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Title	Mitigation of reentry blackout via gas injection in arc-heating facility
Author(s)	Miyashita, Takashi; Sugihara, Yuji; Takahashi, Yusuke et al.
Citation	Journal of Physics D : Applied Physics, 57(32), 325206 https://doi.org/10.1088/1361-6463/ad4718
Issue Date	2024-05-20
Doc URL	https://hdl.handle.net/2115/94952
Rights	This is the Accepted Manuscript version of an article accepted for publication in Journal of Physics D : Applied Physics. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at 10.1088/1361-6463/ad4718 .
Type	journal article
File Information	J. phys. D 57-32_325206.pdf



Mitigation of Reentry Blackout via Gas Injection in Arc-Heating Facility

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7 May 2024

Abstract. Communication blackouts during atmospheric reentry pose significant challenges to the safety and adaptability of spacecraft missions. This phenomenon, caused by the attenuation of electromagnetic waves by the plasma surrounding the spacecraft, disrupts communication with ground stations or orbiting satellites. Therefore, it is crucial to decrease the plasma density in the vicinity of the spacecraft to ensure an unobstructed electromagnetic wave communication path. This study proposes a methodology that involves the injection of gas from the vehicle's wall to create an insulating layer near the surface. This thin layer maintains lower temperatures and reduced plasma density, enabling electromagnetic wave propagation without attenuation. Practical experiments were conducted in an arc-heating facility to simulate atmospheric reentry conditions. The results of the experiments provided empirical evidence of the effectiveness of the technique in mitigating communication blackout phenomena. Numerical fluid analysis within the wind tunnel chamber validated the formation of an air film layer near the experimental model owing to the injected gas. Schlieren imaging revealed distinctive jet shapes, which corroborated the findings of the numerical analysis. The wind tunnel tests that simulated atmospheric reentry environments confirmed the formation of an air film layer through gas injection, which substantiates the reduction in communication blackout. These results have the potential to improve communication reliability in space transport.

1. Introduction

Entering the atmosphere of the Earth or another planet creates a strong shock wave at the front of the spacecraft. Owing to the high entry velocity at entry into the atmosphere, the kinetic energy of the gas is converted into thermal and chemical energy by the shock wave. The gas molecules in the shock layer become plasma due to ionization

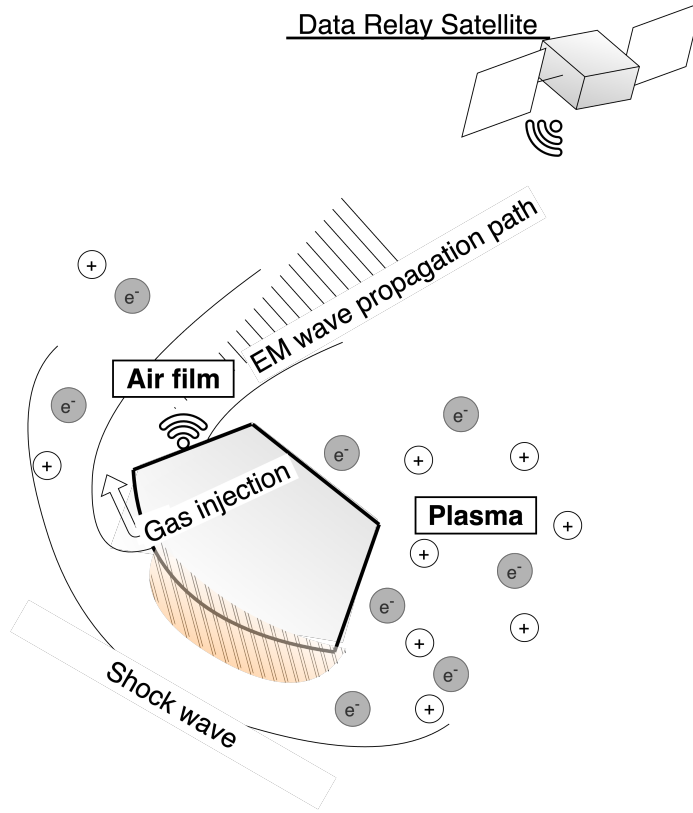


Figure 1: Reentry blackout mitigation by gas injection

and dissociation reactions. Consequently, a communication blackout is known to occur when a spacecraft enters the atmosphere: the high-temperature plasma blocks the electromagnetic waves that enable communication. When a communication blackout occurs, it is difficult to obtain information about the spacecraft from ground stations and observation satellites, making it difficult to determine the status of the spacecraft. Given that communication is lost for several minutes as the spacecraft enters the Earth's atmosphere [1], the inability to determine the position of a spacecraft traveling at high speed reduces the prediction accuracy of landing and splashdown locations. This increases the cost of recovery on the ground. In addition, the inability to send commands to reentry vehicles and the difficulty of investigating the cause of accidents during atmospheric entry significantly impact the diversity and safety of space transportation missions. Thus, there is a need for a method to avoid or reduce the communication blackout phenomenon.

The cause of communication blackouts is plasma. Although plasma as a whole is electrically neutral, it contains positively charged ions and negatively charged electrons. Because of their internal motion, there is a local charge bias in the plasma. Coulomb force causes ions and electrons to be attracted to each other and to oscillate. The ions have a greater mass than the electrons and are considered to be stationary relative to the electrons, while the electrons oscillate individually relative to the ions. The frequency at

this point is defined as plasma frequency f_p . It is expressed by the following equation:

$$f_p = \frac{1}{2\pi} \sqrt{\frac{e^2 n_{\text{ele}}}{m_{\text{ele}} \varepsilon_0}}, \quad (1)$$

where e , n_{ele} , ε_0 , and m_{ele} are the elementary charge, number density of electrons, permittivity in free space, and electron mass, respectively. The plasma generated around the spacecraft during atmospheric reentry features low density and low ionization regardless of altitude. Therefore, it can be regarded as a weakly ionized plasma with negligible thermal motion of electrons. The effect of the geomagnetic field is also negligible because it is low. Thus, the condition for a communication blackout is $f_p \geq f_{\text{link}}$. The following equation is used to evaluate the critical number density of electrons at a communication frequency (f_{link}) of 2.4 GHz at which communication is lost:

$$\begin{aligned} n_{\text{ele, crit}} &= \frac{4\pi^2 \varepsilon_0 m_{\text{ele}} f_{\text{link}}^2}{e^2} \\ &= 7.14 \times 10^{16} \text{ 1/m}^3. \end{aligned} \quad (2)$$

Mitigating communication blackout is achieved by reducing the number of electrons in the vicinity of the vehicle. Previous research has suggested different techniques to reduce communication blackouts. In studies on terahertz wave propagation, Rao et al. [2,3] and Ouyang et al. [4] proposed to reduce communication blackouts by using high-frequency bands to avoid interference with plasma flow.

