Processes in Gerdien arc generated by hybrid gas-water torch

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In the present work the basic principles of the Gerdien arc are described. The arc was generated in the plasma torch with hybrid stabilisation of the arc by water and argon. The paper discusses physical processes determining the arc behaviour and governing plasma generation. As the main mechanism of the plasma generation in the water stabilized part is evaporation from the inner surface of the water vortex, heating and ionisation of vapour, the plasma gas flow rate and composition depends on the working parameters of the torch. The amount of the evaporated water cannot be directly measured and was estimated from the mass and power balances of the torch. The flow rate and composition of the generated plasma for different arc currents and argon flow rates have been studied. Increase of the arc current resulted in higher amount of evaporated water, while modification of the argon flow rate did not influence the evaporation rate.

1. Introduction

Plasma torches, which are widely used in many areas of industry, represent devices, which transfer the electrical energy to thermal. In DC arc torches thermal energy is generated by an arc, which is in most cases stabilized either by a flow of gas or by liquid. Gas stabilisation of the arc has been used more widely than the liquid one in spite of the fact that the first studies of the stabilised arcs were made on the facilities with water vortex. These basic investigations were provided by Maecker in the fifties [1-2]. The arc generator used in his experiments was based on the construction offered by Gerdien and Lotz as far back as in 1922 [3-4]. Therefore, an arc stabilised by water vortex inherited the name of its inventor and is called a Gerdien arc. The basic stabilizing mechanism of the arc column is the cooling of the arc fringes by water vapor evaporated from the wall region and the arc burns in the center of the water vortex. Such an arrangement allows achieving extreme performance characteristics, like high enthalpies and temperatures of the generated plasma. Later on the principle of arc stabilization by water vortex was utilized in plasma torches designed for plasma spraying and cutting [5]. Despite a long history the Gardien arcs have not been described completely yet due to a complex structure of water stabilized torches and lack of understanding of the physical processes taking place in them. The present work is aimed to add to the up-to-day knowledge of the Gerdien arc behaviour.

In the present work the Gerdien arc was generated in the plasma torch in which both principles of stabilisation are applied [6]. The arc chamber consists of two parts – a cathode part with gas stabilisation of the arc and the water stabilised part where plasma is produced by evaporation of the stabilizing water, heating and ionization of the vapor. The arc evaporates as much water as it is required for the given working parameters. Thus, composition and flow rate of the produced plasma are governed by the processes occurring in the arc chamber. These processes are the main subject of the present paper.

2. Experimental setup

The arc was generated in the plasma torch with hybrid gas-water stabilisation (Fig. 1). The argon flow is supplied along the cathode tip and is injected tangentially assuring a proper stabilization of the arc in the cathode nozzle. From the cathode region the argon plasma flows to the water vortex stabilized part, where it passes through the water channel. The length of the argon stabilized arc column is about 6 mm, while the length of the arc column stabilized by

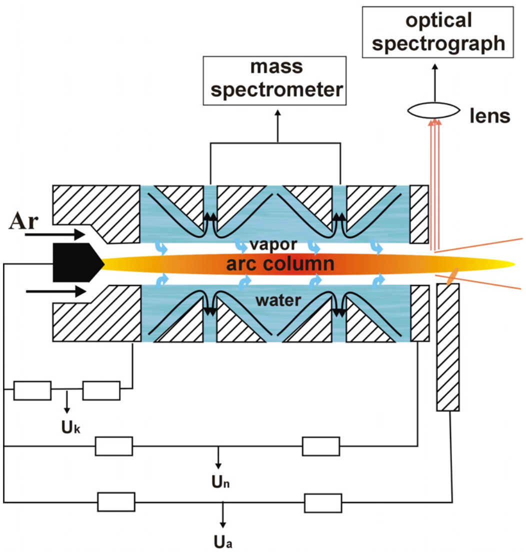

Figure 1: The plasma torch with the gas-water stabilisation of the arc and applied diagnostics.

water vortex is 50 mm. Heated water together with some products of the dissociation and ionisation of the argon and steam is exhausted at two positions along the arc chamber. The diameter of the cylindrical exit nozzle is 5.7 mm. The anode of the torch is represented by a rotating cooper disc located outside of the arc chamber downstream the exit nozzle. Both electrodes are water cooled and the temperature and flow rate of the cooling water was measured together with the temperature and flow rate of the stabilizing water.

