DETERMINATION OF TEMPERATURE AND VELOCITY OF AN ARC-HEATED, SUBSONIC PLASMA JET ISSUING FROM A PLASMA TORCH

F. Reuter and H. Kremer
Lehrstuhl für Energieanlagentechnik, Ruhr-Universität Bochum,
Universitätsstr. 150, 4630 Bochum 1, BRD

Keyword: arc-heated, subsonic N_2-plasma jet

ABSTRACT

A procedure is presented which allows to determine the mean values of enthalpy or temperature and velocity of a subsonic plasma jet issuing from a 40 kW-plasma torch. This can be performed by measuring the gas energy calorimetrically and evaluating the data from thermodynamic equilibrium. Using those initial values it is possible to predict the radial and axial velocity and enthalpy variations for the region of similarity in the free jet. Results are represented for an arc-heated N_2-plasma jet.

1. INTRODUCTION

Meanwhile plasma generators are not only used in those sophisticated ranges of application as for example space research or transformation of energy by MHD-power generation but are employed also in a lot of traditional industrial operations. Mostly burners of low or medium power are installed. In order to apply the right plasma torch to a certain purpose, it is necessary to know the kinetic and thermal gas energy at the nozzle exit and in the following free-jet region. Thereby the operators of this equipment are not interested in rather complicated measuring methods or caldulations. They only want to have at their disposal a simple working procedure, such as an operating characteristic.

In the following a method is presented which allows to evaluate the average exit enthalpy and velocity of an arc-heated plasma jet by means of a calorimetric measurement, combined with the calculation of thermodynamic equilibrium. Making use of these initial data it is possible to predetermine the profiles of temperature and velocity in the free jet for the region of similarity, too.

2. DETERMINATION OF THE INITIAL GAS CONDITIONS

Torch operating conditions and efficiency can be determined calorimetrically. The procedure is described in literature, for example by MARCHANDISE [1]. For the present investigations a simple water-cooled counter-flow heat exchanger touching down directly on the torch was used to measure the total energy of the arc-heated gas flow. The nozzle-calorimeter arrangement is shown shematically in Fig. 1. Applying the first law of thermodynamics to the represented system equation (3) can be derived. When the gas energy at the calorimeter exit is neglected, this formula denotes the measurable heat input to the cooling water and the energy of the plasma flow or the useful work of the torch, accordingly. Assuming that thermodynamic equilibrium prevails in the flow field, all quantities of a dissociated and/or ionized gas, as for example density and enthalpy, can be computed by means of partition functions and with the help of an iterative procedure. As a result of these calculations the N_2-enthalpy [J/g] is plotted in Fig. 2 for p = 1 bar as a function of temperature. For a given torch operating point it is consequently possible to evaluate the initial mean values of jet enthalpy (from eq. 3) and velocity (from eq. 2b) at the nozzle exit. The combination of calorimetric measurement and theoretical computation yields the family of characteristics in Fig. 5. Fig. 5a shows the operating lines measured for the 40 kW-plasma torch which has been used for all experiments. Employing Nitrogen as working fluid the gas energy is plotted as a function of the induced potential energy for three gas flow rates. One obtains the torch efficiency dividing the available energy $\dot{Q}_{Kal}$ by the power input P_{el}:

$$\eta = \dot{Q}_{Kal}/P_{el} \tag{4}$$

The other diagrams show the calculated curves of gas energy (Fig. 5c), momentum flux density (Fig. 5b), velocity and Reynolds number(Fig. 5d), all for a pressure p = 1 bar and as a function of gas temperature. By means of the four diagrams it is possible to read off the average exit temperature and velocity of the plasma jet issuing from the torch nozzle (nozzle diameter: 5 mm) for a given operating condition.

