Advances and Challenges in Fluid Flow Models of Low-Temperature Plasmas Flows

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Fluid flow models are essential tools for the analysis of low-temperature plasma (LTP) systems, especially in industrial application contexts. These models rely on the continuum approximation to describe the diverse range of chemical and thermodynamic nonequilibrium conditions inherent in LTPs. Numerical solutions face compound challenges found in other fields, such as nonlinearity of equation coefficients, resolution of large property gradients, instabilities and turbulence. These challenges are addressed by advanced methods designed for multiphysics and multiscale problems. Representative results of the use nonequilibrium fluid flow models for industrially relevant LTP systems are presented, which depict the challenges faced and approaches for their solution.

1. Introduction

Low-temperature plasmas (LTPs) are at the core of diverse applications, such as materials processing, chemical synthesis, and medicine. The wide range of particle densities and energies in LTPs makes fluid models especially appealing for their description. The interaction of LTP with processing media, such as a gas stream or solid surface, leads to a chemical and thermodynamic nonequilibrium conditions. Such interactions also present complex coupling among fluid dynamics, heat transfer, chemical kinetics, and electromagnetic phenomena.

2. Challenges

Numerical solutions of LTP fluid models face severe challenges found in other fields, including:

- Resolution of large solution field gradients, due to, e.g. boundary layers, sheaths, or shocks, which are often conducive to instabilities and turbulence.
- Handling of highly nonlinear equation coefficients and source terms result of constitutive relations, chemical reactions, Joule heating, etc., which produce numerical stiffness and limit convergence.
- Consistent coupling of multiphysics model requirements, from the fulfilment of the solenoidal constraint of magnetic fields to the coupling between pressure and velocity fields in low-speed flows.

3. Advances

The above challenges are addressed by advanced numerical methods for multiphysics and multiscale problems. Stabilized and Variational Multiscale (VMS) methods exemplify the state-of-the-art among such methods, as evidenced by their use in commercial multiphysics software (e.g. Comsol) and their use in diverse fields, including plasma flows. Fig. 1 shows representative results of their use for the simulation of an arc torch, the core component in plasma spray; and the free-burning arc, a canonical model for the analysis of electric welding [1, 2].

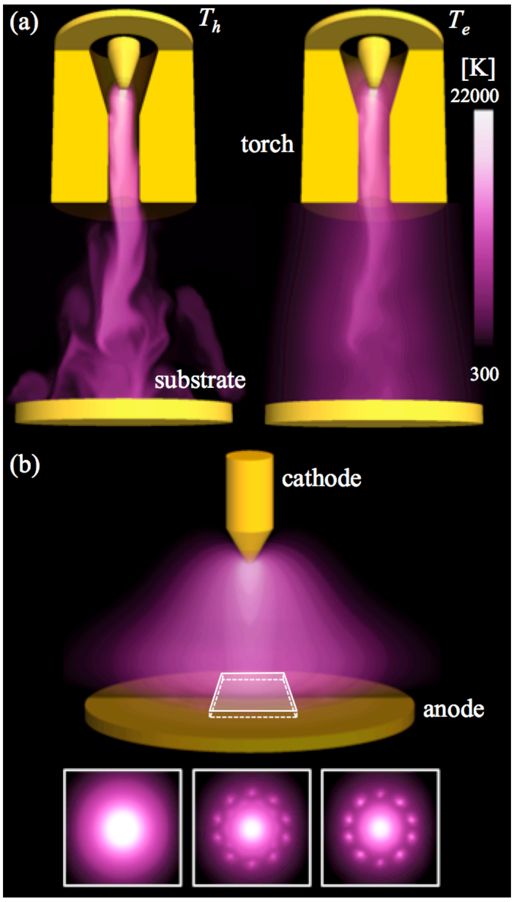

Fig. 1: Fluid flow modelling of: (a) an arc plasma torch showing nonequilibrium between heavy-species (T_h) and electron (T_e) temperatures, and (b) a free-burning arc, depicting the emergence of self-organized anode spots.

4. References

[1] J.P. Trelles, S.M. ModirKhazeni, Comput. Methods Appl. Mech. Engrg (2014) 282, 87-131.

[2] J. P. Trelles, Plasma Processes and Polymers (2016) 14 (1-2), 1600092.