Potentials of the electrodes and nozzles were measured by the high resistance voltage dividers.

The composition and flow rate of the exhausted gases were measured at the exhaust of the water stabilizing system. Nitrogen was used as a trace gas with a flow rate of 10 slm. The gas flow rate was measured with the help of a gas flow meter, while the composition of the gas was determined from the mass spectra obtained with the quadrupole analyser QMS 200. Knowing the flow rate of the exhausted gas and its composition with and without the trace gas, the amount of the exhausted argon can be estimated.

Temperature of the plasma close to the exit nozzle was measured by means of emission spectroscopy using the monochromator Jobin Yvon Triax 550 equipped with a CCD detector. Temperatures profiles were calculated from the spectral lines of the argon assuming Boltzmann distribution of atomic level population.

3. Results and discussion

3.1. Measured characteristics of the arc

The generated arc exhibited a rising volt-ampere characteristic meaning increasing of the arc voltage for higher currents. This fact reflects influence of the water channel inside which the arc is burning. The stabilizing water vortex consumes a part of the energy from the arc and confines growth of the arc in diameter. The other part of transferred energy is absorbed in a vapor zone (between the arc column and the surface of water)

The power losses were determined from calorimetric measurements on cooling loops of the electrodes and of the water stabilizing system. The efficiency of the torch was defined as a ratio of the net power to the power input and it varied between 40 and 60 % depending on arc current and argon flow rate. The efficiency increased with increasing both the arc current and the argon flow rate. The power loss of the arc column downstream the nozzle in the free jet region could not be measured.

It has to be noted that in the case of water stabilized arcs power losses include both losses to the stabilizing water vortex and to the electrodes. The power losses to the stabilising water represent the main constituent of the total power losses and increase with the arc current (Fig. 2). Here water is heated up reaching the temperature of vaporisation on the inner surface of the vortex and vaporized molecules of water are dissociated and ionised. This is the principle mechanism of the plasma generation in the water stabilized part of the arc chamber. This process consumes a big part of energy dissipating by the arc. It has appeared that considerable part of this energy is spent for heating up of the stabilizing water. Increase of temperature of the water entering the arc chamber resulted in minimisation of the power losses and the efficiency of the torch increased significantly – increase of the stabilizing water temperature by 20°C led to increase of the torch efficiency from 55 to 65% (Fig. 3).

The effect of argon flow rate on the arc behaviour has been studied as well. The argon flow rate was increased from 12.5 to 22.5 slm. The obtained results have shown insignificant effect of argon on the arc voltage and power losses. The net power of the torch for three values of the arc current is shown in Fig. 4. The net power was almost unchanged for

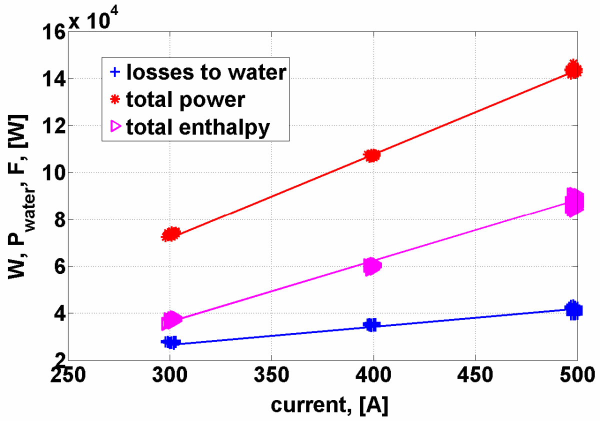

Figure 2: Power balance in the torch as a function of the arc current for Ar – 12.5 slm.

