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Generation of Atomic Oxygen Flows by an Arc-Heater using Hollow Cathode

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For enhancement of oxygen dissociation in constrictor type arc-heater plumes, a hollow cathode arc-heater was developed so as that oxygen passes through a high temperature cathode-jet region. Although the oxygen dissociation could be increased one order magnitude, operational time was limited in less than ten minutes and unstable discharge caused significant cathode erosion. Then, instead of conventional thoriated-tungsten cathode, zirconium cathode with ceramic oxide layer was used. As a result, stable discharge could be kept more than twenty minutes and the cathode erosion could be reduced even if oxygen was supplied at the upstream with argon.

I. Introduction

In developing Thermal Protection Systems for reentry vehicles, arc-heaters are often used to simulate reentry conditions. Constrictor type arc-heaters [1-3] and segmented type arc-heaters [4, 5] are widely used. The segmented type has an advantage of high input power because it can sustain long arc discharge. However, it takes several hours for maintenance after a few minutes operation. On the other hand, the constrictor type is simple and rugged structure, long operational time and requires almost no maintenance after several-hour operation. Therefore, constrictor type arc-heaters are convenient for basic TPS studies.

However, their exact plume conditions are mostly unknown because they are usually in strong thermo-chemical non-equilibrium. Although non-intrusive spectroscopic methods such as emission spectroscopy and Laser Induced Florescence have been actively applied to the characterization of such high enthalpy plumes, and the excitation, vibration, and rotational temperatures of atoms and molecules in the plumes are gradually clarified, [6-9] it is still difficult to measure the chemical compositions by these spectroscopic methods.

Recently, atomic oxygen in a high enthalpy flow is found to play important roles in TPS tests. Atomic oxygen in front of TPS materials recombines with releasing exothermic heat because of its catalytic effects, resulting in a heat flux enhancement up to twice as much as that in non-catalytic case. Another role of atomic oxygen is active-passive oxidation, which determines SiC erosion dramatically.[10]

Then, in our previous research[11], number density distributions of meta-stable atomic oxygen ($3s^5S$) in the constrictor type arc-heater plumes developed at the University of Tokyo were measured by laser absorption

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spectroscopy along with CFD analysis. [11-14] As a result, the measured peak of the distribution was located off axis at the -exit of the nozzle, and then the peak approaches to the axis in the downstream of the plume with the increase in number density as shown in Fig.1. Number density distribution of meta-stable argon ($4s^2[1/2]$) has a peak on the axis at the nozzle exit and then the number density decreases rapidly in the downstream of the plume as shown in Fig.2. The similar result was obtained in the CFD analysis as shown in Fig.3.

Consequently, oxygen is localized off axis near the nozzle exit and diffuses to the axis in the downstream region while it is dissociating. On the other hand, the meta-stable argon number density has a peak on the axis at the nozzle exit and decreases rapidly due to quenching in the downstream region. Therefore, it is thought that oxygen is not enough mixed with argon and not dissociated in the constrictor region. Although the oxygen is mixing in the plume, the dissociation rate is quite small because of the decrease in temperature, resulting in the low number density of atomic oxygen. The mixing process is schematically shown in Fig.4.

This result is due to the specific gas injection system in the constrictor type arc-heaters. In the constrictor type, inert gas such as argon or nitrogen is supplied from the base of cathode rod. Oxygen is added at the constrictor part to prevent the cathode from oxidization. In this study, for the enhancement of the oxygen dissociation, the oxygen injection-port and cathode material was improved.

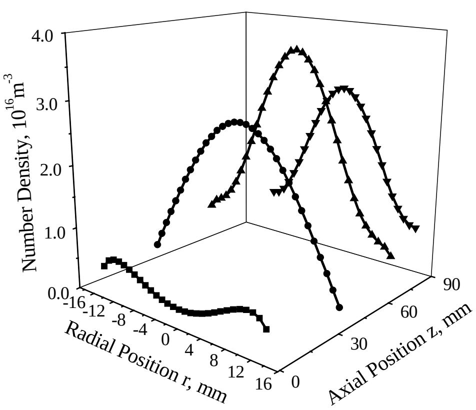

Figure 1. Number density distributions of OI (3s5S).

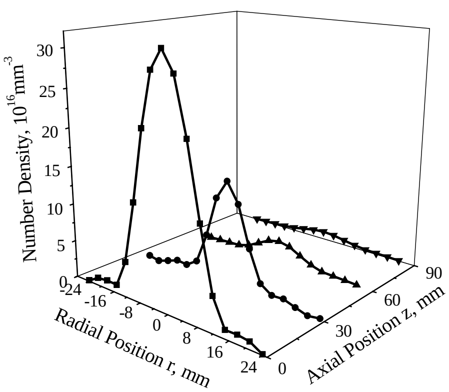

Figure 2. Number density distributions of ArI ($4s^2[1/2]$).

