Application of a 20 kW Arc-Heated Wind Tunnel to Evaluation Tests of Wall Catalysis

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This paper describes the performance characteristics of a 20 kW-class arc-heated wind tunnel and the investigation of material catalysis as an application of this facility. First of all, stagnation heat fluxes and pressures are measured in high-enthalpy air and nitrogen arc jets that are generated by a constrictor-type arc heater. Total enthalpies of the arc jets are estimated based on Pope's theory. The total enthalpies are 7.5–22 MJ/kg for nitrogen and 13–19 MJ/kg for air. The operation envelope of this arc-heated wind tunnel and the applicable conditions for reentry simulation or the thermal protection tests are discussed based on the experimental results. Finally, as an application of this arc-heated wind tunnel, evaluation tests of wall catalysis have been attempted by the use of two flat-faced cylindrical models equipped with two kinds of specimens of catalytic material. The evaluation tests are composed of heat flux measurements and spectroscopic measurements. It is found that there is a certain difference in obtained heat fluxes between the two catalytic materials. Emission spectra from a shock layer formed in front of the model are measured, and wall catalysis is discussed based on the spectra measurements. The results show the existence of catalytic wall effects.

Key Words: Wall Catalysis, Arc-Heated Gas, Arc-Heated Wind Tunnel, Spectroscopic Measurements

1. Introduction

To simulate the aerodynamic heating environment for a hypervelocity vehicle, various ground test facilities have been constructed and developed. An arc-heated wind tunnel is one of these facilities and features long operational time; thus the arc-heated wind tunnel has been used mainly for the development and evaluation of a thermal protection system (TPS) for space transportation systems. Several types of arc heaters (such as Huels, Segment, Constrictor, and MPD) have been adopted as a plasma generator, and their electric power scales are in the range of 10 kW–100 MW. Impact pressure and enthalpy of an arc jet depend on its power level and configuration. It should be mentioned that conditions required for aerodynamic heating simulation are dependent on the kind of mission, the chemical composition of planetary atmosphere, entry orbit, and the type of spacecraft. To satisfy these conditions, the required maximum impact pressure and heat flux must be 100 kPa and 20 MW/m², respectively. In general, large arc-heated wind tunnels can produce this high pressure and enthalpy flows and have the merit of using larger models or specimens. However, large arc-heated facilities have the problem that arc jet flows include larger amounts of contamination because of electrode erosion than small ones do. Since the flow characteristics may be seriously affected by this contamination, it is not desirable to use such a contaminated flow; that is, noncontamination flows are required for the qualification test of TPS materials and

the evaluation test of catalytic wall effects. Thus it is effective to choose a proper power class facility for re-entry aerodynamic heating.

In this work, the performance characteristics experiments of a 20 kW-class arc-heated wind tunnel at the Department of Aeronautics and Astronautics, Kyushu University, have been carried out. The operation envelope of this wind tunnel is obtained and compared with the required conditions for the missions discussed in Ref. 1. The main subject of this study is focused on the investigations of catalytic wall effects, because it is expected that flows with negligible contamination can be obtainable. According to Park,²⁾ the copper atomic lines at 324.7 and 327.4 nm resulting from the erosion of a copper electrode are observed by the spectroscopic measurement of a shock layer over a blunt body in an arc-heated flow. In our measurements, these copper lines are not identified. Therefore measurements of heat flux on catalytic materials and emission spectra from the shock layer formed in front of the catalytic materials have been conducted to investigate the catalytic effects.

2. Experimental Facility

Experiments have been conducted with a 20 kW-class arc-heated wind tunnel. This tunnel consists of a constrictor-type arc heater, a cylindrical test chamber whose diameter and length are both 100 cm, vacuum pumps, and a water-cooling system. A schematic of the wind tunnel is shown in Fig. 1. The test chamber is connected to the vacuum

Fig. 1. Schematic of the arc-heated wind tunnel.

Fig. 2. Constrictor-type arc heater.

pumping system, which is composed of an oil-sealed rotary vacuum pump and a mechanical booster pump. The maximum pumping speed of this system is 7,000 m³/h, and the test chamber pressure is maintained below 100 Pa during operation.

