STRUCTURE OF HOT MIXTURE FREE JET AT THE ARC-HEATER OUTPUT

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Introduction

The final properties of the coating sprayed by thermal plasma are substantially influenced by heat and momentum transfer between the flowing plasma and injected particles. For this reason it is necessary to know the main parameters of the plasma jet along the whole path of the particles. Because of great changes in plasma parameters, different measuring techniques must be used for the parts close to plasma generator output and in the regions far from it. In this paper, attention is focused to the character of flow and to the diffusion of the components of the hot gas mixture in the area near the output nozzle.

Experiments have been carried out on a hybrid water/argon plasma torch in the Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Prague. DC electric arc in it is stabilized by tangential argon flow in the vicinity of the cathode, and mainly by water vortex in the prevailing part downstream. The anode is formed by an external rotating water-cooled disc situated several millimetres downstream of the torch exit orifice (see Figure 1). The plasma jet flows out into the surrounding air of atmospheric pressure. Typical operational parameters of the torch are: arc current between 150 and 500 amperes, voltage between 160 and 270 volts, argon flow rate between 12 and 28 slm. The share of argon and water vapour in the plasma jet outputting the exit nozzle varies not only in dependence on the argon flow, but also according to the input power which influences the evaporation rate of the stabilizing water. This fact must be taken into account in the following computations.

The paper deals with the investigation of the character of flow of the plasma jet near the exit nozzle using radial temperature profiles obtained by spectroscopic measurement and velocities measured by enthalpy probe.

Parameters of plasma leaving the output

The analysed experiment is characterised by the following values: the output orifice diameter 5.6 mm, the arc current \( I = 300 \) A, the arc voltage \( U = 220 \) V, the input power \( P = 66 \text{ kW} \), the efficiency \( \eta = 0.55 \), the output power \( P_{\text{net}} = 36.3 \text{ kW} \), and the net flow-rate of argon \( G_{\text{Ar}} = 0.4126 \cdot 10^{-3} \text{ kgs}^{-1} \). The determination of the flow rate of water vapour at the output \( G_{\text{WV}} \) is very difficult. Of course, the total flow rate of water is measured but the water evaporated from the water swirl is only a negligible portion of it. Thus, the flow rate \( G_{\text{WV}} \) must be computed indirectly using the continuity and energy equation.

The following values of the output quantities have been determined from the measured parameters by the method described in \(^1\): the ratio of components \( \frac{G_{\text{WV}}}{G_{\text{Ar}}} = 0.64 \), Mach number \( M = 0.64 \), the total flow-rate \( G(0) = 6.36 \cdot 10^{-4} \text{ kgs}^{-1} \), and the total moment of the momentum of the mixture for \( z = 0 \) \( A(0) = 0.36 \text{ kgs}^{-2} \).

The centreline temperatures at the region close to the plasma generator exit nozzle have been measured using spectroscopy. They range between 16900 and 8500 K for \( z \) between 0.035 m and 0.050 m. The corresponding measured velocities are between 800 and 200 ms\(^{-1}\). The measured axial dependencies of centreline temperature and axial component of velocity have been approximated by parabolic functions.

The radial dependencies of both temperature (Fig. 2) and axial component of velocity are approximated by exponential (Gaussian) functions

\[
T(r,z) = T(0,z) - T_e \exp \left( -\ln 2 \frac{r^2}{\beta^2(z)} \right) + T_e
\]

\[
v_r(r,z) = v_r(0,z) \exp \left( -\ln 2 \frac{r^2}{\sigma(z)\beta^2(z)} \right)
\]
Investigation of free jet near the output

The radial component of the velocity $v_i(r,z)$ complying with the measured axial velocity was computed by the equation system consisting of the continuity equation

$$\frac{\partial v_i(r,z)}{\partial z} + \frac{\partial v_i(r,z)}{\partial r} = 0$$

(1)

and the axial component of the momentum equation in kinematic expression

$$\frac{v_i(r,z)}{\partial r} = v(r,z) \frac{\partial}{\partial r} \left[ 1 - \exp \left( \frac{\ln^2 r}{\sigma_0} \right) \right]$$

