Transition of thermal plasma jet from subsonic to supersonic regime

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Abstract: The present paper describes some features of the hybrid DC current gas-water torch. Analysis of the measured plasma torch characteristics shows that for some combinations of arc current and plasma gas flow rate the generated plasma jet starts transition to supersonic regime already under atmospheric pressure. This work is devoted to investigation of these limiting modes and the conditions, which cause them.

Keywords: thermal plasma jet, subsonic and supersonic flow

1. Introduction

Thermal plasma jets are often utilized in different branches of industry dealing with heat and mass transfer like spraying, welding, cutting, purification and waste treatment. The successful realization of these processes requires knowledge of basic phenomenon taking place inside and at the exit of plasma generators. The present paper focuses on study the transition of such jets from subsonic to supersonic regime. These two regimes differ a lot in behaviour. The major difference is coming from the fact that the information about the ambient pressure is carried inward the arc chamber by waves of sound speed. As soon as the flow velocity reaches and exceeds the speed of sound the fluid inside the torch does not obtain the information from outside. The jet exit pressure then can differ from the ambient and the flow exhibits a well-known supersonic structure [1]. Thus, the character of the jet can be govern by changing the pressure difference between the arc chamber and surrounding either by modifying the plasma torch parameters as a flow rate of the plasma forming gas, arc current or nozzle geometry or by reduction of the ambient pressure. The present work examines the transition regime of the plasma jet generated by a DC arc torch with gas-water stabilization [2]. In this torch for some combinations of arc current and plasma gas flow rate the jet starts transition to supersonic regime already under atmospheric pressure. This work is devoted to investigation of these limiting modes and the conditions, which cause them.

2. Experimental procedure

A plasma jet was generated by the DC arc torch with gas-water stabilization (**Fig. 1**). The torch combines two principles of stabilisation by gas flow and by water wall. The torch body consists of three main parts: a cathode gas stabilised part, a water stabilised part and an external anode. The cathode part is principally constructed in the same way as plasma torches with gas stabilisation. The stabilising gas, which is usually argon, is supplied tangentially around the cathode providing its protection against water vapour. The internal nozzle not only directs the argon flow, but also separates the cathode part from the water stabilised part.

In the water stabilised part water is supplied tangentially through several holes along the arc chamber. Centrifugal forces together with water exhausting system provide a formation of a channel inside water vortex where an arc is ignited. The main principle of plasma generation in the water stabilised part is evaporation of water from the stabilizing water vortex, heating and ionisation of vapour. This process is governed by the arc itself depending on energy dissipated by the arc. Heated and ionised water products are then mixed up with argon. Thus the flow rate of the plasma forming gas is not set directly and is a function of the plasma torch parameters, especially arc current. The stabilising water is exhausted in two locations: between the gas stabilised and water stabilised parts and right before the torch exit nozzle. Such an arrangement results in exhausting a part of plasma gas together with water from the arc chamber. Thus, only a part of the supplied argon and evaporated water remains in the plasma jet and its amount depends on the torch parameters. Increasing of the arc current results in higher pressure difference between the arc chamber and the water tank, which leads to higher pumping rate and more gas is exhausted. The increase of the argon flow rate also results in higher pressure difference and increase of the exhausted rate. Thus, composition of the plasma gas and its flow rate is a result of several

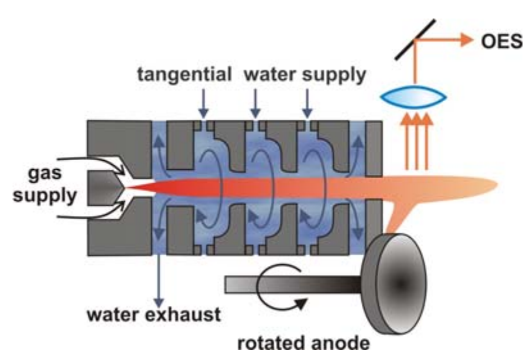

Fig.1 Hybrid gas-water torch and applied diagnostics.

processes, which depend on each other and are governed by the arc itself [3].

The anode is represented by a water cooled rotating disc placed outside the arc chamber following the torch nozzle. This arrangement is due to high heat load in the oxidizing atmosphere of water vapour.

In the present study arc current was varied between 500 and 600 A and the argon flow rate was varied between 22,5 and 40 slm.

An analysis of the plasma jet behaviour was based on measurements of power balances of the torch and temperature profiles at the torch exit. The temperature profiles were measured at 2 mm from the torch nozzle by means of emission spectroscopy (monochromator Jobin Yvon Triax 550 with a CCD detector). Temperature profiles were obtained from the hydrogen H_β line and from argon ionic lines. Potential of the torch exit nozzle was measured by high resistant voltage dividers. Power losses were determined from calorimetric measurements on cooling loops of the electrodes and of the water stabilising system.

