EXPERIMENTAL AND THEORETICAL RESEARCH ON PLASMA SHEATHS AND BOUNDARY LAYERS AROUND STAGNATION POINT ELECTRODES

SEMI-ANNUAL PROGRESS REPORT NO. 3

1 July 1965 to 31 December 1965

NASA Grant NSG 724

Prepared for:

National Space and Aeronautics Administration

Office of Grants and Research Contracts

Prepared by:

Michael Ming Chen
Project Director

Assistant Professor
Department of Engineering
and Applied Science
Yale University
New Haven, Connecticut

SUMMARY

27538

During the period covered by the report, a fairly detailed space resolved experimental survey of the plasma and electrode observables has been made. A parametric macroscopic theory has been developed for a self-sustained thermionic cathode. The stability theory for electrical conduction in a temperature dependent medium, which had been described previously, was being continued. In addition, a re-examination of the microscopic physical processes taking place in the sheath, electrode boundary layer and the electrode surface has been undertaken.

I. Introduction

This report describes the work performed during the third six-month period (1 July 1965 to 31 December 1965) of the two-year program entitled, "Experimental and theoretical research on plasma sheaths and boundary layers around stagnation point electrodes," sponsored by the Office of Grants and Research Contracts, National Aeronautics and Space Administration. The technical monitor for NASA is Mr. Howard Stine, Ames Research Center.

Personnel currently engaged in this research are: Professor Michael M. Chen, Chief Investigator; Messrs. Elihu Zimet and Elliot Wyner, graduate students.

II. Technical Discussions

1. Experimental Program.

The design, calibration, and some preliminary results of the stagnation point electrode experiment had previously been described in previous Progress Reports[1]. During the present period, detailed, systematic measurements of the surface temperature, electrode potential (relative to a reference probe), and space resolved plasma temperature and electron concentration distribution as a function of electrode current have been completed[2,3]. While much remains to be done in terms of further improvements and interpretation, the data probably represents the first measurement wherein space resolved plasma conditions and electrode characteristics are obtained simultaneously. Since it is not possible at this time to make any theoretical calculation of the processes involved without unjustified assumptions, no attempt was made to compare these data with predicted results.

These data are described in Informal Interim Report No. 3 to be submitted simultaneously with the present report. It is planned that after revision, this Informal Interim Report will form the basis for a Special

Technical Report summarizing all the experimental data taken during the first phase of the present research program.

A brief summary of the above report has subsequently been given as a technical paper[3] at the AIAA Plasmadynamics Conference, Monterey, California, March 2-4, 1966. An abstract of this paper is included here as Appendix 1.

2. Parametric Macroscopic Theories.

In order to bypass the overwhelming difficulties in connection with simultaneous solution of macroscopic and microscopic aspects of the problem, it was decided to decouple them through the use of undetermined parameters, leaving the evaluation of the parameters to a separate phase of the program. The intercoupling of the macroscopic equations through these parameters was investigated in an attempt to gain insight on the basically macroscopic phenomena of discharge constriction. Two different studies were made, to be described in two separate Informal Interim Reports. The first study[4], concerning the characteristics of self-sustained thermionic cathodes, showed that if a phenomenological relationship of thermionic emission is known, the detail of the sheath and electron impact zone are unimportant as far as the electrical characteristics are concerned. A linear stability analysis further showed that a uniform discharge is unstable with respect to transverse perturbation whose wave numbers are smaller than the critical value[3]:

$$\alpha_c = [j_e \ (V_s - \phi)(\frac{\phi}{RT} + 2) \frac{1}{T} - 4\sigma\varepsilon T^3 + q' \ (T)]/K_s \qquad (1)$$

where j_e, V_s, ϕ, $\sigma\varepsilon T^3$, q, K_s, denote electron current, sheath potential, work function, thermal radiation, plasma conduction, and solid thermal conductivity, respectively. Equation (1) thus gives an explanation for the tendency of cathodes to revert to "spot mode operation. It is interesting to note that for typical laboratory conditions, the critical wave number corresponds to a dimension of the order of milimeters which is consistant with known cathode spot dimensions.

A second study[5] concerns the tendency of the plasma to constrict due to a coupling between the energy equation and the electrical conduction equation. The study is thus more relevant in the plasma boundary layer surrounding the electrode. Due to the complexity of the mathematical problem, only unrealistically simple boundary conditions have been solved to date. These show that:

(a) In general, contriction is possible if $\frac{j^2 \ell^2}{\sigma_r s_r} >> 1$ and $\frac{d(\ell n \sigma)}{d(\ell n s)} > 1$, where $s = \int_{T_r}^{T} K dT$, σ and K are temperature dependent electrical and thermal conductivities, j is the current density, ℓ is a characteristic thickness, and subscript r denotes reference values evaluated at electrode surface temperature.

(b) For the simplest case, the critical wave number is [5]

$$\alpha_c \simeq E/(\frac{d\sigma}{ds})^{\frac{1}{2}} \qquad (2)$$

The computed wave length for α_c at typical plasma conditions were also consistant with the observed characteristic dimensions. While this agreement is probably fortuitous in view of the simplifications used in the analysis, they are nevertheless valuable in providing new insight to the problem.