(2)

In the centreline, the radial component of velocity must be equal to zero. Using the momentum equation, the relation between $\sigma(z)$ and the dimensionless parameter $c_i$ characterizing the turbulent component of viscosity can be written as follows

$$\sqrt{\sigma(z)} = \frac{4 \ln 2 v(0,z)}{b_i(z)} \left[ 1 + \frac{1}{\nu_i(0,z)} \sum c_i(0,z) v_i(0,z) \right]$$

(3)

where subscript $i=1$ stands for air, 2 for argon, and 3 for water vapour. The turbulent component of the kinematic viscosity follows from Prandtl’s theory of the mixing length

$$v_i(z) = c_i(0,z) \sqrt{\sigma(z)} b_i(0,z)$$

(4)

The total kinematic viscosity includes the turbulent (common for all species of the mixture) and the laminar component as follows

$$\nu(r,z) = v_i(0,z) \left[ 1 + \sum x_i(r,z) e_{\nu_i}(r,z) \right]$$

(5)

$$e_{\nu_i}(r,z) = \frac{\nu_i(r,z)}{\nu_i(0,z)} = \frac{v_i(r,z)}{v_i(0,z)}$$

The radial component of velocity $v_i(r,z)$ can be expressed from the continuity equation and from the axial component of the momentum equation. From the equality of the two relations it follows

$$v_i(r,z) = - \frac{2 v(0,z)}{b_i(z)} v_i(0,z) \left[ \frac{1}{\nu(0,z)} v_i(0,z) + 2 \frac{\partial h_i(z)}{b_i(z)} \right]$$

$$+ \frac{2}{\sigma_0 \nu_i(0,z)} \left[ 1 - \exp \left( \frac{\ln^2 r}{\sigma_0} \right) \right]$$

(6)

The quantities $\sigma(z)$ and $c_i$ and their possible dependencies on the variable $z$ are determined by iterative calculations.

The following relation can be used for the specific mass of the gas mixture in LTE

$$\rho(r,z) = \sum x_i(r,z) \rho_i(r,z)$$

(7)

The continuity equation including the diffusion member for each of the individual components leaving the exit nozzle ($i = 2$ (Ar), 3 (water vapour)) was used for investigating the diffusion of gas mixture components by means of the measured and computed temperature and velocity fields

$$\nabla \cdot (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{D}_{\nu_i} \nabla \nu_i) = 0$$

(8)

Solving this differential equation, we obtain the relation for the distribution of concentrations of individual species of the gas mixture as follows

$$\frac{x_i(r,z)}{x_i(0,z)} = \exp \left[ - B_{\nu_i}(r,z) \right]$$

(9)

$$B_{\nu_i}(r,z) = \frac{2}{\rho_i(r,z)} \frac{dr}{dz}$$

(10)

$$\frac{dr}{dz} = \frac{\rho_i(r,z)}{\nu_i(r,z)}$$

(11)

where the total diffusion coefficient of the $i$-th component is

$$\rho D_{\nu_i}(r,z) = \rho(0,z) b_i(z) \left[ \frac{c_i}{b_i(z)} + e_{\nu_i}(r,z) \right]$$

(12)

and the ratio $dz/dr(z)$ is

$$\frac{dz}{dr} = \frac{x_i(r,z)}{\nu_i(r,z)}$$

From the condition of constant mass flow-rate along the jet axis it follows

$$v(0,z) [x_i(0,z) B_{\nu_i}(z) + x_j(0,z) B_{\nu_j}(z)] = G(0) = G_z + G_j$$

(13)

where

$$B_{\nu_i}(z) = \int_0^z \rho_i[T(r,z)] \exp(-b_i(r,z)) dz$$

(14)

$$b_{\nu_i}(r,z) = \ln 2 \frac{r^2}{b_i(z)} + B_{\nu_i}(r,z)$$
The last condition to be fulfilled by the results of the iterative computation is the constant moment of momentum along the axis of the flow\(^5\)

\[
J(0) = \int_0^\infty \rho(r,z) v_z^2(r,z) 2\pi dr.
\]