3. EVALUATION OF THE ENTHALPY AND VELOCITY VARIATIONS IN THE TURBULENT FREE JET

Employing the respective mathematical interrelationships of the turbulent free jet the axial and radial variations of enthalpy and velocity can be evaluated. Based upon REICHARDTs experimental and theoretical considerations [2] KREMER [3] derived distribution functions yielding the flux density of momentum, heat and mass flow for different nozzle geometries. Concerning momentum and heat flux density they are

$$\frac{\rho u^2}{(\overline{\rho u^2})_o} = \frac{1}{4\cdot c_i^{\,2}\cdot(\frac{y}{d})^2}\cdot e^{-\frac{1}{c_i^{\,2}}\cdot(\frac{x}{y})^2} \tag{5a}$$

$$\frac{\rho u h}{(\overline{\rho u h})_o} = \frac{1}{4\cdot c_q^{\,2}\cdot(\frac{y}{d})^2}\cdot e^{-\frac{1}{c_q^{\,2}}\cdot(\frac{x}{y})^2}\ , \tag{5b}$$

respectively, where $(\overline{\rho u^2})_o$ and $(\overline{\rho u h})_o$ denote the mean values at the nozzle exit, d is the nozzle diameter, y the axial and x the radial coordinate. The transfer factors of momentum c_i and heat c_q must be determined experimentally. For the region of similarity the above equations reproduce the Gaussian distribution of the regarding flux densities in a turbulent jet. Combination of the two expressions results in a relationship which enables to evaluate the enthalpy variation from known velocity profiles. For that purpose the momentum and heat transfer coefficients c_i and c_q have to be replaced by the turbulent Prandtl number which can be defined in terms of the velocity and enthalpy half-widths [4] as

$$Pr_t = [(x_{0,5})_u \ / \ (x_{0,5})_h]^2 \tag{6a}$$

and may be transformed to

$$Pr_t = (c_i/c_q)^2 . \tag{6b}$$

As the result of substitution the following relationship is obtained

$$\rho u h = \rho u^2\cdot \frac{\overline{h}_o}{\overline{\overline{u}}_o}\cdot Pr_t\cdot e^{(\frac{x}{y})^2\cdot(\frac{1}{c_i^{\,2}} - \frac{1}{c_q^{\,2}})} \ . \tag{7a}$$

Taking into account that Pr ≈ 1 seems to be an allowable simplification for turbulent flow of all kinds of gas [5], equations (7a) may be reduced to

$$\rho\cdot u\cdot h = \rho\cdot u^2\cdot \frac{\overline{h}_o}{\overline{\overline{u}}_o} \tag{7b}$$

The above assumption is supported by the present measurements, too.

4. MEASURING METHOD AND RESULTS

Experimental investigations in the flow field of the plasma jet were performed using a water-cooled enthalpy/pressure probe (3 mm o.d.). The measuring arrangement is similar to that described by GREY [6]. With the assumption that the static pressure is equal to the ambient pressure everywhere in the jet, the momentum flux density can be calculated from the measured pressure distribution. For low subsonic gas flows, as in the present case, the Bernoulli equation is available. By means of an iterative procedure velocity and enthalpy of the gas can be computed from equilibrium relationships, consequently.

Fig. 3 and 4 show the results of the experimental and theoretical investigations for a certain torch operating point. At three axial locations the radial distribution of gas enthalpy and heat flux density, as determined by probe measurements, are plotted and compared with the calculated values from equation (7b). A fairly good agreement is displayed at least in the surroundings of the jet axis.

As conclusion the demonstrated procedure seems to be suitable to evaluate gas enthalpy variation from measured pressure distribution, at least on the axis of a turbulent arc-heated gas flow generated in a plasma torch which is similar to the one used in the present investigations. More experimental data must prove this.

REFERENCES

[1] H. Marchandise, "Plasmatechnologie - Grundlagen und Anwendung" (Deutscher Verlag für Schweißtechnik (DVS) GmbH, Düsseldorf, 1970).

