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Numerical studies on plasma plume flows from a cluster of electric propulsion devices

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ABSTRACT

Several hybrid fluid–particle simulations are performed to investigate the plasma plume flows from a cluster of Hall thrusters. These simulations adopt a detailed fluid electron model to describe electron properties. A general finite element solver is developed to solve for these electron properties, and the cathode geometry, facility effects, and vacuum chamber background pressure are included in the simulations; these are compared with available experimental data, and indicate that the cathode had effects on some flow property distributions. They also clearly display charge exchange collision effects and the clustering effects. There exist complex three-dimensional near field structures in the ion number density with Hall thrusters in operation. With four thrusters in operation, a severe impingement is expected right behind the cluster center. Compared with axisymmetric simulations, these three-dimensional simulations have several improvements. When compared with the Boltzmann relation, the detailed fluid electron model displays superiority in predicting the electron temperature as well.

1. Introduction

Electric Propulsion (EP) devices have several important merits (e.g., high impulse and no need of oxidants) over traditional chemical thrusters; they have been widely used in space for primary propulsion, on-orbit applications such as station-keeping, and orbit transfers [17]. There have been active research efforts on EP devices since the mid 1950s; one of the introductory book is by Stuhlinger [24]. Among the active research topics, spacecraft integrations and plume impingements are two important issues for EP devices.

There are several major interests in numerical simulations of plasma flows from a cluster of Hall thrusters. In general, clustering has several advantages over a single large thruster: they are i). convenient to manufacture; ii). less demanding on test facilities; iii). have high mission safety. The performance of a thruster in a cluster may be different from a stand alone situation. Another interest is to estimate plume impingement, which involves high-energy ions and Charge Exchange (CEX) ions onto sensitive spacecraft surfaces such as solar arrays. Severe impingement of ions onto spacecraft surfaces may result eventually in failure of devices or even a final failure of the whole mission. If severe impingement is predicted, then a change of design must be considered to reduce the impingement.

In the past decade, plasma plume flows from a single thruster have been simulated widely with particle methods [20,26]. These simulations adopted simplified axisymmetric configurations, and the plasma potential was usually solved by the simplest Boltzmann relation. There are several problems associated with these simplifications:

1. With multiple thrusters in operation, plasma plume flows from different thrusters may interact with each other. Hence, the flowfield is completely three-dimensional.
2. Some detailed three dimensional near-field objects, such as thruster cathode-neutralizers and conic protection caps, may have significant effects on the near field flow properties and cannot be well represented with axisymmetric simplifications.
3. The simple electron model, the Boltzmann relation, cannot predict some detailed electron properties in the near field. Some important electron properties, such as the electron temperature distributions, change rapidly in the flow field, while the Boltzmann relation [5] assumes that this property follows a constant distribution in the whole flowfield.
4. One important issue for simulation is facility effects of large vacuum chambers. To the EP community, including people working on experiments or numerical simulations, this problem is quite important [3]. EP devices are designed for usage in space, where a nearly perfect vacuum exists, but tested in large vacuum chambers on the ground. The finite background pressure in the large vacuum chambers may have adverse ef-

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Nomenclature

e	electron charge	$1.60217657 \times 10^{-19}$ Co
$\vec{E}$	electric field	V/m
m_c	reduced mass	kg
m_i, m_e	electron and ion mass	kg
n	number density	$1/\mathrm{m}^3$
n_{ei}	electron and ion collision frequency	
n_{en}	electron and neutral collision frequency	
g	relative velocity	m/s
J_a, J_c	current through anode and cathode	A
k	Boltzmann constant	$1.3806488 \times 10^{-23}$ J/K
Kn	Knudsen number	
P	pressure	Pascal
P_e	electron pressure	Pascal
T_e	electron temperature	K
v_e	electron velocity	m/s

Acronyms

CEX	Charge EXchange collisions
DSMC	direct simulation Monte Carlo
EP	Electric Propulsion
MEX	Momentum EXchange collisions
PIC	Particle-In-Cell
VHS	Variable Hard Sphere