Figure 2 illustrates the arc heater, which is composed of a 2% thoriated tungsten cathode and copper anode forming a conical nozzle with a semi-angle of 15°. The nozzle throat and exit are 5 mm and 100 mm in diameter, respectively, which leads to a nominal Mach number of 9.4 for diatomic gas. Argon or nitrogen can be used as a test gas, which is supplied into the discharge section with swirling and is heated by a DC arc discharge. An arc-heated gas expands into the test chamber through the nozzle. Besides the argon and nitrogen-arc jets, an air-arc jet can also be generated. In experiments of the air-arc jet, nitrogen gas is injected first into the discharge section and heated by discharge. Then oxygen is seeded into the heated nitrogen plasma downstream of the cathode to prevent oxidation of the cathode.

3. Performance Characteristics of an Arc-Heated Wind Tunnel

Heat flux and impact pressure are important parameters that represent the aerodynamic heating environment. Stagnation heat flux and pressure are measured. A stagnation

Fig. 3. Current-voltage characteristics (N₂).

Fig. 4. Current-voltage characteristics (Air).

heat flux probe is a water-cooled copper cylinder with a 20 mm diameter of hemisphere nose. The measurements are performed at 5 mm downstream of the nozzle exit. Before heat flux and impact pressure measurements, the discharge characteristics of the arc heater are examined for the stable conditions of various arc currents and volume flow rates. Current-voltage characteristics of the arc heater for nitrogen and air are shown in Figs. 3 and 4, respectively. The arc voltage is increased with the volume flow rate for both nitrogen and air. The relations between volume flow rate and current-voltage characteristics for nitrogen and air are not much different from each other. It can be seen that the dependency of voltage on current is very weak for both nitrogen and air. In these figures, the error bars of voltage value are also indicated for each plotted point, and the deviations from averaged values are within 3.5%. Therefore the repeatability of this arc heater in terms of input power, a product of voltage and current, can be estimated at more than 93%.

3.1. Stagnation heat flux

Heat flux has been measured with a Gardon gauge calorimeter mounted at the stagnation point of the heat flux probe. Transducer accuracy and repeatability of this gauge are $\pm 2\%$ and 1%, respectively. Figure 5 shows the measured stagnation heat fluxes for the nitrogen-arc jet against the arc current. The heat flux is in the range from 0.45 MW/m² to 1.9 MW/m². It can be seen from this figure that the heat flux increases proportionally with the arc current. The results for air-arc jets are shown in Fig. 6. In this case, the range of heat flux is from 1.05 MW/m² to 1.65 MW/m². It turns out that the characteristics of the heat flux are very similar for nitrogen and air.

Fig. 5. Stagnation heat flux (N₂).

Fig. 6. Stagnation heat flux (Air).

Fig. 7. Impact pressure (N₂).

Fig. 8. Impact pressure (Air).

Fig. 9. Atmospheric entry/reentry conditions required for various missions.

pressure level. However, the lower pressure part of winged-vehicle conditions, that is, high-altitude rarefied air conditions, can be covered with the operation envelope of the arc-heated wind tunnel. To apply this wind tunnel to a simulation of other missions, further efforts to increase stagnation pressure are needed.

Moreover, total stream enthalpy for arc jet flow can be determined by the use of a heating-rate method.³⁾ The relationship among heating rate q , probe nose radius R , stagnation pressure p , and enthalpy H at the boundary-layer edge is given by the following formula for a fully catalytic surface:

$$q(R/p)^{0.5} = KH \quad (1)$$

where, K is a specific constant given for test gas species. The catalytic reaction-rate constants for most metals are so large that the surface of copper probe used for heat flux measurement can be assumed to be fully catalytic to atom recombination. Measured heat flux and stagnation pressure are used here to determine the total stream enthalpy by the use of Eq. (1). The enthalpies obtained for nitrogen and air are 7.5–22 MJ/kg and 13–19 MJ/kg, respectively.

3.2. Impact pressure

Impact pressure has also been measured with the same probe, and the measured pressures are shown in Figs. 7 and 8. The impact pressure increases with the volume flow rate and arc current for both nitrogen and air, and the ranges of the obtained values are 300–800 Pa for nitrogen and 500–700 Pa for air. Furthermore, the ambient pressures inside the test chamber have also been measured. They are 20–70 Pa for nitrogen and 25–45 Pa for air.

