Numerical Investigation of Supersonic Hybrid Argon–Water-Stabilized Arc for Biomass Gasification

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***Abstract*—This paper presents a numerical simulation of temperature and flow fields in the discharge and near outlet regions of the hybrid argon–water-stabilized electric arc. The calculations for an argon mass flow rate of 0.450 $g \cdot s^{-1}$ reveal the transition from a transonic plasma flow for 400 A to a supersonic one for 600 A with the maximum Mach number of 1.57. The comparison with available experimental data for 400 A shows satisfactory agreement.**

***Index Terms*—Hybrid stabilized arc, shock diamonds, supersonic flow.**

THE SO-CALLED hybrid stabilized electric arc, which was developed a few years ago at IPP AS CR in Prague, utilizes a combination of gas and vortex stabilization. In the hybrid argon–water plasma torch, the arc chamber is divided into the short cathode part, where the arc is stabilized by tangential argon flow, and the longer part, which is stabilized by water vortex. This arrangement provides not only the additional stabilization of the cathode region and the protection of the cathode tip but also offers the possibility of controlling plasma jet characteristics in wider range than that of pure gas- or liquid-stabilized arcs [1]. The arc is attached to the external water-cooled rotating disk anode at a few millimeters downstream of the torch orifice. The experiments made on this type of torch [1] showed that the plasma mass flow rate, velocity, and momentum flux in the jet can be controlled by changing the mass flow rate in the gas-stabilized section, whereas thermal characteristics are determined by the processes in the water-stabilized section. At present, this arc has been used for plasma spraying using metallic or ceramic powders injected into the plasma jet, as well as for the pyrolysis of waste (biomass) and production of syngas [2], which seems to be a promising environmentally friendly application of thermal plasma jets. Numerical simulation provides an efficient tool for the optimization of operating conditions (arc current and mass flow rate) and the prediction of temperature and velocity structures for these applications.

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In the numerical simulation, we assumed one-fluid 2-D axisymmetric compressible and turbulent plasma flow with homogeneous mixing of water and argon species. The resulting set of MHD equations includes atmospheric-pressure temperature-dependent transport and thermodynamic properties and radiation loss for the argon–water plasma through the net emission coefficient [3]. For time integration, LU-SGS method is used, which is coupled with Newtonian iterative method. To resolve compressible phenomena, convective term is calculated by using a third-order MUSCL-type TVD scheme. For electric potential, we chose TDMA algorithm enforced with the block correction method. Large eddy simulation (Smagorinsky model) is applied to capture possible turbulent behavior.

Fig. 1(a) and (b) shows the temperature and velocity fields in the discharge region and the near outlet for 400 and 600 A with water mass flow rates of 0.315 $g \cdot s^{-1}$ (400 A) and 0.363 $g \cdot s^{-1}$ (600 A) [4] and an argon mass flow rate of 0.450 $g \cdot s^{-1}$. Argon flows axially into the domain, whereas water evaporates in the radial direction from the "water vapor boundary." Argon mass flow rate is a controllable quantity, and its relatively high value, which is used also in experiment, was chosen in this paper to demonstrate compressible phenomena. The result for 400 A shows a transonic case with a Mach number of around one at the axial outlet region, a maximum temperature of 17 880 K, and a velocity of 5750 $m \cdot s^{-1}$. A qualitatively different picture is obvious for 600 A with the formation of shock diamonds in the downstream of torch exit. The corresponding velocity maxima overlap with the temperature minima and vice versa. The maximum 1.57 Mach number for the 10 200 $m \cdot s^{-1}$ velocity occurs near the axial position of 60 mm, and further downstream the velocity amplitude decreases. The maximum temperature reaches 23 700 K.