Belov et al. [5] investigated the effects of body shape on the mitigation effect via wind tunnel tests. Kim et al. [6, 7] reported a method to control the plasma density by applying a magnetic field around the vehicle, and the mitigation effect was experimentally demonstrated by Steffens et al. [8]. Jung et al. [9] and Takasawa et al. [10] showed both numerically and experimentally that catalysis of the surface of the body head promotes recombination reactions in the plasma and reduces the ambient electron number density. Takahashi et al. [11] suggested that the use of a reentry capsule with a flexible membrane structure can achieve low-speed reentry and suppress plasma generation in the flow by reducing the surface heat flux.

Good et al. [12] attempted to clarify the effect of gas injection on communication blackout reduction using numerical analysis. By considering non-equilibrium chemical reactions, it was confirmed that the injected gas lowers the plasma sheath temperature and reduces the plasma frequency. This research, though, only focused on the gas cooling effect and did not take into account the advection effect of an insulating layer in the wake.

Real flight tests of atmospheric reentry can effectively prove the performance of the air film effect in avoiding or reducing communication blackouts. However, there are few experimental opportunities for this and it demands extremely high preparation costs. Therefore, we conducted experimental verification using a ground test facility. This allows for low-cost and recurrent experimentation compared to real flight tests. This study was carried out in an arc-heated wind tunnel. Arc-heated wind tunnels are test

facilities that can reproduce the aerodynamic heating environment during atmospheric entry by generating a high-enthalpy flow by expanding the high-temperature plasma produced by the arc discharge through a nozzle. Recent studies have clarified the distribution of various quantities inside such facilities, and numerical analysis techniques are being established [13, 14].

The long-term goal of this study is to leverage the insulating layer formed by gas injection to mitigate communication blackouts shown in Fig. 1. The previous study confirmed that the heating rate was reduced, suggesting that the injected gas created an insulating layer on the surface of the body, preventing heat input from the environment [15, 16]. Based on this background, a gas injection technology to mitigate communication blackouts was conceived by Miyashita et al. [17]. Computational fluid dynamics (CFD) simulations demonstrated the effectiveness of gas injection in mitigating communication blackouts in the arc-heating facility at the German Aerospace Center (DLR). Electromagnetic waves can propagate through the layer to the exterior, which is expected to avoid or reduce communication blackouts.

In this study, a communication test was conducted in the 1 MW arc-heated wind tunnel of the Institute of Space and Astronautical Science (ISAS) of the Japan Aerospace Exploration Agency (JAXA) to experimentally demonstrate the mitigation effect due to the gas injection. Numerical analysis was carried out with a CFD-based analytical model to reproduce the conditions of the experiment. Spatial distributions of various plasma parameters were calculated to compare with experimental results and to investigate the reduction mechanism. In the future, we aim to demonstrate the reduction effect by testing in a real flight environment. This study is positioned as the foundation of this project.

The configurations of the high-enthalpy wind tunnel test are described in Section 2. Section 3 provides an overview and conditions for the computational analysis of the experiment. Section 4 presents the results of the experiment and plasma flow calculations, their comparison, and discussion. Finally, Section 5 presents conclusions.

2. Experiment in 1 MW arc-heating facility

2.1. Communication tests

For an experimental demonstration of the mitigation of communication blackout through gas injection, communication tests were conducted utilizing the 1 MW arc-heated wind tunnel owned by JAXA/ISAS shown in Fig. 2. This facility is equipped with a segmented arc-heater. The gas that is exited by the anode and cathode electrodes flows into the nozzle throat. In this experiment, a nozzle diameter of 25 mm was employed. The operation conditions of the arc-heating facility in this study are presented in Table 1, which is used in the wind tunnel analysis described in Section 3.2. The inflowing gas was air. The arc-heated flow inside the nozzle during wind tunnel operation under these conditions was determined by Takahashi et al. [18, 19].

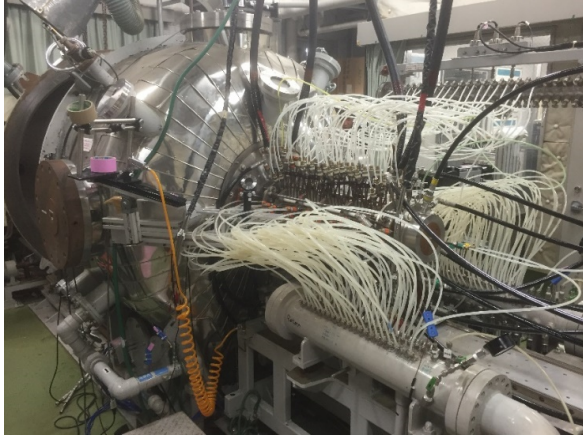


Figure 2: ISAS 1 MW arc-heating facility [10]

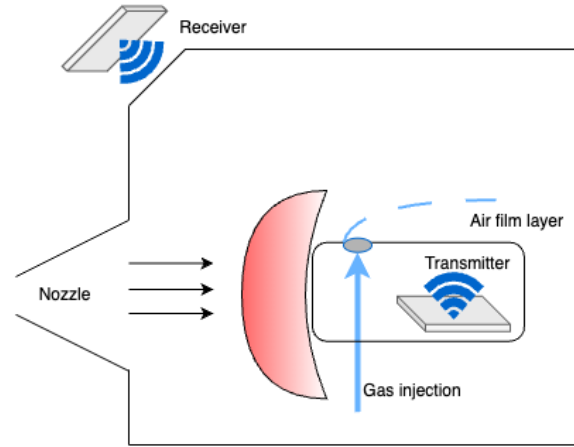


Figure 3: Experimental setup

Before initiating the arc discharge, the vacuum chamber is evacuated down to approximately 10 Pa. During operation, inflow gas is electrically heated using the arc heater and accelerated through the nozzle into the vacuum chamber. The chamber pressure is maintained at an average of 160 Pa to simulate reentry conditions.