\(J(0)\) is the moment of momentum of the components (argon and water vapour) at the output of the plasma generator. Using relation (7), the condition of constant momentum can be written as follows

\[
v_z^2(0,z) = \begin{cases} 1 + & \left[ \frac{\rho_{\text{Air}}[T(r,z)]}{\rho_{\text{Air}}[T(r,z)]} \right] \exp[-B_{\text{Air}}(r,z)] \right] \\
+ x_{\text{Air}}(0,z) \left[ \frac{\rho_{\text{WV}}[T(r,z)]}{\rho_{\text{WV}}[T(r,z)]} \right] \exp[-B_{\text{WV}}(r,z)] \\
+ x_{\text{Ar}}(0,z) \left[ \frac{\rho_{\text{Ar}}[T(r,z)]}{\rho_{\text{Ar}}[T(r,z)]} \right] \exp[-B_{\text{Ar}}(r,z)] \end{cases} 
\]

The previous computations\(^4\) have proved extremely low value of the laminar component of the diffusion coefficient compared to its turbulent component. Its influence on the iteration procedure is negligible. Thus, the coefficient \(Sc(z)\) is used to fit the leading turbulent component.

The iterative computation starts with the chosen coefficient \(Sc(z)\) in the relation for diffusion (10) and \(\sigma(z)\). Using (3), (6), and (12), the turbulent coefficient \(c_{\nu}\), radial velocity \(v(r,z)\), and concentrations \(x_i(r,z)\) are computed until the above mentioned conditions are met. Finally, the condition (15) is tested, and if not fulfilled, the computation is repeated with a different value of \(Sc\).

### Results and discussion

In Fig. 3 to 5, the results of the computations are given when the recommended and in literature commonly used value of coefficient \(Sc=1\) has been applied. During these first calculations the momentum conservation condition (15) has not been tested yet. Fig. 3 shows the computed radial profiles of the axial and radial component of velocity as an example for the distance of 0.045 m from the plasma generator exit orifice. The dependencies were computed for several positions near the output (between 0.035 to 0.050 m). Naturally, both velocity components are decreasing with the increasing distance. Simultaneously with the increasing distance from the output, the maximum value of the radial component of velocity shifts from the axis of the jet. The maximum value of the axial component of velocity is about ten to twenty times higher than the maximum value of the radial component of velocity.

An example of the computed radial dependency of mass concentration of the components of the gas mixture for the distance of 0.045 m from the output is given in Fig. 4. The concentration of argon and water vapour steeply decrease with radius. Fig. 5 demonstrates a low share of the laminar component of viscosity (at \(z = 0.045\) m from the output again). Due to this weak influence of the laminar component, parameter
Concerning the turbulent component has been taken as another free parameter for the iterative computation in order to meet the momentum conservation condition.

The condition (15) has been fulfilled with \( Sc \) significantly lower than 1 (e.g. for \( z = 0.045 \) m with \( Sc = 0.18 \)). It results in a steeper decrease of both velocities with the increasing radius and a higher ratio of maximum values of the axial and radial component of velocity (see Fig. 6).

The lower value of parameter \( Sc \) causes a higher value of the diffusion coefficient \( D_m \) (see relation (10)) and a lower value of exponent \( B(r,z) \) in relation (9). This leads to substantially slower decrease of the concentrations of individual species compared to the computation with \( Sc = 1 \). The ratio of laminar to turbulent component of viscosity with \( Sc = 0.18 \) has been computed almost three times higher than with \( Sc = 1 \) but it remains of order of several hundredths.

**Conclusions**

The computation enabling to estimate the parameters describing the hot gas mixture jet behaviour and development from the measured quantities near the arc heater output has been designed and tested on real measured data. The radial dependencies of velocity components, concentrations of species and laminar to turbulent viscosity ratio have been determined. Very weak influence of laminar viscosity even in the area close to the arc heater output has been found.

The change in parameter \( Sc \) has influenced the computed dependencies strongly which points to the necessity of deeper investigation of diffusion. The momentum conservation condition should be considered again with respect to radiation and radial heat convection losses which have not been taken into account yet.

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**REFERENCES**