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Generation of thermal plasmas in liquid-stabilized and hybrid dc-arc torches*

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Abstract: The paper presents survey of principles and basic physical parameters of liquid and hybrid gas/liquid dc-arc plasma torches and discusses physical mechanisms that control plasma properties. Special attention is devoted to properties of generated plasma that are decisive for performance characteristics in plasma spraying. Characteristics of water and water-argon torches are compared with typical characteristics of commonly used gas torches.

INTRODUCTION

Plasma jets generated in dc-arc torches are utilized in several plasma-processing technologies like plasma spraying, plasma cutting, and decomposition of persistent chemical substances. In commonly used plasma torches, the arc is stabilized by gas that flows along the arc column in the arc chamber. The gas is often injected into the arc chamber tangentially so that vortex motion of gas is produced. Performance characteristics of a torch in a specific application are determined by plasma-jet characteristics that can be adjusted by torch design, choice of plasma gas, and by arc current. There are some limits of range of adjustable plasma-jet characteristics that are given by principle of stabilization of arc.

Substantially different plasma-jet parameters can be achieved in plasma torches with arc stabilized by liquid. In torches with liquid stabilization, the arc column is confined inside of a vortex of liquid and it is stabilized by its interaction with inner wall of a vortex. Plasma temperatures and enthalpies achieved in this type of arc are substantially higher than in common gas-stabilized sources of thermal plasmas, plasma density is lower. As also other plasma parameters are extreme the torches based on this principle exhibit special performance characteristics in some applications such as plasma spraying or waste treatment.

Physical limits of principles of gas and liquid stabilization of arcs do not allow to cover a wide gap in plasma parameters between high enthalpy, low-density plasmas generated in liquid-stabilized torches, and lower enthalpy plasmas generated in gas torches. Thus, a new type of hybrid torch was investigated that is based on a combination of principles of liquid and gas stabilization of arc and that offers the possibility of control of plasma-jet characteristics in a wide range from values typical for liquid-stabilized torches to values typical for gas-stabilized torches.

This paper presents a survey of plasma-jet parameters of liquid and hybrid arc torches and discusses physical mechanisms that control plasma properties. Special attention is devoted to properties of jets that are important for performance characteristics in plasma spraying.

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COMPARISON OF GAS- AND LIQUID-STABILIZED PLASMA TORCHES

Electric arc stabilized by a vortex of liquid was described more than 70 years ago by Gerdien and Lotz [1]. Although the principle has been known for a long time, the Gerdien arc is utilized in practical applications substantially less frequently than arc stabilized by gas flow. Up to now, the only industrial-scale application of Gerdien arc has been realized in water-stabilized plasma-spraying torches [2]. Increasing interest in this type of arc in recent years has been evoked by special performance characteristics of these torches, especially extremely high spraying rates and spraying of materials with high melting points.

Schematics of gas- and liquid-stabilized arcs in dc arc torches are shown in Fig. 1. In gas torches the arc is stabilized by axial flow of gas, often with vortex component. In liquid torches the arc is ignited in a center of vortex of liquid, which is created in a cylindrical arc chamber with tangential injection of liquid. The principle physical mechanisms that control arc and plasma properties in both types of arc are axial heat transfer by convection and radial transfer by heat conduction and radiation. The substantial difference of the both arc types is in processes that determine plasma mass flow rate. While in gas torches, mass flow rate is controlled independently by a flow rate of supplied gas, for liquid torches, the flow rate is determined by arc processes. Plasma is created by heating and ionization of steam that is produced by evaporation of water from the inner surface of the vortex. The steam that flows into arc column is heated by absorption of radially transferred heat. The flow rate of plasma is thus controlled by a balance of heat transfer in the arc column and cannot be adjusted independently like in gas-stabilized torches.

The comparison of operation regimes of water-stabilized torches and conventional gas-stabilized torches is presented in Fig. 2.