An overview of the experiment is depicted in Fig. 3. The figure presents a schematic representation of the interior of the wind tunnel chamber during the experiment. Figure 4 shows the inside of the chamber. The experimental model equipped with a communication device was installed. A receiver located outside the chamber registered the history of the telecommunication quality. The pair of communication devices was set face-to-face. Plasma flow generated by the nozzle came into the chamber from the nozzle exit, which was depressurized to near vacuum conditions. This formed a shockwave in front of the experimental model. Owing to the high temperature behind the shockwave, ionization reactions of gas molecules and atoms occurred. This led to an increase in plasma density near the experimental model. Therefore, communication between the inside and outside of the chamber was cut off, reproducing the communication blackout phenomenon. In this situation, gas was injected from the experimental model and created an insulating film at the model's surface. Improvement in communication intensity under these conditions experimentally demonstrated the mitigation effect of communication blackout via gas injection. The distance between the experimental equipment and the nozzle exit was set to 150 mm. With a similar setup, this facility was used to conduct research on communication blackout mitigation with a concept focused on the catalytic properties of materials to promote the recombination of ionized gases [10]. The experimental model used in the wind tunnel experiment is shown in Fig. 5. The model was a cylinder made of copper with a diameter of 50 mm and a length of 80 mm. To withstand the high temperatures that were reached when the wind tunnel generated plasma, cooling water circulated inside the cylinder. The storage space for the transmitter was covered with a ceramic plate and insulation material to

Table 1: Operation conditions of the facility

Test gas	Air
Input current [A]	450
Mass flow rate [g/s]	18
Total temperature of inlet gas [K]	300

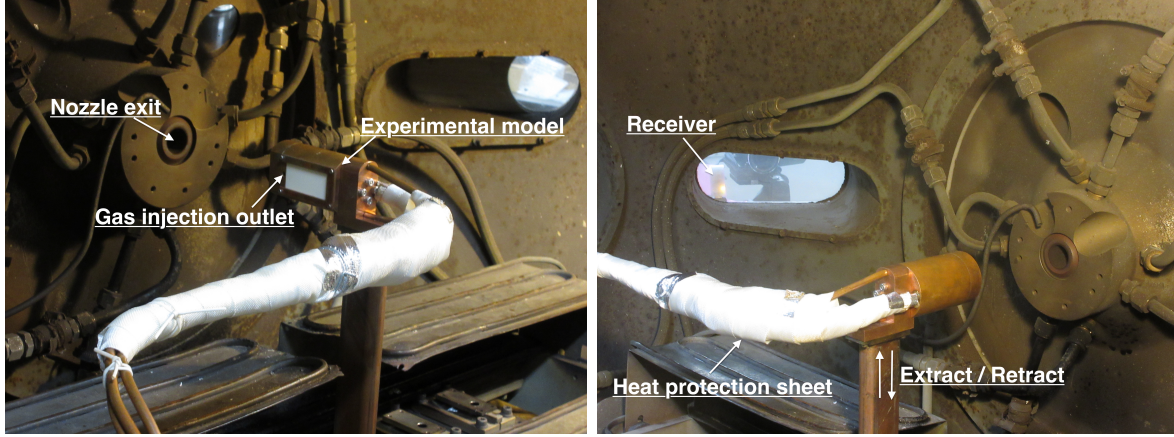


Figure 4: Experimental model in the chamber

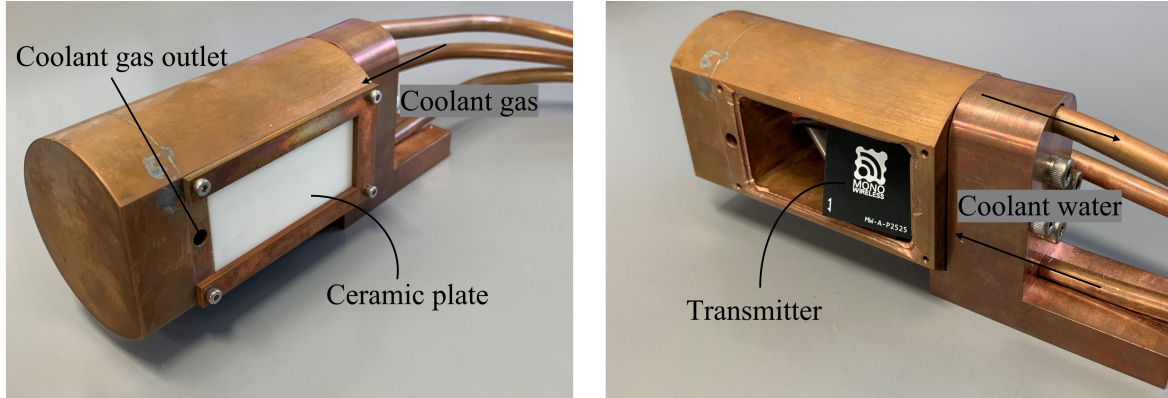


Figure 5: Experimental equipment

protect the transmitter from heat input. The gas injection section was located in front of the communication equipment storage space, and gas was injected from here through the interior of the experimental object. In this experiment, nitrogen gas was used as the injection gas at room temperature. The flow rate was regulated by a mass flow controller outside the wind tunnel and then introduced into the experimental model inside the chamber. The transmitter inside the experimental model communicated with the receiver outside the chamber at a frequency of 2.4 GHz.

