TWO TEMPERATURE PLASMA PROPERTIES OF ABLATED PTFE VAPOUR USED FOR PULSED PLASMA THRUSTERS

W. Z. WANG[1]*, M. LI[1], X. TU[2]

[1] Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology, 100094, Beijing, People's Republic of China
[2] Department of Electrical Engineering and Electronics, The University of Liverpool, L69 3GJ, Liverpool, United Kingdom
*wangweizong@gmail.com

ABSTRACT

This paper deals with two temperature plasma properties of ablated PTFE vapour which is generated by a discharge ablation in Pulsed Plasma Thrusters (**PPTs**) as a form of electric spacecraft propulsion. The species composition and thermodynamic properties are numerically determined using two-temperature Saha equation and Guldberg-Waage equation. Transport properties are calculated with most recent collision interaction potentials by adopting Devoto's electron and heavy particle decoupling approach in the frame of Chapman–Enskog method. The database obtained here clearly shows the influence of non-equilibrium effects on plasma properties and hence will serve as reliable reference data for simulation of non-equilibrium plasma behaviour in **PPTs**.

1. INTRODUCTION

Pulsed plasma thrusters (**PPTs**) as a method of spacecraft propulsion use an arc of electric current adjacent to a solid propellant (typically Polytetrafluoroethene, PTFE $(C_2F_4)_n$, commonly known as Teflon), to produce a quick and repeatable burst of impulse. **PPTs** have been used on a number of satellites for station-keeping maneuvers [1]. However, very little knowledge exists on the non-equilibrium properties of PTFE and this is unfortunate for numerical modelling of electric discharge near PTFE surfaces especially and other non-equilibrium flows [1].

This paper deals with plasma properties of ablated PTFE vapour under both thermal equilibrium and non-equilibrium conditions in a two-temperature model where heavy particles and electrons still follow a Boltzmann energy distribution but with different temperatures: to the knowledge of the authors, the latter data have not been reported in the literature. The results are computed at atmospheric pressure and ratios of the electron temperature to the heavy particle temperature from 1 to 5 with electron temperature range from 300 to 30 000 K.

2. DEVELOPMENT OF MODEL FOR ABLATED PTFE PLASMA COMPOSITION

Prediction of plasma behaviours for and interpretation of experimental results from a non-LTE plasma system requires knowledge of the thermodynamic and transport properties of the plasma gas which can be determined once the composition of the system is known. The calculations are based on the conservation of the elements, Dalton's Law, the law of mass action (Saha law and Guldberg-Waage law) and electrical quasi-neutrality. The law of mass action, i.e. the Saha and Gulberg–Waage's equations are given in the form proposed by Van de Sanden et al. and we use the heavy particle temperature T_h as the excitation temperature for dissociation reaction and molecular ionization reaction and the electron temperature T_e as an excitation temperature for atomic ionization reaction[3]-[4].

In the calculation, it is assumed that the mixture of ablated PTFE plasma is composed of a total of 24 different species including relevant atoms, ions and molecules as well as electrons: C_2F_4, C_2F_2, CF_4, CF_3, CF_2, CF, C_5, C_4, C_3, C_2, F_2, F, C, CF_3^+, CF_2^+, CF^+, C^+, F^+, F^-, C^{2+}, F^{2+}, C^{3+}, F^{3+} and e. The required thermodynamic data for neutral

atoms and atomic ions were calculated from the internal partition functions, which were derived from the energy levels tabulated by the most recent data of NIST [5]. Data for other species including relevant reaction energy for each chemical reaction were taken from the JANAF [6]. For the determination of internal partition function, we assume that translational, rotational and vibrational motions of the heavy species are governed by T_h, but electronic excitation and translational motion of the electrons are controlled by T_e.