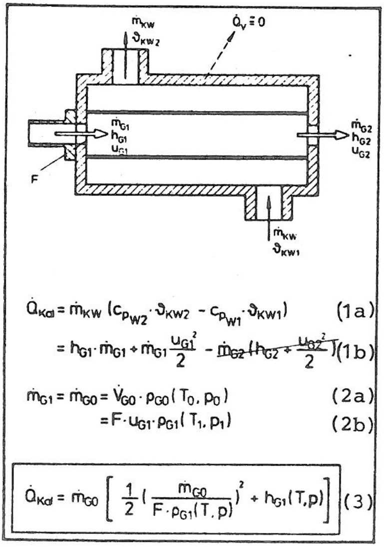
[2] H. Reichardt, "Gesetzmäßigkeiten der freien Turbulenz" (VDI-Forschungsheft 414, 2. Aufl. 1952)

[3] H. Kremer, "Zur Ausbreitung inhomogener, turbulenter Freistrahlen und turbulenter Diffusionsflammen" (Dissertation an der TH Karlsruhe, 1964)

[4] T.J. O'Connor, E.H. Comfort and L.A. Cass, AIAA J. 4, 2026 (1966)

[5] S.I. Pai, "Fluid Dynamics of Jets" (Van Nostrand, New York, 1954)

[6] J. Grey, P.F. Jacobs and M.P. Sherman, Rev. Sci. Instr. 33, 738 (1962)



$$\dot Q_{Kal} = \dot m_{KW}\,(c_{p_{W2}}\cdot\vartheta_{KW2} - c_{p_{W1}}\cdot\vartheta_{KW1}) \qquad (1a)$$

$$= h_{G1}\cdot\dot m_{G1} + \dot m_{G1}\frac{u_{G1}^2}{2} - \cancel{\dot m_{G2}\left(h_{G2}+\frac{u_{G2}^2}{2}\right)} \qquad (1b)$$

$$\dot m_{G1} = \dot m_{G0} = \dot V_{G0}\cdot\rho_{G0}(T_0,p_0) \qquad (2a)$$

$$= F\cdot u_{G1}\cdot\rho_{G1}(T_1,p_1) \qquad (2b)$$

$$\boxed{\dot Q_{Kal} = \dot m_{G0}\left[\frac{1}{2}\left(\frac{\dot m_{G0}}{F\cdot\rho_{G1}(T,p)}\right)^2 + h_{G1}(T,p)\right]} \qquad (3)$$

Fig.1 Energy balance for the nozzle-calorimeter-arrangement

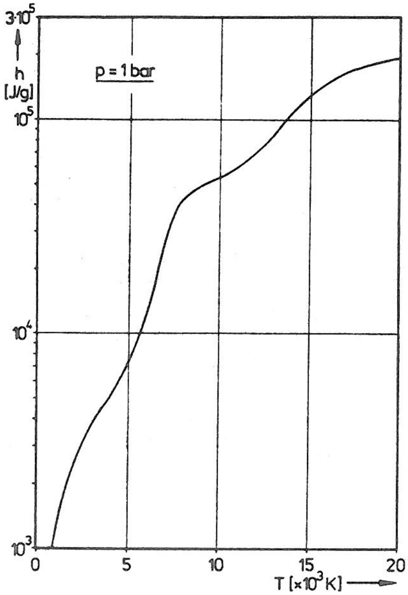


Fig.2 Enthalpy of Nitrogen as function of temperature

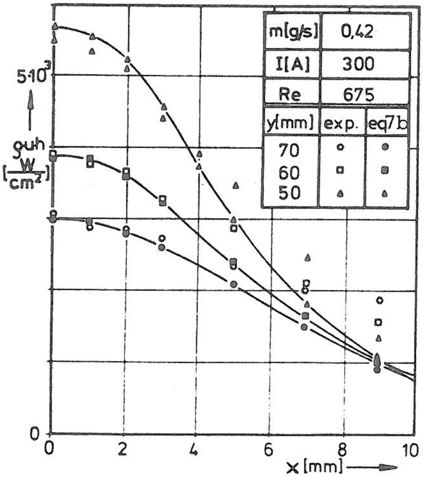


Fig.3 Radial heat flux density of a N_2-jet issuing from a plasma torch

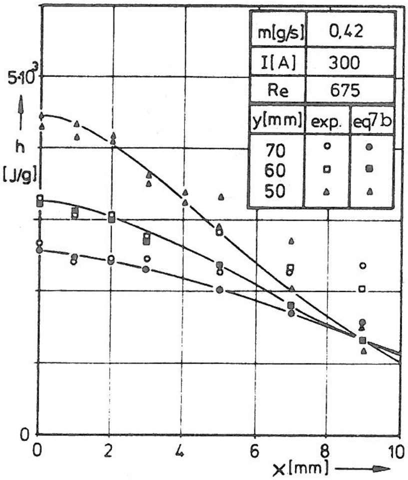


Fig.4 Radial enthalpy profiles of a N_2-jet issuing from a plasma torch

(pressure: p = 1 bar; nozzle: d = 5 mm i.d.)

