FLOW SEPARATION AND ARC–FLOW INTERACTION IN NON-TRANSFERRED PLASMA TORCHES

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Non-transferred plasma torches (plasma burners) are widely used as high-temperature heat sources in industrial processes. Their operation is governed by strongly coupled interactions between electromagnetics, fluid flow, and heat transfer, characteristic of thermal plasma systems [2, 4]. In particular, the near-cathode region plays a critical role in arc formation and stability. Under certain geometric configurations, especially for flat cathode designs, the incoming gas flow may separate at the cathode tip and form a recirculating vortex structure. This separation occurs in a region of strong gradients in velocity, temperature, and electrical conductivity, where both inertial and electromagnetic effects are of comparable magnitude.

The governing equations consist of the compressible Navier–Stokes equations coupled with electromagnetic effects. The momentum equation can be written as

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \nabla\cdot\tau + \mathbf{J}\times\mathbf{B}, \qquad (1)$$

where $\mathbf{J}\times\mathbf{B}$ represents the Lorentz force and τ is the viscous stress tensor. The energy equation, including Joule heating, is given by

$$\rho c_p(\mathbf{u}\cdot\nabla T) = \nabla\cdot(k\nabla T) + \mathbf{J}\cdot\mathbf{E}, \qquad (2)$$

and the current density follows

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u}\times\mathbf{B}). \qquad (3)$$

These equations define a strongly nonlinear system in which transport coefficients depend on temperature and, indirectly, on the solution itself.

A three-dimensional multiphysics model is employed to resolve the arc–flow interaction under realistic operating conditions. The results show that flow separation at the cathode tip is driven by the combined action of adverse pressure gradients and swirl-induced radial momentum transport. The imposed swirl generates a significant azimuthal velocity component, which redistributes axial momentum and promotes vortex formation when the local pressure recovery exceeds a critical threshold. The location and extent of the recirculation zone exhibit strong sensitivity to inlet distribution, suggesting the presence of a bifurcation-like response to small perturbations in boundary conditions.

The resulting vortex modifies the balance between convection, Joule heating, and Lorentz forcing, thereby altering current density distribution and arc anchoring. The coupling is intrinsically nonlinear: temperature-dependent conductivity governs current paths, which in turn determine electromagnetic forcing and volumetric heating, feeding back into the flow through density and viscosity variations. This feedback loop leads to localized amplification of gradients and a high sensitivity to both geometry and operating parameters [1, 3].

The analysis indicates that flow separation can be either stabilizing or destabilizing depending on the relative magnitude of convective and electromagnetic forces. While increased residence time may enhance arc attachment, non-uniform heat fluxes can promote localized electrode degradation. Strategies for controlling the separation are discussed, including modulation of swirl number, redistribution of inlet mass flow, and geometric shaping of the cathode. These findings highlight the importance of resolving coupled MHD instabilities and provide a framework for predictive modelling of plasma torch flows.

References

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