(a) $\theta = T_h/T_e = 1$
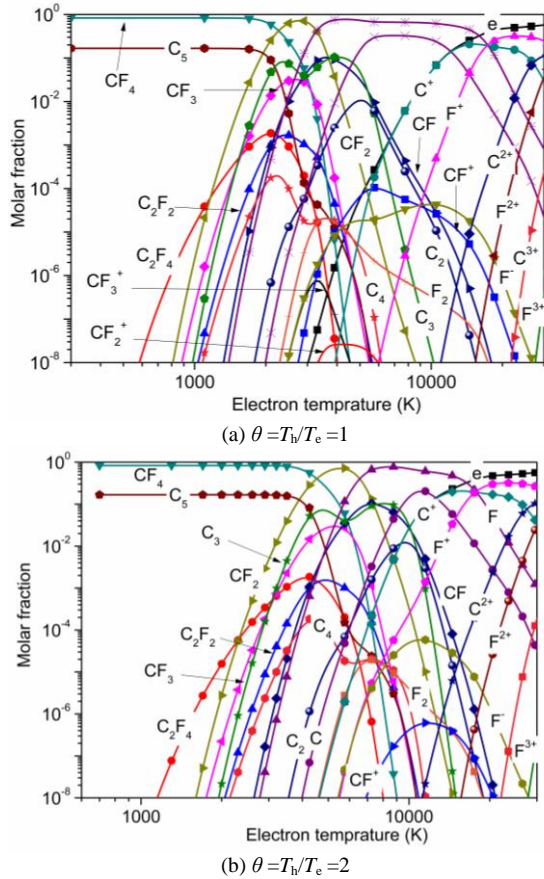

(b) $\theta = T_h/T_e = 2$

Fig. 1 Species composition of ablated PTFE plasmas at atmospheric pressure

Chemical equilibrium compositions for ablated PTFE plasmas as a function of electron temperature under equilibrium and non-equilibrium condition at atmospheric pressure are shown in Fig. 1-2. For the equilibrium case, the predominant species in ablated PTFE vapour at room temperature are CF_4 and C_5 which dissociate respectively into CF_3, CF_2 and C_4, C_3 at around 2300K and 2800K. Further temperature increase brings the dissociation of CF_3, CF_2 into CF as well as F at around 3400K and C_4, C_3 into C_2 and C at around 5000K. The ionization of plasma starts at very lower temperature mainly by the attachment of

electrons with atomic fluorine and produces the electric negative ion F^- and the molecular ionisation of CF_3, CF_2, CF. The first ionization of C and F respectively occurs at around 11000K and 17000K. In the conditions out of thermal equilibrium, the dissociation reactions which are governed by T_h are shifted towards higher electron temperature as presented in Fig. 1b for the non-equilibrium degree of $\theta = T_h/T_e = 2$. Variations of the molar fraction of fluorine atoms as a function of electron temperature are presented in Fig. 2. With the increase of non-equilibrium degree, the biggest molar fraction of atomic fluorine decreases due to the dramatic ionization once it is produced by the dissociation which is shifted towards a higher electron temperature.
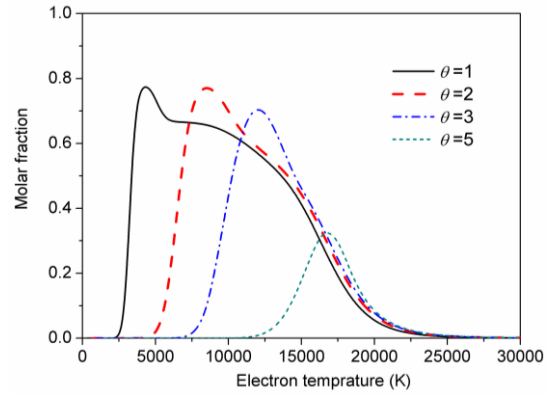

Fig. 2 Molar fraction of atomic fluorine in ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure