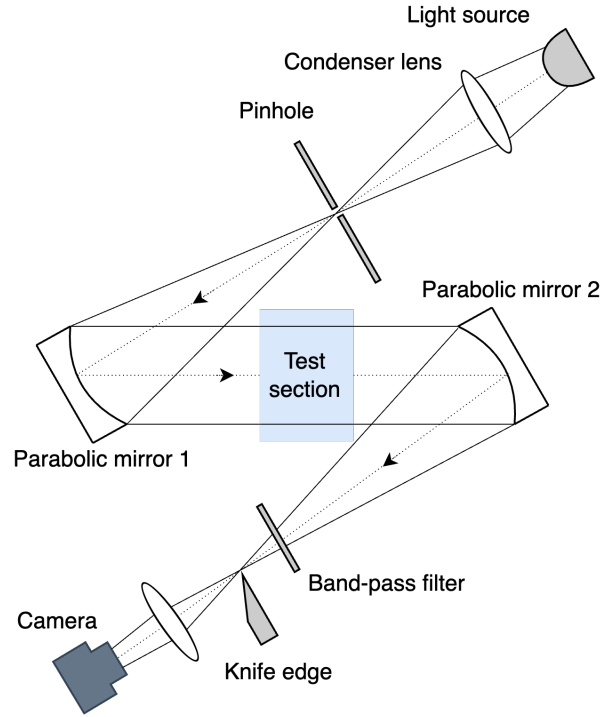
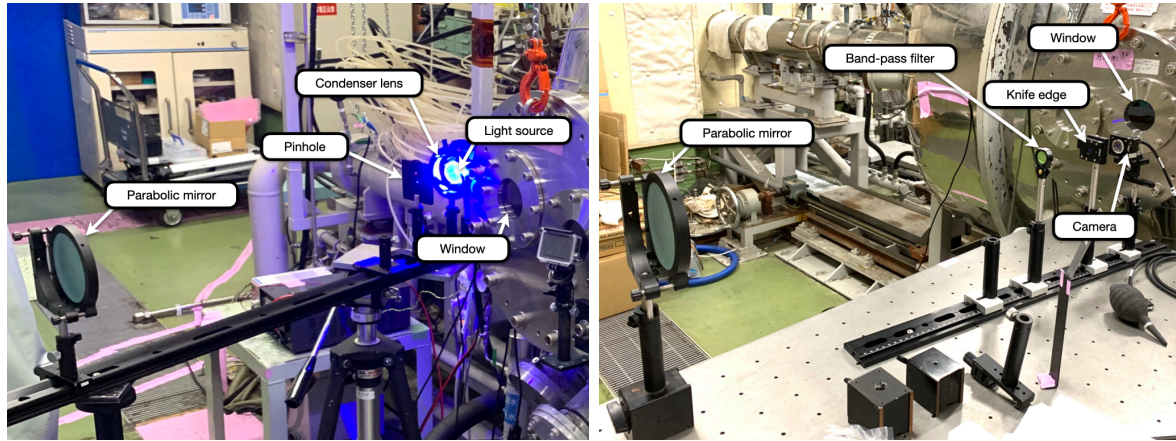


Figure 6: Schlieren imaging technique



(a) Light source side

(b) Camera side

Figure 7: Schlieren optical system

2.2. Schlieren photograph

An investigation was also carried out to visualize the injected gas inside the chamber. The Schlieren method was used to observe the density gradient created in the vicinity of the gas injection area by the injection of cooling gas. Figure 6 shows the arrangement of optical components necessary for visualizing density gradients using the Schlieren method. Using a convex lens, the light emitted by the light source is focused to bring it close to the point light source so that the light source forms an image near the pinhole shown in the figure. By making the pinhole smaller than the image of the

light source, the light intensity at the cross-section of the pinhole becomes uniform. However, the amount of light passing through the pinhole is reduced, so the image on the screen becomes darker and requires fine adjustment. The light rays passing through the pinhole are reflected by the concave mirror to form parallel beams. Given that the density gradient is obtained by refracting this collimated light within the observation area, the accuracy of the incident collimated light is important. After passing through the observation area, the light rays are again focused to a single point using a parabolic mirror and enter the camera through a bandpass filter and a convex lens. The bandpass filter prevents the flow emission from entering the camera. The light is partly blocked by a knife edge, and an illuminance image reflecting the density gradient of the flow field is displayed on the screen.

Figure 7 shows the installation of the Schlieren optical system around the wind tunnel. The knife edge was placed vertically to obtain the density gradient in the mainstream direction (horizontal) would be obtained. A blue LED with a center wavelength of 455 nm was chosen as the light source. The parabolic mirrors had a diameter of 102 mm and a focal length of 700 mm. A grayscale CMOS camera captured Schlieren photographs at a speed of 60 frames per second for 10 seconds. The amount of information per pixel was set to 12 bits. The target area in this experiment was the interior of the chamber, and the center of the field of view was 180 mm from the nozzle exit. The camera's optics were adjusted to capture the area above the gas jet when the experimental model was injected into the high-enthalpy air stream.

3. Numerical modeling

In this study, the flow fields inside the test chamber of the 1 MW arc-heated wind tunnel [20] were numerically investigated. This section briefly explains the physical and numerical models used to simulate the plasma flow field. The governing equations and physical models of the plasma flow calculations closely follow those used by Takahashi [21]. Detailed descriptions of the models can be found in the reference.

3.1. Plasma flow

The numerical analysis model described next was embedded in the solver RG-FaSTAR [21], which was designed for high-enthalpy flows. This software is based on FaSTAR [22], an unstructured mesh CFD analysis software developed by JAXA, with the addition of real gas effects.