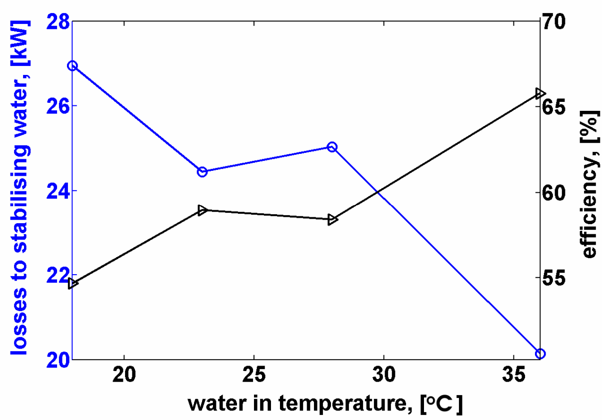

Figure 3: Dependence of the arc characteristics on the temperature of the stabilizing water.

each current when the argon flow rate was modified.

Temperature profiles measured by the emission spectroscopy for four different conditions (two arc currents and Ar flow rates) are shown in Fig. 5. Increase of the arc current resulted in higher temperatures of the generated plasma. The temperature rise was connected with higher Joule heating being released by the arc. The temperature profiles were just slightly affected by the change of the argon flow rate from 12.5 to 22.5 slm. The absence of the argon influence was caused by the strong difference of the enthalpies of water steam

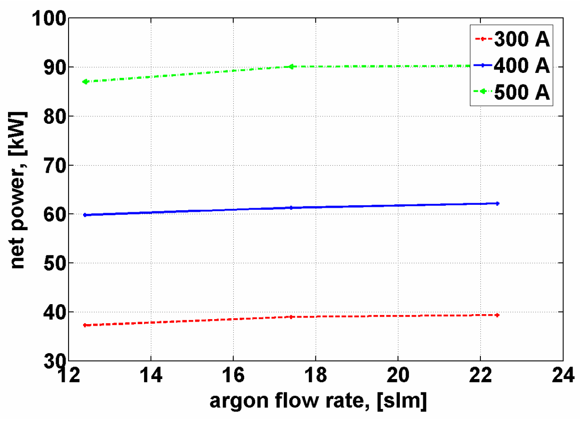

Figure 4: Net power of the torch as a function of the argon flow rate for different arc currents.

and argon. Argon with low enthalpy requires much less energy to be heated up to the given temperature. Hence, addition of a quite high amount of argon has little effect on the total energy balance of the arc as it was shown above. Thus the temperature remained almost unchanged.

3.2. Composition of the generated plasma

The plasma gas flow rate and its composition depend on the evaporation rate from the inner surface of the water vortex. As evaporation is caused by the Joule heating dissipated by the arc amount of the evaporated water depends on the arc generation conditions. The direct measurement of the evaporated water is impossible because the whole process takes place inside the arc chamber, but its amount can be estimated from the measured power balances of the torch and temperature profiles at the torch exit nozzle.

One more important parameter is the amount of argon remaining in the plasma after passing through the arc chamber. After entrance into the water stabilising part, argon plasma is mixing with the evaporated steam and is being exhausted together with stabilising water. Thus, only a part of the supplied argon remains in the plasma jet and the amount of remaining argon depends on the torch input parameters as it is shown in Fig. 6. Increasing of the arc current resulted in higher pressure difference between the arc chamber and the water tank, which led to higher pumping rate and more argon was exhausted. The increase of the argon flow rate also resulted in higher pressure difference and increase of the amount of the exhausted gas. However, more argon remained in the plasma for higher argon flow rates.

The amount of steam in the plasma was determined from the mass and energy balances at the torch exit nozzle. The mass flux is given by the flows of argon f_{ar} and steam f_{st}, thus the total mass flux at the exit nozzle is:

$$f_{ar} + f_{st} = \int 2\pi r \rho V dr, \qquad (1)$$

where ρ – density of the plasma at the given point r within the nozzle, and V – plasma velocity. The plasma velocity can be expressed as $V = M \cdot c(T)$, where M is the Mach number and c the sound velocity. Under the assumption that radial pressure gradients are negligible and radial velocities are

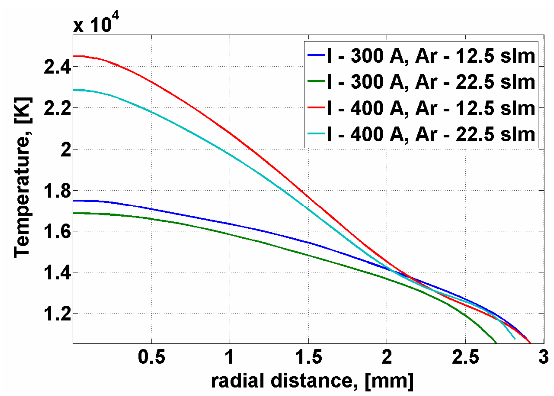

Figure 5: Temperature profiles measured at the torch exit nozzle for different operation conditions.