3. THERMODYNAMIC PROPERTIES

After obtaining the partition functions of each species, the calculation of thermodynamic properties proceeds in a straightforward manner, employing standard relationships. Of these, specific heat at constant pressure for electrons and heavy particles are obtained respectively by the numerical differentiations of respective specific enthalpy components with respect to electron temperature and heavy particles temperature [3]-[4]. Mass densities and partial specific heat at constant pressure for ablated PTFE plasmas as a function of electron temperature for different values of the non-equilibrium parameter are described respectively in Fig. 3 and Fig.4. The mass density increases at a fixed electron temperature as the θ value rises due to the delayed dissociation and ionization. The peaks of partial specific heat curves are respectively contributed by the multiple dissociations of molecular species and the

multiple ionizations of monatomic specie and also move to a higher electron temperature with rising non-equilibrium degrees.
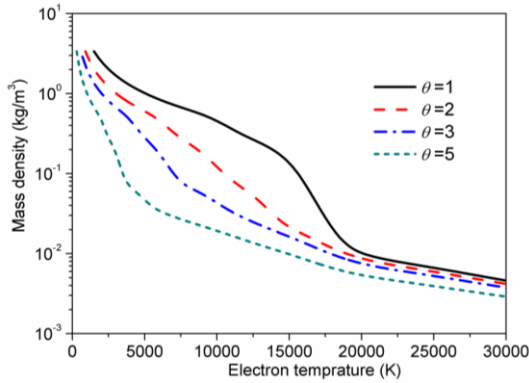

Fig.3 Mass density of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure
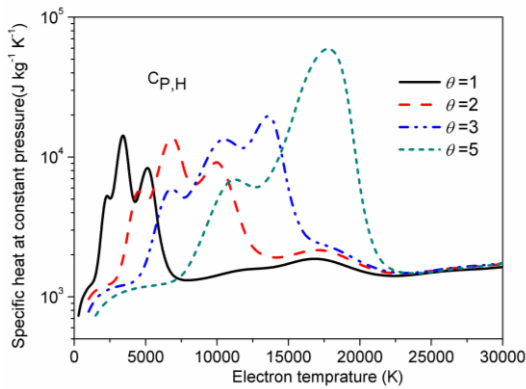

Fig.4 Partial specific heat at constant pressure of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure ($C_{P,H}=\partial h_T/\partial T_h$,h_T is the total specific enthalpy)

4. TRANSPORT COEFFICIENTS

Transport coefficients namely diffusion coefficients, viscosity, thermal conductivities and electrical conductivity, are calculated using the classical Chapman–Enskog method. Consequently, we have used the simplified approach of Devoto[7] assuming that the change in the perturbation function in electrons is greater than that of heavy species during interactions involving both types of particles with a third-order approximation for transport properties (except for viscosity for which the second-order approximation has been adopted). The thermal conductivity evaluated by above-mentioned principle is the translational component and is supplemented by the contributions from the internal energy and chemical reactions, i.e. internal and reactive thermal conductivity components. They are respectively using the Hirschfelder–Eucken approximation and an expression derived through reactive heat flux

treating the electrons and heavy particles separately [3]-[4].

Full use of more reliable interaction potential studies was made to describe the interaction potentials involving in this work. Of those, Murrell-Sorbie and Exponential Repulsive potential energy functions were fitted to the pair interaction of monatomic neutral-neutral (F-F and C-C) and neutral-charged species (C-C$^+$, F-F$^+$, C-C$^-$ and F-F$^-$) obtained by more accurate ab initio calculations from quantum-mechanically derived potential energy surfaces. Additionally, the newly developed phenomenological description of interaction potentials for elastic collisions interactions was utilized to build an internally-consistent database characterized by a good accuracy. Meanwhile, updated experiment investigation and theoretical calculation on the more accurate electron-neutral as well as the resonant charge transfer cross section were used to improve the reliability of the relevant interaction potentials. Detailed descriptions of our used cross sections data were summarized in our recent publication [8] and not presented here. Charged species interactions were described by a Coulomb potential screened at the Debye length by the presence of charged particles. The Debye length is calculated taking into account both the contribution from electrons and ions.
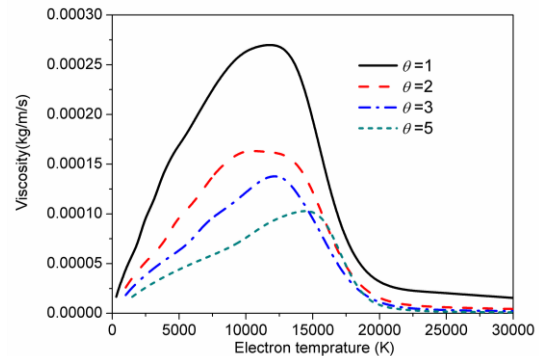