3.3. Operation envelope

Figure 9 shows the conditions for the atmospheric entry of space transportation systems in the relation between impact pressure and aerodynamic heating rate.¹⁾ The operation envelope of the 20 kW arc-heated wind tunnel is also indicated in this figure with a black-painted area. The range of measured heat flux sufficiently meets the conditions for winged vehicle and Mars aerocapture. On the other hand, in regard to pressure level the figure indicates that for winged-vehicle atmospheric entry simulation, the impact pressure needed is around 1 kPa, which is slightly larger than the measured

Fig. 10. Section view of the catalysis model.

Fig. 11. Driving device of the catalysis models.

Table 1. Flow conditions of the evaluation tests of wall catalysis.

No.	Volume flow rate (l/min)			Arc current (A)	Arc voltage (V)	Arc power (kVA)	Ambient pressure (Pa)
	N ₂	O ₂	Ar				
1	—	—	30	200	51.6	10.3	26.4
2	—	—	50	200	60.3	12.1	38.4
3	40	—	—	100	110.1	11.0	34.3
4	60	—	—	140	121.4	17.0	53.5
5	40	8	—	140	125.2	17.5	44.3
6	32	8	—	150	122.4	18.4	38.0
7	40	8	4	140	126.0	17.6	54.8

4. Experiments of Catalytic Wall Effects

This section describes the evaluation tests of the effects of the catalytic wall on aerodynamic heating in high-temperature dissociated gases. Two kinds of catalytic materials, stainless steel (18Ni-8Cr) and alumina ceramic (Al₂O₃), are prepared as specimens. Stainless steel is considered to be close to fully catalytic material, whereas alumina ceramic is selected as a noncatalytic material. To investigate the effect of catalytic wall on heat flux, the heat fluxes are measured by using the specimens, and the results for three different arc-heated gases argon, nitrogen, and air are compared with one another. Furthermore, emission spectra from the shock layer formed in front of a model are measured with a spectrometer.

4.1. Heat flux on catalytic wall

Figure 10 illustrates a 20 mm diameter flat-faced cylindrical model used for the evaluation tests of wall catalysis. A test piece is a thin circular disk 10 mm in diameter and 1.5 mm thick, and it is set up at the stagnation point of the model with a silicon nitride cap. A chromel-alumel thermocouple is bonded on the rear surface of the test piece. Two kinds of models, stainless steel and alumina ceramic, are installed in a driving device, shown in Fig. 11. These models can be rapidly driven to a point of measurement, which is 8 cm downstream and on the nozzle axis.

In the measurements, the models are exposed to the arc

Table 2. Thermal properties of the materials.

Material	Specific weight (kg/m ³)	Specific heat (kJ/kg·K)	Thermal conductivity (W/m·K)
Alumina (Al ₂ O ₃)	3,900	0.800	21.4
Stainless steel (18Ni-8Cr)	7,920	0.498	11.9

jet flow for about 3 seconds, resulting in a temperature rise of around 230 °C on the rear surface. Thus the temperature histories of the rear surface have been obtained experimentally. The working gases used here are argon, nitrogen, and air (nitrogen/oxygen mixture). Table 1 shows the flow conditions during the measurements. Since these models are driven to the steady arc-jet flow sequentially and quickly during each measurement, the test conditions between two catalysis models would be expected to be identical. Eventually, input heat flux on the surface is determined based on the database of the rear surface temperature histories calculated with a one-dimensional unsteady equation of heat conduction. The thermal properties of the materials shown in Table 2 are employed in the preceding calculation.

4.2. Spectroscopic measurements

Figure 12 shows a schematic of the experimental arrangement for spectroscopic measurements. The emission spectra are observed from 1 mm upstream of the model. The shock standoff distance is estimated to be about 2 or 3 mm.

Fig. 12. Schematic of the experimental arrangement for spectroscopic measurements.

Spatially resolved emission spectra are obtained with an intensified charged-coupled device (ICCD) camera (576×384 array) attached to a spectrograph. The focal length of the spectrograph is 250 mm and the f number of the optical system is 4.3. A 1,800 line/mm grating is equipped with the spectrograph. The reciprocal dispersion of the system is 2 nm/mm, and the spectral resolution is 0.035 nm/pixel. Cut-off filters are used to remove higher-order spectral lines. The wavelength calibration of the spectrograph is performed with a mercury lamp. The emission spectra from the freestream as well as the shock layer are measured for comparison with each other.