The plasma flow employed in this study can be considered a laminar, steady, and continuum flow. The flow field is described by the Navier-Stokes (NS) equations, and the equation of state extended to thermochemical nonequilibrium flow. The compressible NS equation, which assumes an ideal gas, was composed of the total mass conservation law, the momentum conservation law, and the total energy conservation law. Considering thermal nonequilibrium flow, the temperature was modeled separately. In the arc-heated

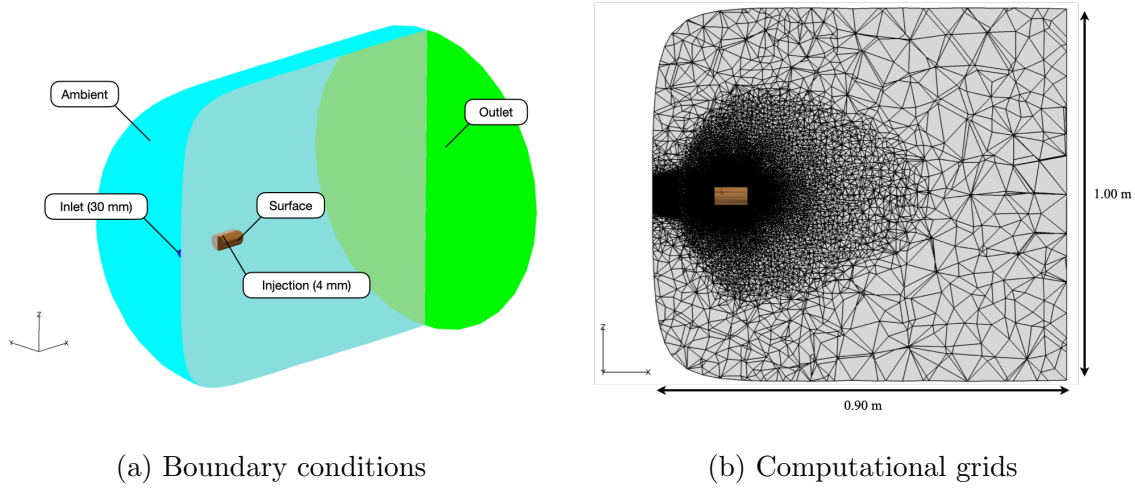


Figure 8: Computational domain for plasma flow simulations

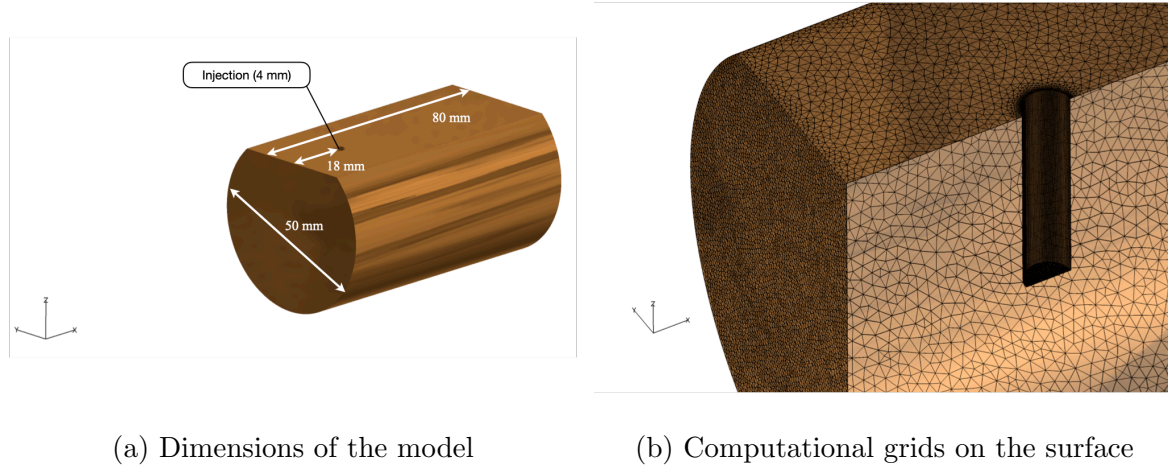


Figure 9: Experimental equipment for numerical analysis

wind tunnel used in this study, the relaxation times between translation and rotation, and vibration and electron temperature, were sufficiently short. The eleven chemical species in the air system (N_2 , O_2 , NO , N_2^+ , O_2^+ , NO^+ , N , O , N^+ , O^+ , and e^-) were considered to be described by chemical nonequilibrium and the mass conservation law of chemical species.

3.2. Calculation conditions

The analysis domain of the ISAS 1 MW arc-heated wind tunnel chamber is shown in Fig. 8. An unstructured mesh was employed for the analysis, and a hexahedral mesh was fitted near the experimental model boundary (Surface) and inlet boundary (Inlet), respectively. An enlarged view of the vicinity of the experimental model is shown in Fig. 9. It is the same design as that of the experimental model used in the wind tunnel test, featuring a cylindrical shape with a diameter of 50 mm and a total length