Fig.5 Viscosity of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure

Fig.5 gives the viscosity of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure. The viscosity firstly increases with temperature, and then decreases as the strong Coulomb interaction starts to dominate. The non-equilibrium degrees have a significant influence on the viscosity. With increasing values of θ, a decreasing viscosity peak height and a shift of ionization onset toward to higher

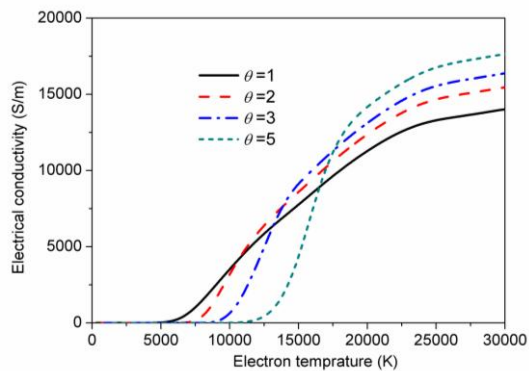electron temperature but to a lower heavy particle temperature is observed.

Fig.6 Electrical conductivity of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure

Fig.6 gives the electrical conductivity of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure. Dissociation of molecules, which is related to the heavy particle temperature, does not occur until the corresponding electron temperature is reached. This shifts the ionization towards higher electron temperature as θ increases. Once the dissociations starts, the electrical conductivity value rises fast because the ionization is favoured. For each value of θ, the electrical conductivity first increases and then slightly decreases mainly caused by the variation of the electron number density.
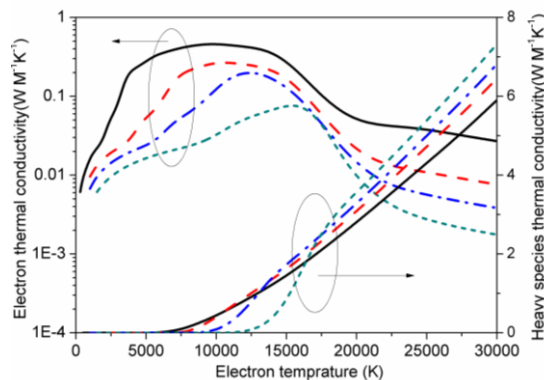

Fig.7 Translational thermal conductivity of ablated PTFE plasmas under different non-equilibrium degrees at atmospheric pressure

Translational thermal conductivities of ablated PTFE plasmas for different values of θ are reported in Fig.7. The heavy species component firstly increases because the collision integrals for the interactions between neutral species decrease; after a plateau it then decreases slowly owing to the occurrence of ionization. The heavy particle component shows the behaviour of multiple peaks due to the continuous reactions occurring with the increasing T_e. Electron

translational thermal conductivity depends on the electron number density and its interactions with other species and show a smaller value with rising θ in low temperature range due to delayed dissociation reactions and a larger value once dissociation is finished .

CONCLUSIONS

The database obtained here clearly shows the influence of non-equilibrium effects on plasma properties and hence will serve as reliable reference data for simulation of non-equilibrium plasma behaviour in **PPTs**.

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