5. Results and Discussion

5.1. Heat flux on catalytic wall

Heat fluxes into the two catalytic materials are shown and compared with each other in Fig. 13 for arc-input power. It is clear that the heat flux values of stainless steel (a fully catalytic material) are especially larger than those of alumina ceramic (a noncatalytic material) in case of nitrogen/oxygen mixture gases (Nos. 5, 6, and 7 on Table 1). Figure 14 shows the ratios of the heat flux on stainless steel to the heat flux on alumina ceramic for arc-input power. It is found that heat fluxes on stainless steel for argon or nitrogen are almost the same or slightly larger (10% larger) than those on alumina ceramic, but heat fluxes on stainless steel for nitrogen/oxygen mixture gases are 38% larger than those on alumina ceramic. In the data analysis of heat flux tests, the margin of error is estimated at 5%. From these results, it seems that oxygen significantly contributes to an increase in heat flux; that is, the dissociation energy released by the recombination of oxygen atoms occurring on the catalytic wall is transferred to the wall, resulting in the observed increase of heat flux.

Attention is focused on an understanding of species mole fractions on the wall. The degree of dissociation of oxygen and nitrogen in the discharge section of the arc heater, in which chemical equilibrium would be formed, are calculated with a code of equilibrium chemical composition for air

Fig. 13. Comparison of the heat-flux values between stainless steel and alumina ceramic.

Fig. 14. Ratios of the heat flux on stainless steel to the heat flux on alumina ceramic.

Fig. 15. Degree of dissociation calculated by a program of equilibrium chemical composition for air ($N_2:80\%$, $O_2:20\%$).

($N_2:80\%$, $O_2:20\%$).⁴⁾ Figure 15 shows the calculated curves of the degree of dissociation for oxygen and nitrogen as functions of discharge section temperature and pressure. The results shown in this figure indicate that oxygen molecule dissociates substantially for several thousand kelvins above 2,000 K, whereas nitrogen molecule scarcely dissociates below 4,000 K. Typical values of the degree of dissociation are 72% and 0.1% for oxygen and nitrogen, respectively, at a temperature of 4,000 K and a pressure of 1.0 atm. In the experiments, discharge section pressures are measured to be from 0.6 atm to 0.9 atm. The same calculation is done only for nitrogen gas, and the obtained curves are similar to or slightly smaller than those in Fig. 15. Therefore it seems that the recombination of oxygen atoms occurred sufficiently because of wall catalysis; consequently the recombination energy is to be transferred to the wall. Even though the recombination of nitrogen atoms resulting from the effects of

Fig. 16. Comparison of measured spectra among the shock layers of the stainless steel model, the shock layers of the alumina ceramic model, and freestream (without a model) for the nitrogen-arc jet; the test condition is No. 4 on Table 1.

Fig. 17. Comparison of measured spectra among the shock layers of the stainless steel model, the shock layers of the alumina ceramic model, and freestream (without a model) for the air-arc jet; the test condition is No. 6 on Table 1.

Fig. 18. Comparison of measured spectra between the shock layers of the stainless steel model and the alumina ceramic model for the argon-arc jet; the test condition is No. 1 on Table 1.

catalytic wall might have occurred, the reaction did not occur enough so that the recombination energy could not be transferred to the wall. On the other hand, since argon is a monatomic molecule, ionization reaction must be argued instead of the dissociation reaction. There is a possibility that ionization energy released by the recombination reaction is

transferred to the wall. However, the degree of ionization of argon is of the order of 10^{-3} ; thus the influence on heat flux because of the wall catalysis would be negligible.

5.2. Spectroscopic measurements

Emission spectra have been measured for a wavelength range of 343–393 nm for nitrogen and air-arc jets. The com-

parisons of the obtained spectra are shown in Figs. 16 and 17, in which the test conditions are nitrogen-arc jet of No. 4 and air-arc jet of No. 6 on Table 1, respectively. The identified spectra in this region contain molecular band systems of $N_2^+(1-)$ and atomic lines of N. The former is dominant throughout this region, especially in the shock layers (Figs. 16, 17), and the latter is clearly identified only in the freestream of nitrogen arc jet (Fig. 16).