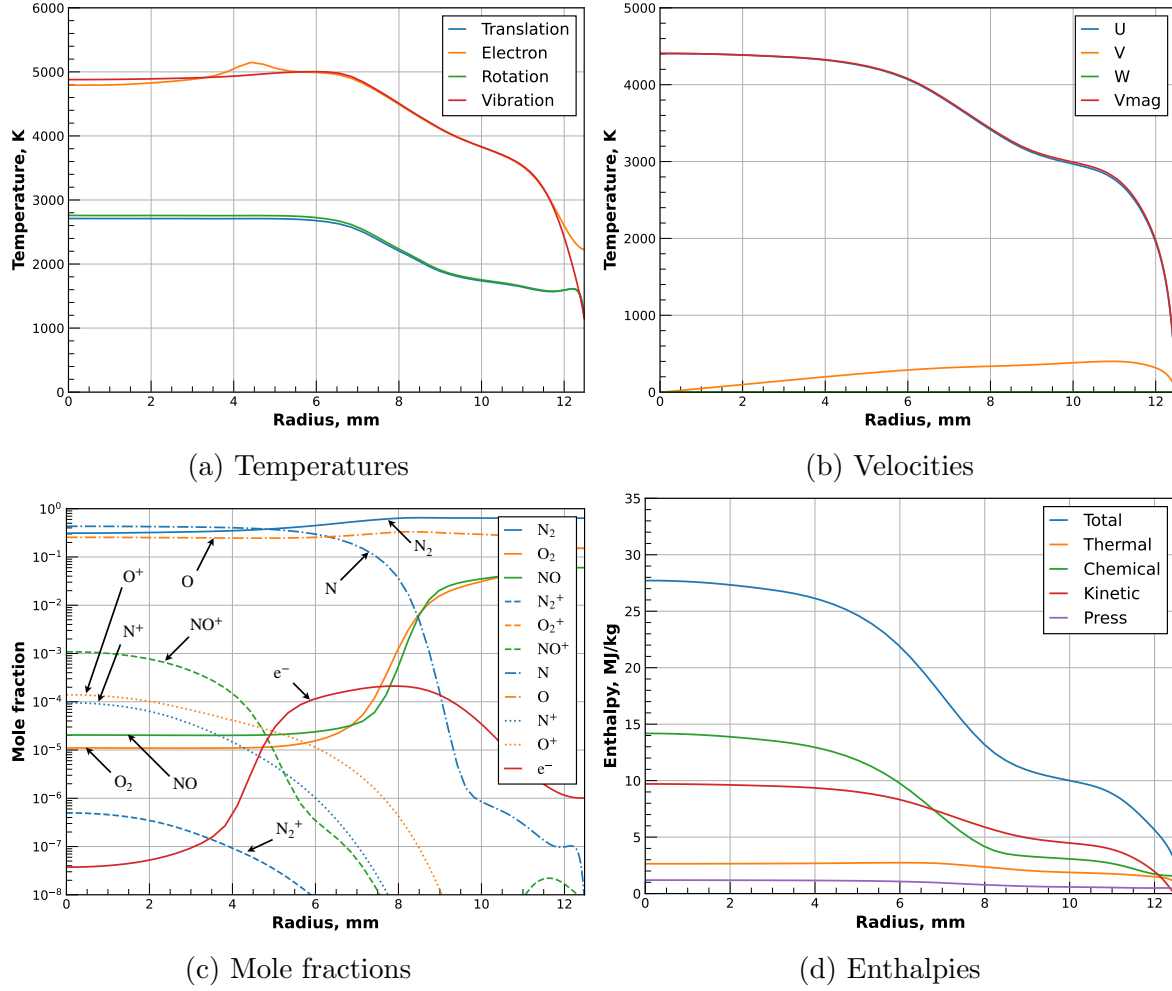


Figure 10: Radial distributions of the flow parameters at the nozzle exit

(x direction) of 80 mm. A 4 mm diameter gas jet was located on the central axis of the model. The gas jet was located 18 mm from the front of the experimental model, i.e., 168 mm from the nozzle exit. In this case, the experimental model was placed at a distance of 3 mm from the nozzle exit and on the centerline of the nozzle. The gas injection was located inside the experimental model, and hexahedral grids were created inside the model. The number of computational grids was 27.87 million in total.

The inflow boundary was obtained by Takahashi et al. [14] through arc-heated wind tunnel nozzle analysis. In this analysis, two-dimensional axisymmetry was assumed and four temperature models and eleven chemical species in the air system were considered. The radial distributions of temperature, velocity ($z = 0$), mole fraction, and enthalpy at the nozzle exit are shown in Fig. 10. U , V , W , and V_{mag} in the figure represent the x , y , z components of the velocities and the absolute value of the velocity, respectively. The large difference between the translational and electron temperatures indicates thermochemical nonequilibrium. Given that the translational and rotational temperatures and the electron as well as vibration temperatures are similar, it is

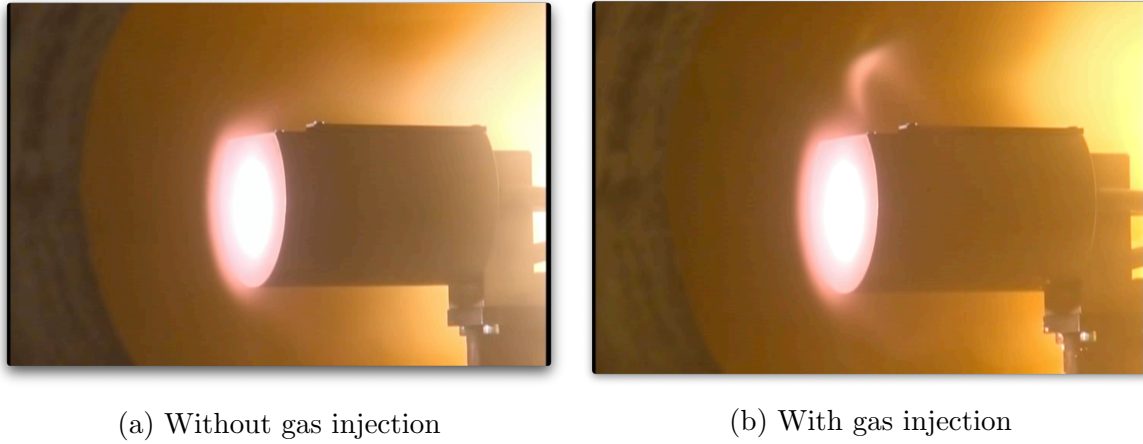


Figure 11: Experimental equipment in the arc flow

reasonable to adopt a two-temperature model for the analysis of the chamber. The velocity is dominated by the x component and the radial velocity component is almost zero. The blue, orange, and green lines in Fig. 10c describe the mole fractions of N (N_2 , N_2^+ , N, and N^+), O (O_2 , O_2^+ , O, and O^+), and NO (NO and NO^+) species, respectively. N_2 , N, and O were dominant. The ionized species were highly distributed near the nozzle center and decreased toward the outer side of the nozzle. This trend corresponds to the higher temperatures and enthalpies of the flow at the center of the nozzle. At the Outlet boundary, all flow properties were determined by zero-order extrapolation. The surface boundary was assumed to be an isothermal no-slip wall of 300 K. The Ambient condition was set as constant pressure of 10 Pa, isothermal temperature of 300 K, and flow velocity of 0 m/s. Concerning the gas inlet (Injection), the injected gas was N_2 at an isothermal temperature of 300 K. The mass flow rate was set by specifying the mass flow rate. In this study, five cases in total were analyzed with mass flow rates of 0.00, 0.25, 0.50, 0.75, and 1.00 g/s.