Portions of the above results have subsequently been described in a presentation at the Seventh Symposium on Engineering Aspects of Magnetohydrodynamics[6]. An abstract of this presentation is given in Appendix 2.

3. Microscopic Physical Processes.

Neglecting non-uniformities and other macroscopic features, a critical examination of the atomic scale physical processes governing refractory cathode operation has been carried out for typical laboratory conditions[6]. These included transport processes in the cathode interior, on the cathode surface and in the plasma sheath, collision processes in the plasma and on the surface, and the emission processes. Consistency arguments and approximate calculations were used to judge the plausibility and relative importance of each competing process. The result indicated that many of the existing models of cathode operation were either theoretically inconsistent or not applicable to refractory cathode operations. In particular, it was found that (a) Cathode heat conduction is not neglible as often assumed (b) Ion current cannot account for all the electrode heating (c) Radiative transfer and thus photoemission cannot be neglected without further study. In view of these conclusions, a new model of refractory cathode is tentatively formulated, assuming that the electron emission to be a combined result of field enhanced thermal emission and photoemission, and that the electrode heating to be caused by both electron impact and atomic line radiation. Preliminary checks of this model with experimental data showed it to be more satisfactory than earlier models. However, the model cannot be quantitatively evaluated until some key parameters, particularly the ratio of ionizing collisions and versus excitation collisions and the ratio of high energy photons (photoemitting) and low energy photons can be found either experimentally or theoretically.

The details of this analysis are to be described in a forthcoming Informal Interim Report[7].

III. Financial Report

Since a separate financial report is being submitted, the matter shall not be dealt with here.

IV. Future Plans

In the remaining six-month period of the current program, emphasis will be placed on the final refinement and interpretation of the results obtained to date. These will be described in a series of four technical reports.

A proposal for a continued research program describing the planned activities for the next two years, has already been submitted to NASA.

REFERENCES

1. "Experimental and Theoretical Research on Plasma Sheaths and Boundary Layers around Stagnation Point Electrodes", Semi-Annual Progress Reports No. 1, Jan. 1965. No. 2, Aug. 1965. Grant No. NSG 724, Submitted by Yale University to National Aeronautics and Space Administration.

2. "Experimental Investigation of a Stagnation Point Electrode", Informal Interim Report No. 3, NASA Grant NSG 724, prepared by M. M. Chen and E. Zimet, Yale University, (April 20, 1966).

3. Chen, M. M. and Zimet, E., "The Stagnation Point Electrode Experiment", AIAA Paper No. 66-190. Presented at the AIAA Plasmadynamics Conference, Monterey, California, March 2-4, 1966. AIAA Bulletin 3, 1, p. 25 (1966). (Results of these experiments are described in detail in reference 5 above).

4. "Characteristics and Stability of Self-Sustained One-dimensional Thermionic Cathode", Informal Interim Report No. 1 NASA Grant NSG 724, (April 20, 1966).

5. "Fundamental Conditions for Uniform Current Distribution in a Medium with Temperature Dependent Conductivity", Informal Report No. 2, NASA Grant NSG 724, prepared by M. M. Chen, Yale University, (April 25, 1966).

6. Chen, M. M., "Some Elementary Considerations Concerning the Uniformity of Electrical Conduction Through Gases", Preprint Book of Seventh Symposium on Engineering Aspects of Magnetohydrodynamics, Princeton, New Jersey, March 30 - April 1, 1966. (Materials contained in this presentation are discussed in references 3 and 4).

7. "Physical Processes Governing the Operation of Refractory Cathodes in Dense Gases", Informal Interim Report No. 4, NASA Grant NSG 724, prepared by M. M. Chen, Yale University, (April 25, 1966).

APPENDIX I

Abstract: "Stagnation Point Electrode Experiment"

By: M. M. Chen and E. Zimet - Yale University

Paper AIAA No. 66-190 - AIAA Plasmadynamics Conference, Monterey, California, March 2-4, 1966.

By placing a test electrode in the stagnation region of an arc heated argon jet, stable symmetric electrode operation could be achieved. When operated as an anode up to about 10^2 Amp/cm^2. The current-voltage characteristics showed clear departures from the usual probe characteristics. When operated as a cathode, the electrode followed the usual probe ion current curve until a breakdown point is reached. After which it behaved thermionically, reaching a current density of 10^2A/cm^2. The voltage current characteristics could be represented approximately by the simple theoretical result $J(V_c-\phi)$ = const. spectroscopic measurements were also made, showing the excited states to be not in equilibrium with the plasma conditions.

APPENDIX 2

Abstract: "Some Elementary Considerations Concerning the Uniformity of Electrical Conduction Through Gases"

By: M. M. Chen

Seventh Symposium on Engineering Aspects of Magnetohydrodynamics, Princeton, New Jersey, March 30-April 1, 1966.