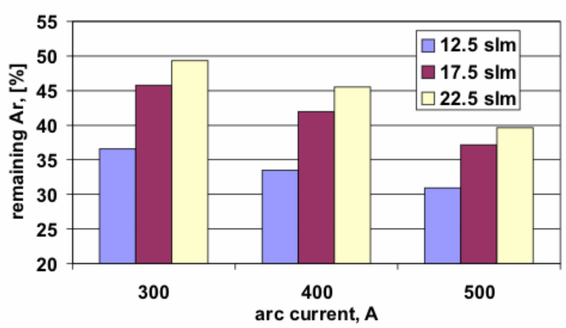

Figure 6: Argon remaining in the plasma after leaving the plasma arc chamber for different conditions.

small compared to the axial velocities, the Mach number can be assumed to be independent of radial coordinate at the exit nozzle. This assumption is often applied in description of high current arcs in nozzle flows [7]. The Mach number can be calculated from the power balance of the torch:

$$M = \frac{F_e}{\int 2\pi chrdr}$$

where h is plasma enthalpy and F_e net power of the torch. Plasma enthalpy and density is a function of temperature and composition. The temperature profiles were obtained experimentally (Fig. 5). The plasma gas composition is the unknown parameter. If the mass fraction of argon in the plasma is x_{ar}, then the mass fraction of the steam is $x_{st} = 1 - x_{ar}$. Then Eq. 1 can be expressed as:

$$\frac{f_{ar}}{x_{ar}} = Fe \frac{\int \sqrt{\rho_{mix}}\, rdr}{\int \sqrt{\rho_{mix}}\, hrdr} \qquad (2)$$

Thermodynamic properties of water steam and argon were calculated by the computer code ADEP [8]. Applying the mixing rules for the plasma enthalpy and density:

$$h_{mix} = h_{ar} x_{ar} + h_{st} x_{st}, \qquad \rho_{mix} = \frac{1}{\frac{x_{ar}}{\rho_{ar}} + \frac{x_{st}}{\rho_{st}}}$$

the amount of argon and steam in the plasma was obtained from Eq. 2 by interpolation.

Composition of the generated plasma for different plasma torch parameters and water evaporation rate are summarized in Table 1.

Table 1: Water evaporation rate and plasma gas composition for different conditions.

Torch parameters		Properties of generated plasma				
I, [A]	Ar, [slm]	Mass flow rate, [g/s]		Molar fraction, [%]		Total gas flow rate, [g/s]
		Ar	H_2O	Ar	H_2O	
300	12.5	0.133	0.176	25	75	0.31
300	22.5	0.322	0.181	44	56	0.5
400	12.5	0.122	0.248	18	82	0.37
400	22.5	0.3	0.245	35	65	0.55

Increase of the arc current resulted in higher amount of evaporated water as the evaporation rate is determined by the fraction of total power reaching water, thus it is increasing with the arc current. Modification of the argon flow rate did not influence the evaporation rate though. This is again due to insignificant effect of argon on the energy balance of the arc.

3. Conclusions

In the present paper processes taking place in the Gerdien arc generated by the hybrid torch with gas-water stabilisation have been studied. The results have shown that the losses to the stabilising water represent the main part of the total power losses of the torch. They can be minimized by increasing the temperature of the stabilising water. Change of the argon flow rate did not influence significantly processes in the arc chamber, while change of the arc current resulted in higher amount of energy contained in the generated plasma with higher temperatures. Moreover, the composition of the generated plasma was also determined. The amount of evaporated water was estimated based on the measured temperature, energy and mass balances of the torch. Increase of the arc current resulted in higher amount of evaporated water, while modification of the argon flow rate did not influence the evaporation rate.

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