4. Results and discussions

4.1. Communication test

Communication tests were conducted using the ISAS 1 MW arc-heated wind tunnel. The arc heater was operated to produce a plasma flow with the communication device model retracted out of the nozzle center line. Then, N_2 gas was supplied at a controlled mass flow rate. After confirming that the gas flow rate had transitioned to a constant value, the experimental model was placed in the arc flow so that its center point was located on the nozzle center axis at a position 150 mm away from the nozzle exit. The experimental model was placed at the center of the chamber, exposed to the plasma flow for approximately 4 seconds, and removed from the flow.

The experimental model placed in an arc flow is shown in Fig. 11. The front surface of the experimental model shows an emission phenomenon, indicating that the shock

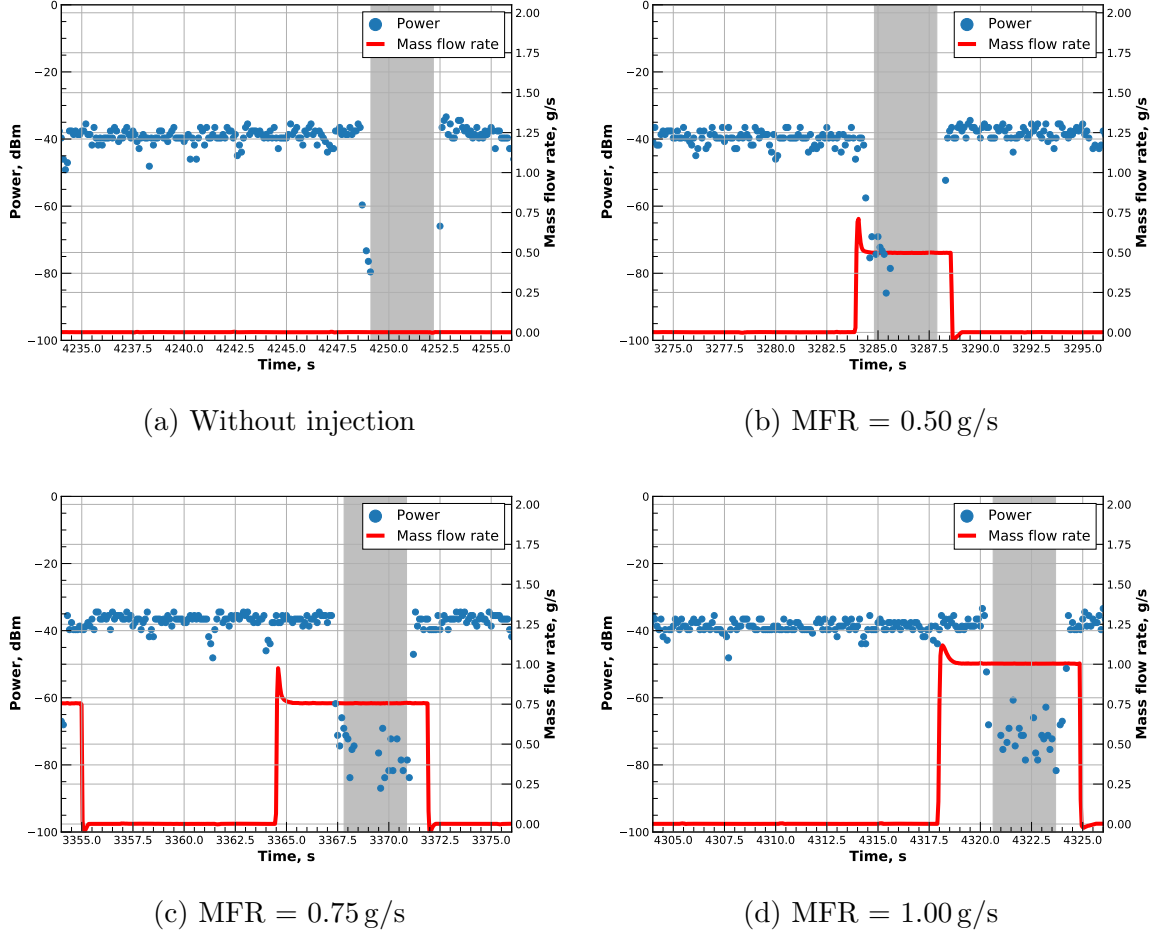


Figure 12: Communication intensity history

wave generated in front of the model caused the model to reach a high temperature. Comparing the results with and without gas injection, an emission region was observed near the top part of the injection port. This indicates that a high-temperature region existed near the boundary between the main flow and injected gas. This is because the main flow was prevented and compressed by the injection gas, which rapidly expanded toward the low-pressure region inside the chamber.

The time histories of the communication intensity are shown in Fig. 12. MFR stands for the mass flow rate of the injection gas (N_2). The horizontal axis represents the time since the start of the arc-heated wind tunnel operation, whereas the gray area represents the section where the transmitter was placed in the flow. The red traces in Fig. 12 represent the mass flow rate of the injected gas. The mass flow rate of the gas was held constant during the section in which the object was loaded into the arc flow. The transmitter transmitted at a rate of 10 times per second and good communication was ensured in all cases before being placed into the flow. In the case without the injection gas (Fig. 11a), the communication was cut off in this section. Thus, we can conclude that a communication blackout was created in the chamber. In contrast,

although there was a decrease in communication power intensity and communication frequency, data could be received even during the extract duration in the case of gas injection. The communication frequency increased with an increase in the mass flow rate of the injected gas. After the experimental model was released from the stream, communication was as good as before entering the stream in all cases. The above results experimentally demonstrate the reproduction of communication blackout phenomena in an arc-heated wind tunnel and the effectiveness of gas injection in mitigating blackout.

In actual reentry, the atmospheric pressure at an altitude of 80 km, where communication blackouts can occur, is 1 Pa, and at an altitude of 50 km, it is around 100 Pa. Therefore, the vacuum chamber pressure conditions in this experiment, less than 100 Pa, approximate the relevant atmospheric environment for blackout mitigation. The jet shape and surrounding plasma configuration depend on the ratio of the jet momentum to the ambient pressure. For the same jet injection conditions, the lower ambient pressure during reentry means the jet expands and penetrates farther from the vehicle surface compared to the wind tunnel case. To effectively mitigate blackouts, the injection angle must be controlled to promote the gas flow along the vehicle surface, creating an insulating air layer around the plasma sheath. The optimal injection angle may differ between the wind tunnel and reentry because of geometric effects.