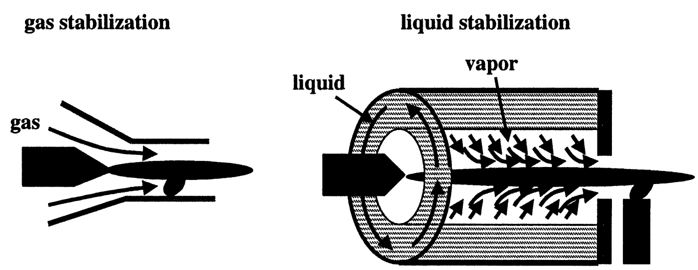

Fig. 1 Schematics of gas- and liquid-stabilized arcs.

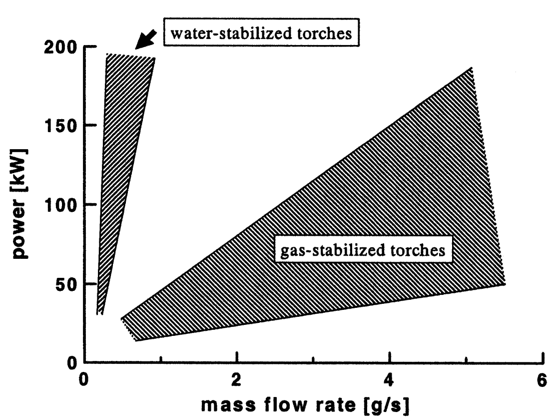

Fig. 2 Operation regimes of plasma spraying gas- and water-stabilized torches.

In Table 1, basic parameters of plasma torches are compared. The values presented in the table were evaluated for typical operation regimes of water-stabilized torch WSP-500 and gas-stabilized torches Plasma-Technik F4 (Ar/H_2) and Plazjet (N_2/H_2). Water torches are characterized by low mass flow rates and especially very low ratio of mass flow rate G to the arc length L. This leads to high arc power and very high plasma enthalpy and temperature [3,4]. The main consequence of differences of the two principles in above given characteristics is difference in spraying rates. For water-stabilized torches, the spraying rate is almost one order higher than spraying rates of common gas-stabilized torches.

Table 1 Typical parameters for plasma-spraying torches. Values for mixtures Ar/H_2 correspond to plasma torch Plasma-Technik F 4, values for N_2/H_2 were evaluated for torch PlazJet (TAFA).

Plasma medium	Arc current (A)	Arc power (kW)	Mass low rate (g/s)	G/L (kg/s·m)	Enthalpy (MJ/kg)	Temperature (K)
Ar/H_2 (65/3 slpm)	750	44	1.93	0.15	13.5	12 100
Ar/H_2 (33/10 slpm)	500	25	0.98	0.08	15.3	10 800
N_2/H_2 (235/94 slpm)	500	200	5.0	0.1	24	6 200
water	300	54	0.20	0.004	157	13 750
water	600	133	0.33	0.006	272	16 200

The spraying rate is limited by a decrease of temperature and velocity of plasma jet that is loaded by powder particles. Part of plasma enthalpy and momentum is spent for heating and acceleration of particles. Due to decrease of plasma temperature, heat flux to particles decreases. Maximum powder throughput can be determined by analyzing the relation between heat flux to particles and power spent for heating of powder. This relation is shown in Fig. 3 for typical mixtures of gases and for water. Thermal efficiency of plasma jet is defined as

$$\eta = (P_{jet} - G{\cdot}h)/P_{jet} = 1 - h{\cdot}G/P_{jet} \qquad (1)$$

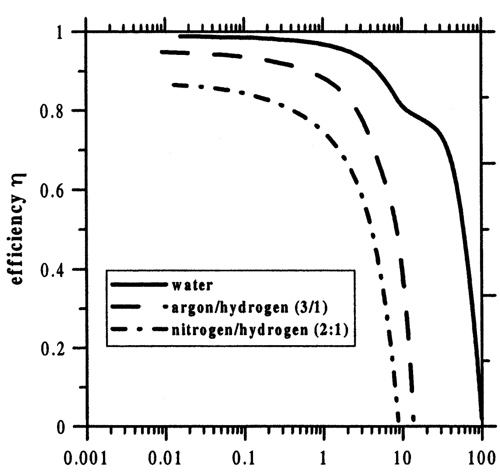

Fig. 3 Dependence of thermal efficiency of plasma jet on heat flux potential for typical operation conditions of gas- and water-stabilized plasma spraying torches.

