of plasma flow processes, where high accuracy of measurements are of great importance, their application is limited.

6. LITERATURA

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Fig. 1. Enthalpy probe

1 - water inlet and outlet
2 - micro orifice
3 - electromagnetic valve
4 - vacuum pump
5, 6 - differential pressure transducer
Fig. 2a. Temperature probe

Fig. 2b. Temperature and flux signals

Fig. 3. SCHEMATIC DIAGRAM OF APPARATUS
1. PENDULLUM 2. PITOT-PROBE
3. PRESSURE TRANSDUCER 4. OPTICAL DETECTOR 5. TORCH

Fig. 4. SCHEMATIC DIAGRAM OF MEASURING SYSTEM PITOT-TUBE PRESSURE TRANSUDCER
Fig. 5. Axial distribution of stagnation enthalpy

Fig. 6. Axial distribution of stagnation pressure

Fig. 7. Axial distribution of temperature

Fig. 8. Axial distribution of velocity
Fig. 9. Axial profiles of stagnation pressure obtained by flying Pitot-probe.

Fig. 10. Radial profiles of temperature.