3. Evaluation of measurements

A simple method based on energy and mass balances at the torch exit was used to determine properties of the generated plasma, which can not be measured, from the measured characteristics. Obtained temperature profiles, amount of argon remaining in plasma and net power in the torch arc chamber were used as initial parameters. The plasma gas composition, water evaporation rate, the flow rate of the plasma forming gas, Mach number and corresponding velocity profiles of the plasma jet at the torch exit were calculated. Compressibility effects were not taken into account in the present calculations. The pressure in the jet at the torch exit was assumed to be constant through the nozzle cross section and was equal to atmospheric. However the temperature profiles were measured at 2 mm from the nozzle, they were supposed to be equal to the temperatures at the nozzle exit. Temperature on the nozzle wall was assumed to be 1000 K. As temperature profiles at the torch exit were considered, only energy dissipated by arc between the cathode and the torch exit nozzle was considered and used in further evaluation. The processes in the free burning part of the arc between the nozzle and anode were not considered in the present calculations. Thermodynamic and transport properties for different mixture of argon and steam were calculated by the method described in [4].

The amount of water steam in the plasma gas was calculated based on temperature profiles, argon flow rate and power balances of the torch. The calculation of plasma forming gas composition is based on interpolation of the net power and the total enthalpy flux through the nozzle calculated from the temperature profiles for different Ar/H_2O mixtures [3]. Knowing the flow rate of argon in plasma and its volumetric percentage in Ar/H_2O mixture an amount of water steam in the generated plasma and the total plasma gas flow rate can be calculated.

The velocity profiles at the nozzle exit were determined from the temperature profile and net power dissipated inside the torch chamber for calculated plasma gas composition assuming LTE. First, the Mach number M was obtained from the equation:

$$M = \frac{F_e}{\int_0^R 2\pi r \rho c h \, dr}$$

where F_e is the total plasma enthalpy near the nozzle exit, ρ the plasma density, h the plasma enthalpy, c the sound velocity, R the radius of the nozzle (R = 3 mm). Under the assumption that radial pressure gradients are negligible and radial velocities are small compared to the axial velocities, the Mach number can be assumed to be independent of radial coordinates at the nozzle exit. Plasma enthalpy and density is a function of temperature and composition and their profiles were obtained from the measured temperature profiles and tables of thermodynamic properties for the given plasma gas composition. Knowing the value of Mach number, the velocity profile can be derived from the measured temperature profile using the relation:

$$V(r) = M \cdot c\{T(r)\}$$

where sound velocity c is again a function of temperature and composition for equilibrium conditions in the plasma. As the dependence of the sound velocity value on the

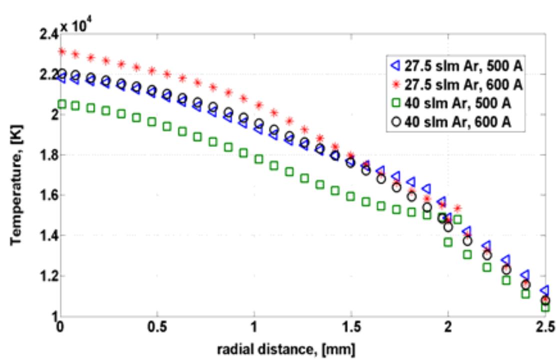

Fig.2 Temperature profiles in plasma flow for different plasma torch operation parameters.

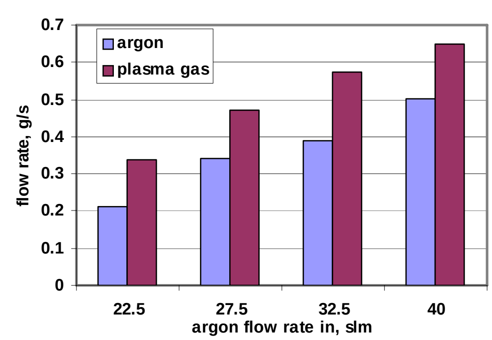

Fig.3 Effect of supplied argon flow rate on argon flow in generated plasma jet and on total plasma gas flow rate for I =500 A.

pressure is weak, the possible erroneous estimation of the pressure has a negligible effect on the resulting values of velocity.

4. Results and discussion

The parameters of the plasma torch determine properties of the generated plasma. As the generated arc exhibits a rising volt-ampere characteristic, arc current has a huge effect on plasma torch power and thus net power and on temperature of generated plasma (**Fig. 2**). The temperature rise for higher currents is connected with higher Joule heating released by arc. Argon flow rate has a negligible effect on the torch power balances. Nevertheless, addition of argon results in temperature reduction. This effect is connected with modified amount of argon in plasma and following changes of the plasma enthalpy and electrical conductivity. Addition of argon does not affect water evaporation rate [5], but amount of argon and thus total gas flow increased. **Fig. 3** shows effect of supplied argon flow rate on amount of argon remaining in plasma and total gas flow for 500 A of arc current. More argon is supplied, more is exhausted due to higher exhausting rate, but more argon also remains in plasma. Higher plasma gas flow rate should require more energy to be heated and to provide the required arc current. However, low enthalpy of argon reduces the total enthalpy of the plasma gas [4] and counterbalances the total energy balance in the jet.