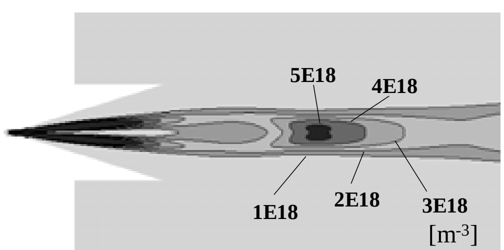

Figure 3. Computed contours of number density of atomic oxygen.

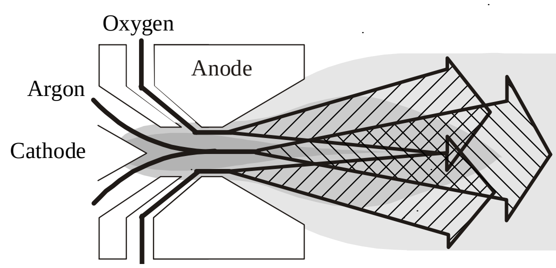

Figure 4. Mixing process.

II. Arc-heater using Hollow Cathode

As mentioned above, the experimental and numerical results show that in the constrictor type arc-heater plumes, oxygen is not enough mixed with argon and not dissociated in the constrictor region resulting in the low number density of atomic oxygen. Therefore, instead of a conventional rod-cathode, a hollow cathode is used and oxygen is supplied through the cathode tip so as that oxygen passes through a high temperature cathode-jet region as shown in Fig.5.

The experimental conditions were argon mass flow rate of 6 slm, input power of 1 kW (current of 50 A) and ambient pressure of 70Pa. The oxygen mass flow rate was 0.2 slm, which was one-fifth of that of the constrictor type arc-heater. At the more mass flow rate, the arc discharge couldn't keep.

Number density distribution of meta-stable oxygen and translational temperature distribution at the nozzle exit along with those in the constrictor type arc-heater are shown in Figs.6, 7. The number density distribution in the hollow cathode arc-heater plume has a peak on the centerline. The maximum number density is four times as high as that in the constrictor type arc-heater plume, which corresponds to be one order higher considering the mass flow rate of oxygen. On the other hand, the translational temperature in the hollow cathode arc-heater plumes is around 1100K, which is much lower than that in the constrictor one.

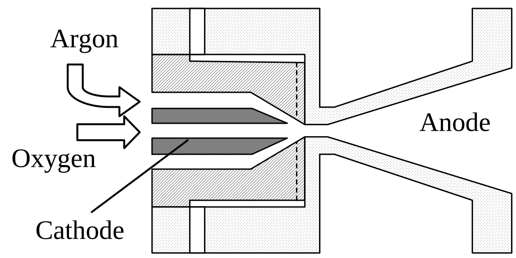

Figure 5. Hollow cathode arc-hater.

This would be due to that the input enthalpy of the hollow cathode arc-heater is used for dissociation of oxygen much more than that of the constrictor one. The low translational temperature also indicates the low electronic excitation temperature. Therefore there is a possibility that the number density of the ground state oxygen in the hollow cathode arc-heater plume is much higher than that in the constrictor one, though that of meta-stable in the hollow cathode arc-heater is the same order as that in the constrictor one.

However, operation time is limited less than ten minutes because severe cathode erosion causes unstable discharge and spark as shown in Fig.8. The erosion after one hour off and on operation is as much as 10 mm as shown in Fig.9. This is because the melting point of the cathode goes down from 3680 K (tungsten) to 1470 K (tungsten oxide) due to the oxidation. The severe erosion not only limits the operation time but also causes plume contaminations. Then, the reduction of cathode erosion is required.

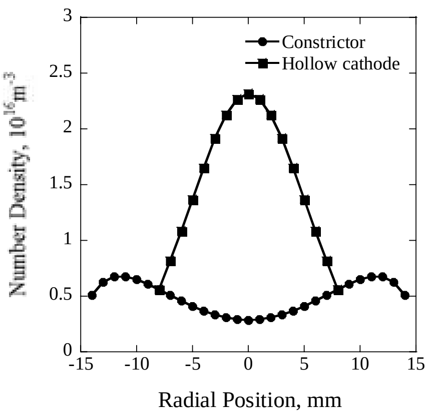

Figure 6. Number density distributions in hollow and constrictor type arc-heater plumes.

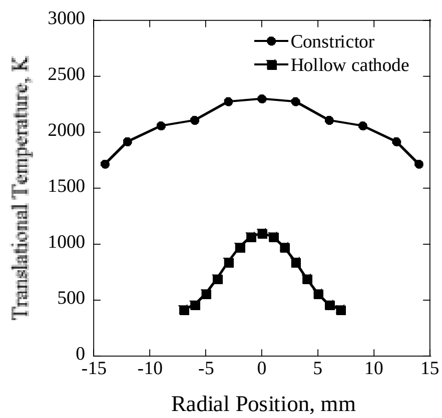

Figure 7. Translational temperature distributions in hollow and constrictor type arc-heater plumes.

Figure 8. Photo of unstable hollow cathode arc-heater plume.