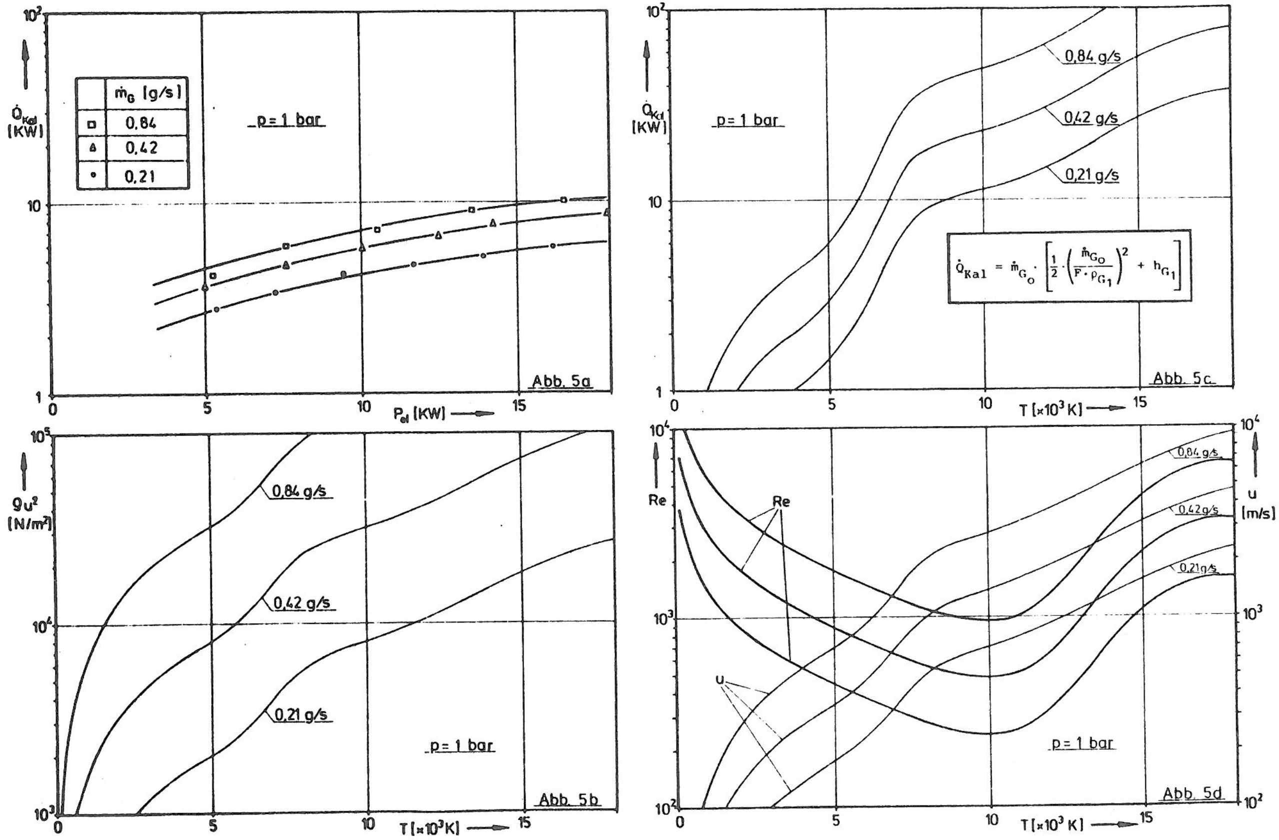


Fig.5 Characteristic curves of a 40 kW-plasma torch (working fluid: N_2; nozzle: d = 5 mm i.d.)