where P_{jet} is total enthalpy flux in the jet, G plasma mass flow rate and h is plasma enthalpy after loading by powder. In Fig. 3 the thermal efficiency η is plotted against heat flux potential $S = \int_{2000}^{T} k\, dT$ calculated for temperature T corresponding to plasma enthalpy h. Heat flux potential S represents heat flux by conduction to particle with temperature of surface $T = 2000$ K. Curves in Fig. 3 were calculated for ratios G/P_{jet} that correspond to values given in Table 1. It can be seen that substantially higher part of plasma power can be spent for powder heating for given heat flux to particles in the case of water torch. This is the main reason of differences in spraying rates of the two principles.

Hybrid plasma torches

There is a relative large gap between operation regimes and thus in plasma properties of gas- and liquid-stabilized torches. For better control of plasma-jet characteristics a new type of dc plasma torch has been designed which utilizes combined gas-liquid stabilization. In this hybrid torch, plasma produced in arc chamber with vortex gas stabilization enters the second chamber where it interacts with vortex of liquid [5]. This arrangement offers the possibility of control of plasma-jet parameters in extremely large range from parameters typical for gas torches to the ones obtained in liquid torches. If argon is used for gas stabilization, the torch keeps thermal characteristics of water torch with high enthalpy and temperature but plasma density, velocity, and momentum flux can be increased substantially. This is illustrated in Fig. 4 where plasma density and enthalpy flux density in water and hybrid torches are compared. The curves were evaluated from measurements of energy balance, mass balance, and temperature profiles in plasma jet at the torch nozzle exits [2,5].

It was found in the experiments that plasma density, velocity, and momentum flux were substantially increased while total enthalpy flux and plasma temperature changed only slightly. It is due to the substantial difference in plasma properties of argon and steam plasmas. Enthalpy, heat conductivity, radiation intensity, and absorption coefficients of argon plasma are much smaller than in the case of steam plasma. Thus, properties of plasma that are controlled by heat transfer change only slightly while change of properties related to mass balance is substantial.

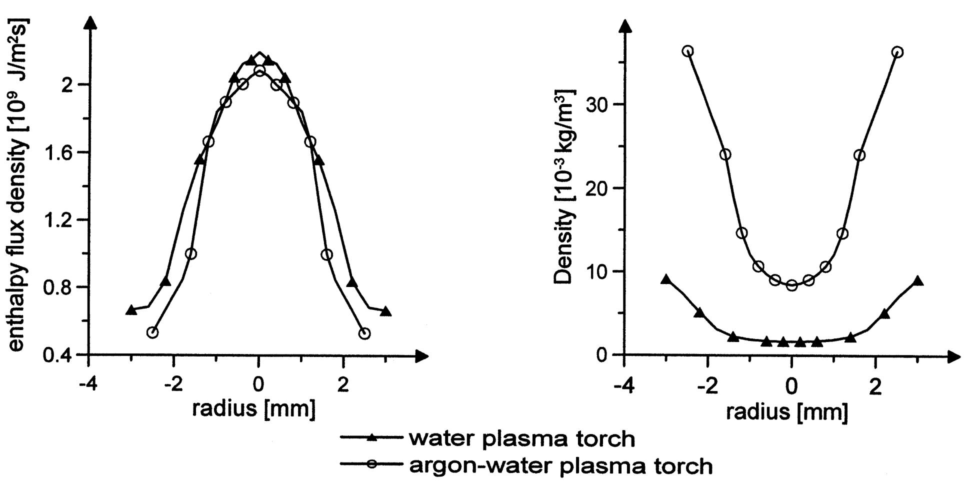

Fig. 4 Radial profiles of enthalpy flux density and plasma density at the nozzle exit of water-stabilized and hybrid torch at arc current 400 A.

In plasma spraying, the hybrid torches provide thermal efficiency somewhat lower than water torches, but particle velocity can be increased substantially. They may be operated in the range of parameters between gas- and water-stabilized torches.

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