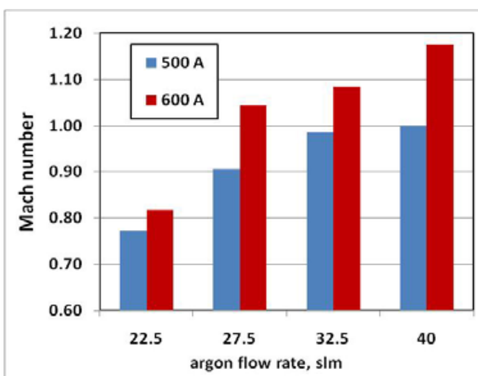

Fig.4 Mach number at the torch exit as a function of secondary gas flow rate for two arc currents.

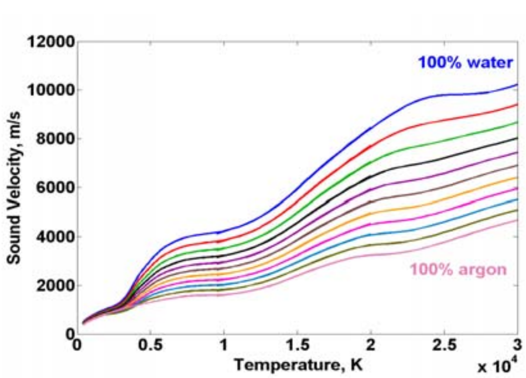

Fig.5 Sound velocity as a function of temperature and plasma gas composition.

The calculated Mach numbers for 500 and 600 A are shown in **Fig. 4** as a function of the supplied argon flow rate. Mach number increased as a result of increase of both the argon flow rate and the arc current. The arc current in most cases played more significant role. In the plasma torch Mach number changes not only due to increase of the flow velocity, but also due to change of the sound speed value caused by changes of the plasma temperature and composition (**Fig. 5**). Increase of water amount and temperature of the plasma result in increase of the sound velocity values and the flow stay subsonic for rather high values of velocity. Some calculated velocity profiles are shown in **Fig. 6**. The similar values of velocities for the current 500 A correspond to subsonic case for 27.5 slm of Ar and to transonic case with sonic velocities for 40 slm of Ar. The velocity profiles indicate huge effect of the arc current on the flow velocity, which is much higher than effect of argon. For higher arc current water amount in plasma increases due to higher evaporation rate. The increased mass flux through the constant nozzle area accompanied by much smaller plasma density, results in increase of the flow velocity. The effect is more pronounced due to higher ionisation level for increased plasma temperatures. At the same time increased argon amount is compensated by higher density. Such a huge difference in the calculated velocity values could be also caused by neglecting of the particular features of supersonic flows. Increasing of the pressure different between the torch and surrounding will not increase the nozzle Mach number beyond unity. Supersonic velocities can not be reached right at the nozzle exit, but downstream the flow in the expansion zone. The real values of velocity for the regimes with Mach numbers exceeding one should be lower.

Nevertheless, the transition from the subsonic to supersonic regime was not observed visually under the present conditions. The transition probably starts in the centre of the jet and a diamond structures are hardly visible due to strong radiation of the hot medium. Formation of the supersonic structure with shock diamonds in the central part of the discharge was obtained from the numerical simulations as well [7]. More precise analysis of the measured

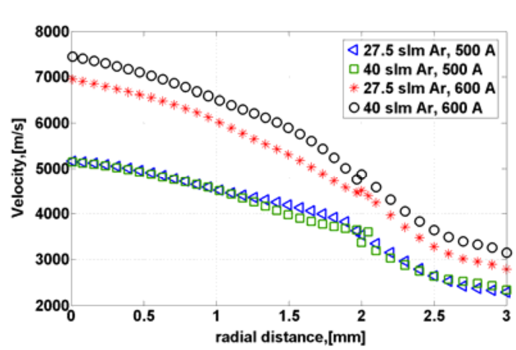

Fig. 6 Velocity profiles in plasma flow for different plasma torch operation parameters.

parameters including compressibility effects and pressure modification should be done.

Conclusions

The present paper examines transition regimes in the plasma torch with gas-water stabilisation of arc. Analysis of the measured parameters has shown that increase of arc current and argon flow rate resulted in such changes in flow velocity that it reaches sonic and supersonic values under atmospheric pressure conditions. The main factors governing this process are increased plasma gas flow rate accompanied by reduction of density for the higher plasma flow temperatures.

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