Journal of Computational Physics 300 (2015) 779–799

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

Modeling weakly-ionized plasmas in magnetic field: A new computationally-efficient approach

Bernard Parent [a,*], Sergey O. Macheret [b], Mikhail N. Shneider [c]

[a] Dept. of Aerospace Engineering, Pusan National University, Busan 609-735, South Korea
[b] School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907-2045, USA
[c] Dept. of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544-5263, USA

ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form 13 July 2015
Accepted 6 August 2015
Available online 12 August 2015

Keywords:
Convergence acceleration
Weakly-ionized plasma
Magnetized plasma
Magnetohydrodynamics (MHD)
Non-neutral plasma
Quasi-neutral plasma
Generalized Ohm's law
Gauss's law
Cathode sheath
Dielectric sheath

ABSTRACT

Despite its success at simulating accurately both non-neutral and quasi-neutral weakly-ionized plasmas, the drift-diffusion model has been observed to be a particularly stiff set of equations. Recently, it was demonstrated that the stiffness of the system could be relieved by rewriting the equations such that the potential is obtained from Ohm's law rather than Gauss's law while adding some source terms to the ion transport equation to ensure that Gauss's law is satisfied in non-neutral regions. Although the latter was applicable to multicomponent and multidimensional plasmas, it could not be used for plasmas in which the magnetic field was significant. This paper hence proposes a new computationally-efficient set of electron and ion transport equations that can be used not only for a plasma with multiple types of positive and negative ions, but also for a plasma in magnetic field. Because the proposed set of equations is obtained from the same physical model as the conventional drift-diffusion equations without introducing new assumptions or simplifications, it results in the same exact solution when the grid is refined sufficiently while being more computationally efficient: not only is the proposed approach considerably less stiff and hence requires fewer iterations to reach convergence but it yields a converged solution that exhibits a significantly higher resolution. The combined faster convergence and higher resolution is shown to result in a hundredfold increase in computational efficiency for some typical steady and unsteady plasma problems including non-neutral cathode and anode sheaths as well as quasi-neutral regions.

1. Introduction

Generally referred to as magneto-plasmadynamics or magnetohydrodynamics (MHD), the process of applying a force on a fluid in motion using a magnetic field is the main mechanism behind several new aerospace technologies such as shockwave control in supersonic flows [1,2], power generation during re-entry using a MHD generator [3–5], heat shield in hypersonic flows [6,7], thrust generation using a Faraday accelerator [8,9], or efficiency improvement of pulse detonation engines through MHD energy bypass [10]. In such devices, the working fluid on which the magnetic field acts is air ionized either through high electric fields, through electron or microwave beams, or through potassium or cesium seeding.

* Corresponding author.
E-mail addresses: parent@pusan.ac.kr, bernparent@gmail.com (B. Parent).
URL: http://bernardparent.ca (B. Parent).

http://dx.doi.org/10.1016/j.jcp.2015.08.010
0021-9991/