Comparison with experiment for the same operating conditions is available only for 400 A. In the experiment [5], the potential drop for the domain shown in Fig. 1 was 155 V, the averaged velocity at the outlet is 6877 $m \cdot s^{-1}$ [Fig. 1(a)], and the efficiency is 63% (determined as $1 - P/(U^*I)$, where P is the power loss to stabilizing water vortex and to the cathode due to radiation and conduction and U^*I is the input power for the water-stabilized section). The corresponding numerical values 153 V, 5728 $m \cdot s^{-1}$, and 62% exhibit very good agreement with the experiment. Somewhat lower numerical value of velocity can be caused by omitting the reabsorption of radiation in the model. For 600 A, we have obtained a brand new comparison with experiment at the arc axis

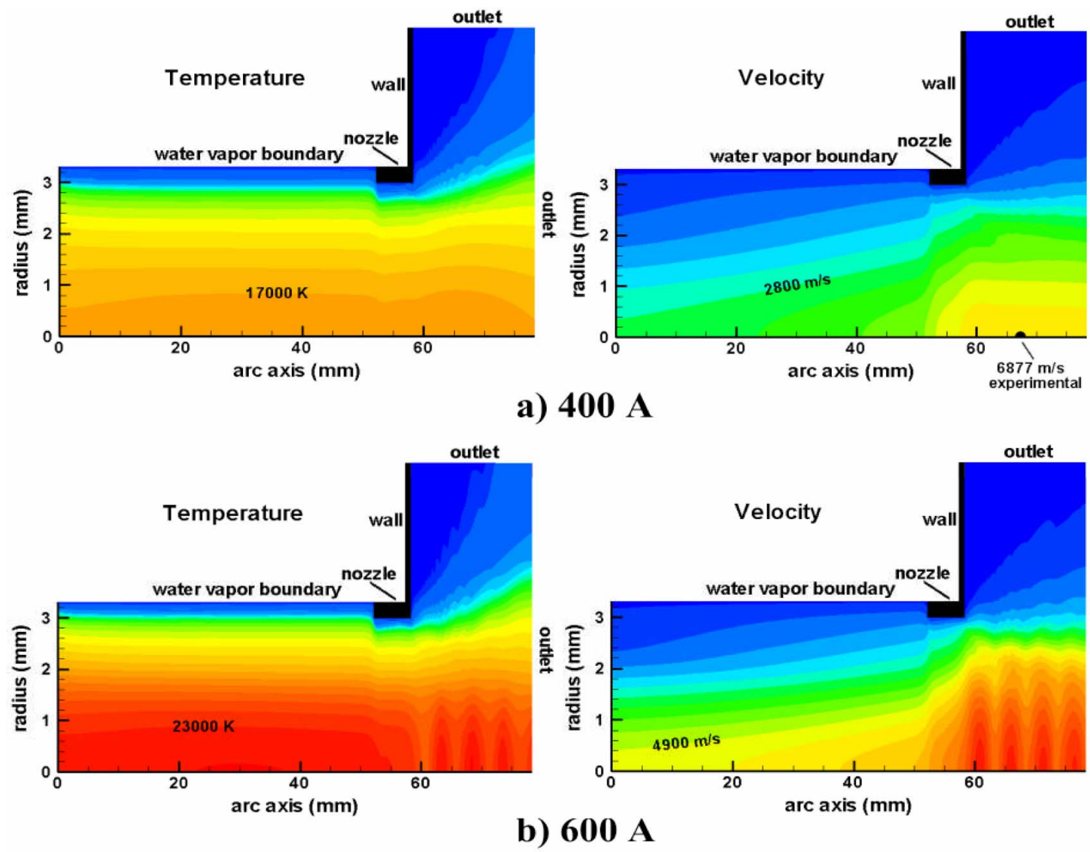

Fig. 1. Temperature and velocity contours for (a) 400-A and (b) 600-A arcs. Water mass flow rates are 0.315 $g \cdot s^{-1}$ (400 A) and 0.363 $g \cdot s^{-1}$ (600 A); argon mass flow rate is 0.450 $g \cdot s^{-1}$ for both currents. The transonic flow field for 400 A converts to a supersonic flow structure with clearly distinguished shock diamonds for 600 A. Contour increments are 1000 K for temperature and 500 $m \cdot s^{-1}$ for velocity.

2-mm downstream of the nozzle exit for temperature, velocity, and the Mach number but for an argon mass flow rate of 0.312 $g \cdot s^{-1}$, i.e., 31% lower than that in Fig. 1 (~25 000 K, 9300 $m \cdot s^{-1}$, and $M = 1.15$—experiment; 23 300 K, 9200 $m \cdot s^{-1}$, and $M = 1.24$—our calculation), evidencing the existence of the supersonic region at the outlet. The complex experimental investigation of the calculated transition to supersonic flow and the flow structure for high currents and argon mass flow rates is being prepared.

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