In Figs. 16 and 17, the spectral intensity measured for the stainless steel model is stronger than that for the alumina ceramic model throughout this region. This fact is significantly interesting. According to Gökçen et al.,⁵⁾ these quantitative characteristics of the spectral intensity is derived from an increase in the number density of N_2^+ and/or to a lesser degree from an increase in temperature. Moreover, species mole fractions on the stagnation streamline of a shock layer for FCW (fully catalytic wall) and NCW (noncatalytic wall) are calculated and reported by Doihara,⁶⁾ in which the reentry of a super orbital capsule at an altitude of 64 km is assumed. In that work, the number density of N_2^+ for FCW is much larger than that for NCW at very near the surface of the wall, which is derived from a series of chemical reaction calculations that consider a catalytic recombination reaction on the wall. In consideration of this, it is concluded that an increase in intensity of N_2^+ for the stainless steel model is caused by an increase in the number density of N_2^+ because of the catalytic effect of the stainless steel. That is, the stainless steel would promote the atomic recombination reaction.

Next, another measurement has been conducted in argon-arc jets to confirm whether the stainless steel surface had actually affected atomic recombination reaction. Argon is a monatomic molecule; therefore atomic recombination does not occur on the surface. It is thus expected that the spectral intensities would be identical for both the stainless steel and alumina ceramic. The result for argon-arc jet is indicated in Fig. 18. In this figure, no remarkable differences are observed. On the contrary, the intensity for the stainless steel is appreciably weaker than that for the alumina ceramic. If an obvious difference is observed even in the result for argon-arc jet, the phenomenon shown in the results for nitrogen and air-arc jets would be caused by an effect other than the catalytic effect of the stainless steel surface. No remarkable difference is observed, however, and this also shows the validity of the spectroscopic measurements. In these tests,

measurements have been conducted for 2 seconds from the instant of model input, and close attention has been paid to uniform test conditions.

6. Conclusions

In this paper, the performance characteristics of a 20 kW-class arc-heated wind tunnel have been measured. Based on these results, this facility sufficiently meets the heating rates encountered by the reentry of a winged vehicle. Next, as an application test of this facility, the catalytic effects of two kinds of catalytic materials, stainless steel and alumina ceramic, have been investigated by means of heat flux measurements and spectroscopic measurements. The results obtained in the present investigation are summarized as follows:

(1) Heat flux onto the stainless steel (a fully catalytic material) is greater than that onto alumina ceramic (a noncatalytic material).

(2) The heat flux ratio is especially greater in the case of a working gas including oxygen. This implies that the recombination of oxygen atoms on the wall resulting from the catalytic effect of the stainless steel significantly contributes to an increase in heat flux.

(3) An increase in the number density of N_2^+ as a result of the catalytic effect of stainless steel is observed.

References

- 1) Hinada, M., Inatani, Y., Yamada, T. and Hiraki, K.: Performance Characteristics of the ISAS Huels-Type Arc Heater, 19th International Symposium on Space Technology and Science, 94-d-37, Yokohama, 1994.
- 2) Park, C.: Evaluation of Real-Gas Phenomena in High-Enthalpy Aerothermal Test Facilities: A Review, *J. Thermophys. Heat Transfer*, **11** (1997), pp. 330–338.
- 3) Pope, R. B.: Measurements of Enthalpy in Low-Density Arc-Heated Flows, *AIAA J.*, **6** (1968), pp. 103–110.
- 4) Prabhu, R. K. and Erickson, W. D.: A Rapid Method for the Computation of Equilibrium Chemical Composition of Air to 15000 K, NASA TP 2792, 1988.
- 5) Gökçen, T., Park, C. S., Newfield, M. E. and Fletcher, D. G.: Computational Simulation of Emission Spectra from Shock-Layer Flows in an Arcjet Facility, *J. Thermophys. Heat Transfer*, **12** (1998), pp. 180–189.
- 6) Doihara, R.: A Thermochemical Nonequilibrium Flow around a Super Orbital Reentry Capsule, Dr. Eng. Thesis, Kyushu University, 2001, pp. 123–133 (in Japanese).