Numerical Investigation of Thermochemical Nonequilibrium Inductively Coupled Plasma Flow

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論 文 名　:　Numerical Investigation of Thermochemical Nonequilibrium Inductively Coupled Plasma Flow
（熱化学的に非平衡な誘導結合プラズマ流に関する数値解析的研究）

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論　文　内　容　の　要　旨

Research Background and Objective

Inductively coupled plasma (ICP) wind tunnels are important ground-based facilities used to investigate the thermal protection systems (TPSs) of atmospheric reentry vehicles. Because of their distinctive heating system, ICP wind tunnels can produce clean, stable and high-enthalpy flows with peak temperatures of about 10000 K. A working gas such as nitrogen and air is injected into a quartz tube, and is vigorously heated by an alternating electromagnetic field induced by a radio-frequency current that runs through a helical coil surrounding the quartz tube. Because complex heating phenomena occur in ICP wind tunnels, it is extremely difficult to measure all of the flow parameters, such as spatial distributions of temperature, velocity, and concentration of chemical species. Numerical investigations using computational fluid dynamics methods are an attractive approach to study the flow fields in ICP wind tunnels. The main purpose of the present study is to make clear the flow and electromagnetic fields inside the 10-kW and 110-kW ICP wind tunnels.

Thermochemical Nonequilibrium Properties

Previously, for inductively coupled plasma simulations the hypothesis of local thermochemical equilibrium (LTE) was usually used for simplicity. This hypothesis is very useful for studying the transport of mass, momentum and energy, but limited to some restricted conditions e.g., atmospheric pressure condition, in which the internal energy exchange of chemical species can sufficiently carry on through frequent elastic collisions. Compared with the atmospheric pressure, the working pressure of the 10-kW and 110-kW ICP wind tunnels (p=3~10 kPa) is low. Therefore the assumption of LTE will result in big numerical errors on the evaluation of temperature field for these two facilities. Thus, a thorough study with considering the thermochemical nonequilibrium characteristics for ICP flows is necessary to understand the flow properties more correctly under the reduced pressure conditions. Therefore, a four-temperature model (Y. Takahashi, H. Kihara K. Abe, Journal of Thermophysics and Heat Transfer, Vol. 24, pp. 31-39, 2010) with the modified electron-vibration relaxation time was employed in the present study to investigate the thermochemical nonequilibrium properties of the ICP flows.

Radio-frequency Inductive Discharge

Radio-frequency inductive discharge is one of important characteristics for ICP flows. Maxwell’s electromagnetic equations need to be solved to describe this phenomenon and obtain the Joule heating rate distribution. In past decades, a standard electromagnetic model (J. Mostaghimi and M. I. Boulos, Plasma

Chemistry and Plasma Processing, Vol. 9, No. 1, pp. 25-44, 1989) was widely used to describe the inductive discharge for ICP flows. This model is mathematically elegant, physical correct and can be used for the 110-kW ICP wind tunnel. However, for the 10-kW ICP wind tunnel, under some low-pressure operating conditions (e.g., p=3.9 kPa) this standard model tended to be incorrect and failed to form plasma flow in the simulation due to its assumption that current carry rings of the coil is infinite thin. To remedy this, in this study, a more accurate far-field electromagnetic model (S. W. Xue, et al, Journal of Physics D:Applied Physics, Vol. 34, No. 12, pp. 1897-1906, 2001) was also introduced into the computational code to describe the inductive discharge and solve the Joule heating distribution for these two wind tunnels.

High-Order-Accuracy Electron Transport Properties

In the last decade, for simplicity, the first-order formula of Chapman-Enskog approximation was widely used to calculate the electron transport properties such as electrical conductivity and electron thermal conductivity for ICP simulations. However, because of the tight coupling between aerodynamic and electromagnetic fields in an ICP simulation, the electrical conductivity will affect distributions of the Joule heating rate and Lorentz force significantly. Therefore, it is better to compute the electron transport properties using the high-order perturbation technique of Chapman-Enskog theory. While the calculation with this high-order technique needs much more collision integral data and is complex. In this study, the third-order-accuracy electron transport properties for nitrogen and air were computed according to the latest available collision integral data and applied to the simulations for the 10-kW and 110-kW ICP wind tunnels.

Conclusions

Numerical simulations were carried out to study the plasma flows in the 10-kW and 110-kW ICP wind tunnels with nitrogen and air as the source gases. The simulated results were compared with corresponding experimental data, and generally revealed qualitative and quantitative agreement between them. It was confirmed that the plasma flow is thermal nonequilibrium in the discharge region. Due to the comprehensive effects of pressure, Lorentz force and severe Joule heating in the coil region, recirculation flows were detected in both of these two ICP wind tunnels. The axial and radial Lorentz forces played important roles in the momentum transfer in the coil region. The position of the Joule heating rate was mainly determined by the radial Lorentz force. Through the comparisons of the numerical results obtained under the local thermal equilibrium and thermal nonequilibrium assumptions, the four-temperature model was observed to play an important role in predicting the flow field properly. It was also clarified that the electron transport properties with the third-order accuracy are necessary and useful to improve the modeling accuracy for inductively coupled plasma simulations.

〔作成要領〕

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