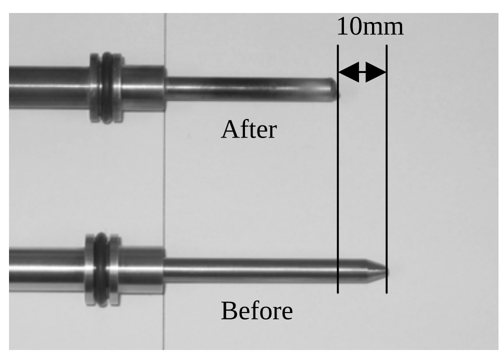

Figure 9. Cathode erosion (one hour off and on operation).

III. Arc-heater using Zirconium cathode

To reduce the cathode erosion, zirconium was focused on instead of conventional tungsten. Although the melting point of zirconium (2100K) is lower than that of tungsten (3680K), it reacts with oxygen and forms oxide ceramic layer on the cathode surface. [15] This layer composed of zirconium dioxide called zirconia has high melting point (3000K) and low vapor pressure, resulting in much lower erosion rate than that of tungsten in the reactive gas flows. Then, in cutting, welding and spraying fields, zirconium cathodes are widely used for air plasma torches. [16-19] However, there are few reports on details of zirconium cathodes and most of work has been done in Russia. In this study, zirconium cathode was applied and operational behavior was observed.

A. Oxidation of Zirconium Cathode

To enhance the melting point and reduce the erosion of the cathode, refractory oxide layer is required to be formed on the zirconium. The existing constrictor type arc-heater was used for the oxidation. Figure 10 shows the oxidation system. Operational conditions of the arc-heater were 6 slm of argon, 1.5 slm of oxygen, 1.0 kW of input power and 70 Pa of ambient pressure. A target cathode was set on a movable stage. After the plume became stable, the cathode was moved to 60 mm from the nozzle exit where number of atomic oxygen was thought to be largest in the plume by the previous measurement. The cathode was exposed to the plume for ten minutes and then cooled off in the vacuum chamber filled with oxygen. Figure 11 shows the cathode before and after oxidation. As seen in this figure, the silver zirconium cathode became black and then its surface was thought to be oxidized.

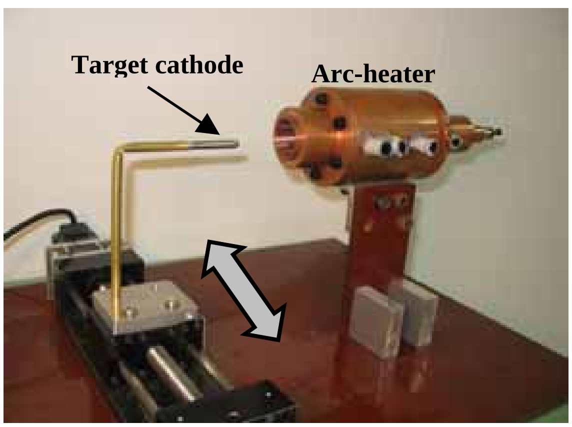

Figure 10. Oxidation system

Figure 11. Zirconium cathode before and after oxidation

B. Operational Behavior

Figure 12 shows a photograph of zirconium cathode arc-heater plume. Operational conditions are same with those in the hollow cathode case. Although the oxide ceramic layer is non-conductive at room temperature, discharge could be successfully ignited and sustained. This is because conductivity of the layer increased with increase in temperature during the ignition. Even if the oxygen was supplied from the upstream with argon, stable operation shown in the figure could be kept more than twenty minutes.

Figure 13 shows zirconium cathodes before and after twenty minutes operation. The cathode erosion is less than 2 mm and reduced smaller than that of tungsten cathode. Since the cathode length and tip shape are same with tungsten one, there is much room for improvement of cooling design and gas supply system such as swirl injection or axial injection.

Figure 12. Photo of zirconia cathode arc-heater plume

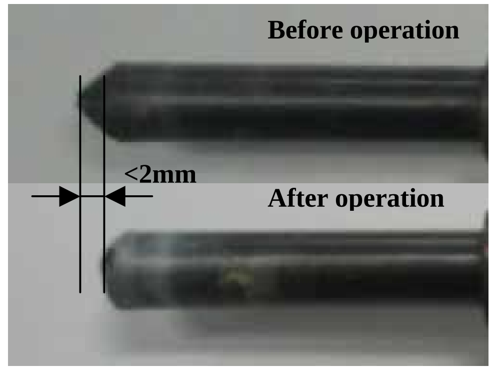

Figure 13. Zirconia cathode before and after twenty minutes operation

IV. Conclusion

A hollow cathode arc-heater was developed and number density distributions of meta-stable oxygen and translational temperature distributions in the plume were measured by laser absorption spectroscopy. As a result, oxygen dissociation was enhanced one order higher than that in a constrictor type arc-heater plume. However, its operational time was limited in less than ten minutes due to the severe cathode erosion. Using zirconium cathode covered with oxide ceramic layer, stable operational time could be prolonged more than twenty minutes and cathode erosion was reduced.

Acknowledgments

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