Greek symbols

κ	thermal conductivity	W/(m K)
σ	electron conductivity	$\mathrm{A}^2\,\mathrm{s}^3/(\mathrm{m}^3\,\mathrm{kg}^{-1})$
ϕ	electric potential	V
ψ	stream function	m^2/s
ω	viscosity index	

Sup-/subscripts

e	electron properties
w	wall properties

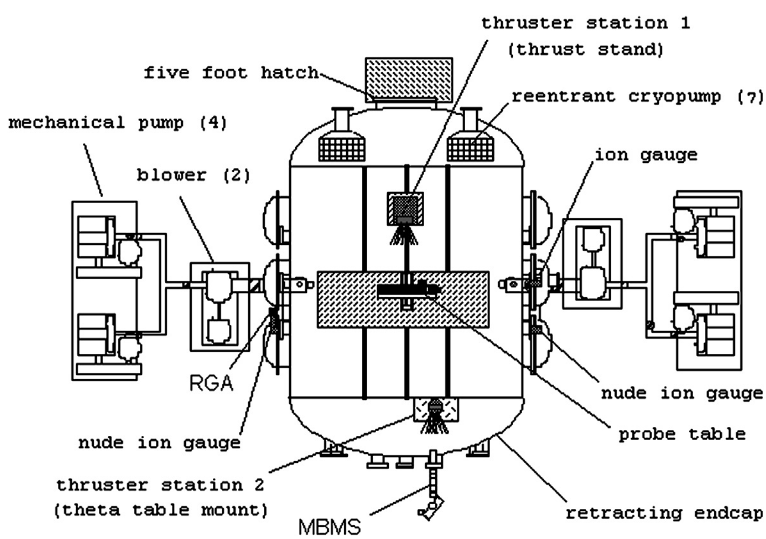

Fig. 1. LVTF at the University of Michigan.

fects on the performance of EP devices in experiments and on particle simulations of plume flows.

This paper aims to report some comprehensive investigations of plasma plume flows from a cluster of EP devices. Some complex yet advanced modelings will be presented. The following sections are organized as follows: In Section 2, we present some background details for the work, in Section 3, some simulation results will be presented and compared with experimental data; and the last section will include some summaries and conclusions.

2. Investigation details

We use specific EP device models for benchmark test cases. Some experimental data available in the literature will be used for benchmark test cases. The devices considered in this study are a cluster of four BHT-200 Hall thrusters, which were investigated experimentally [28,2]. Some past data [2] were taken in the Large Vacuum Test Facility (LVTF), at the University of Michigan. As illustrated by Fig. 1, it is a large cylindrical vacuum chamber with a diameter of 6 m and a length of 9 m. Fig. 2 is a photograph of the thrusters in operation. These four thrusters are configured in a 2

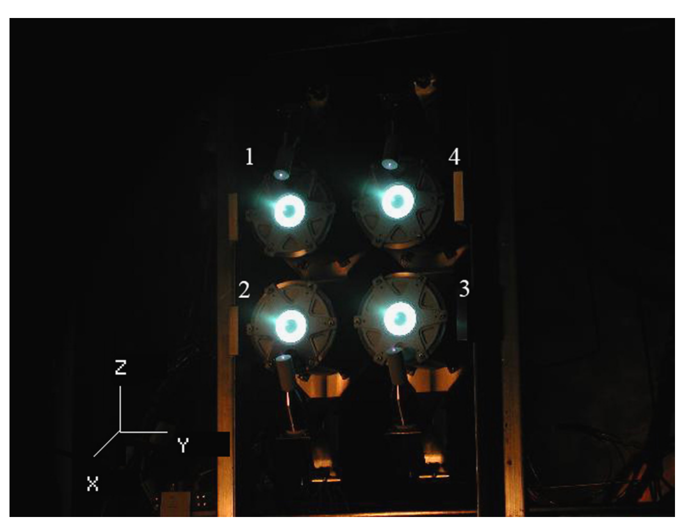

Fig. 2. BHT-200 Hall thrusters in operation.