4.2. Schlieren photography

Adding the communication test, Schlieren photographs were taken. The camera started to take images continuously right before the experimental model was put in the arc flow for 10 seconds.

Results of Schlieren visualization are shown in Fig. 13. The flow direction of the wind tunnel is from left to right in the figure. The experimental equipment masks the lower part of the view because it was introduced from the lower part of the figure. The partial shape of the shadow is observed in the area around the gas jet, which is supposed to result from high-density areas around the gas jet being visualized. An increase in the mass flow rate of the injected gas leads to a denser shadow of the jet shape, indicating a greater density difference with the surrounding area. These results suggest a distinct gradient in the density distribution ahead and behind the injection outlet. The jet gas expands toward the low-pressure region inside the chamber while accelerating, and the jet shape appears to lean rightward because of the main flow interaction. In addition, a clear Mach disk can be observed, especially in the case of high flow rates. The distance between the Mach disk and the model surface was significant when the jet flow rate, i.e., the momentum of the jet, was large. Vertical injection of gas relative to the main flow was studied by Papamoschou et al. [23]; the results obtained in this study are consistent with those reported by these authors. The shadow near the gas injection section was caused by a U-shaped lid used to secure the ceramic plate installed in the communication window of the experimental model, as shown in Fig. 5. The lid of the experimental model had a U-shape and did not cover its center. Moreover, it had no

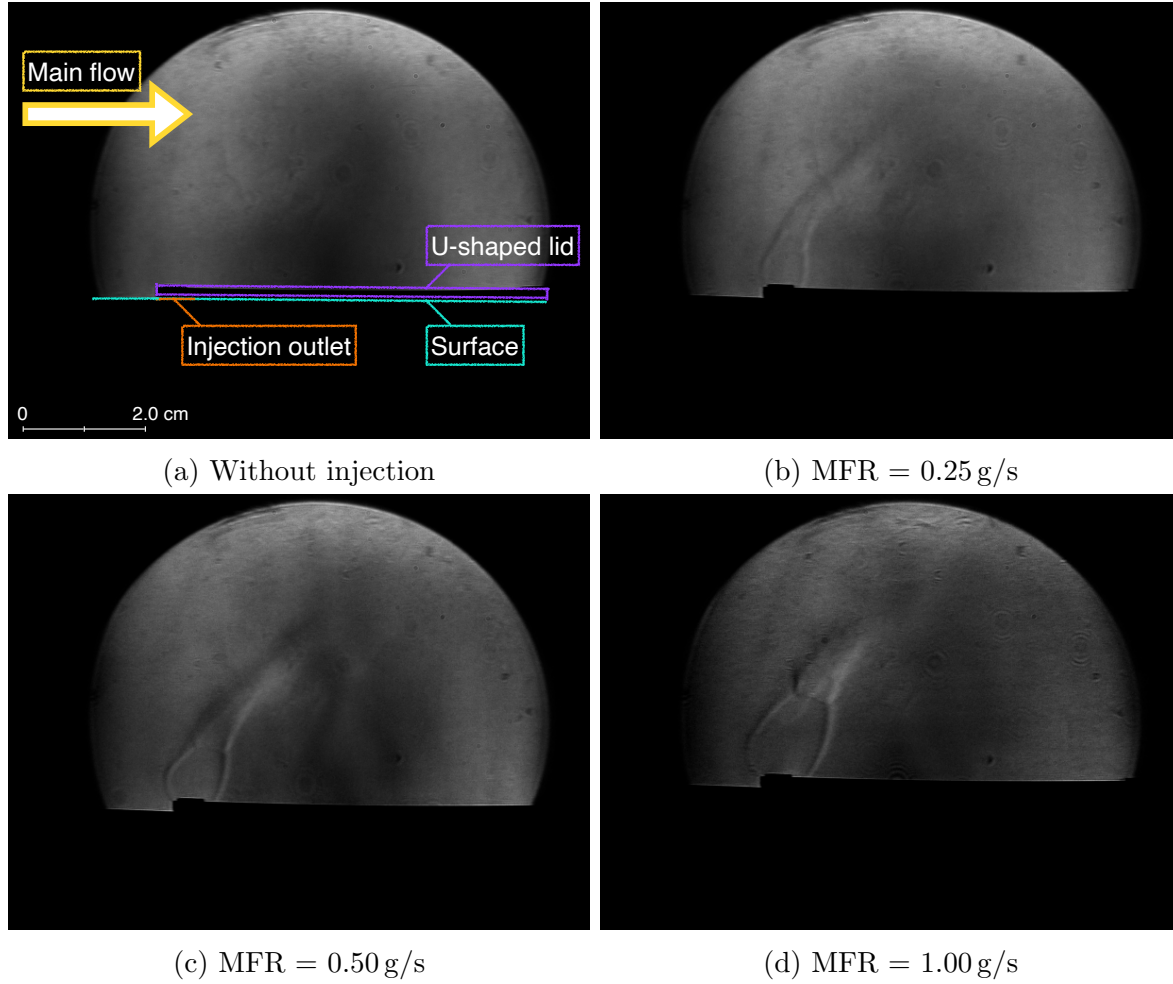


Figure 13: Injection gas visualization

impact on the area surrounding the gas injection section.

4.3. CFD analysis without gas injection

The Mach number distribution is shown in Fig. 14a and the translational temperature distribution in Fig. 14b. These distributions are at the center cross-section of the test section without gas injection.

The Mach number distributions indicate that strong shock waves were generated in front of the experimental model. In addition, there were regions of high Mach number regions at the top and bottom of the experimental model. These high Mach number regions were caused by supersonic expansion of the arc flow flowing into the low-pressure region inside the chamber. This temperature distribution is typical of arc-heated wind tunnels and is not observed during real atmospheric entry. The arc flow was compressed by the shock wave, resulting in a decrease in the Mach number behind it. The translational temperature distribution indicates that pressure of a high-temperature region exists at the front of the model. The region behind the shock wave

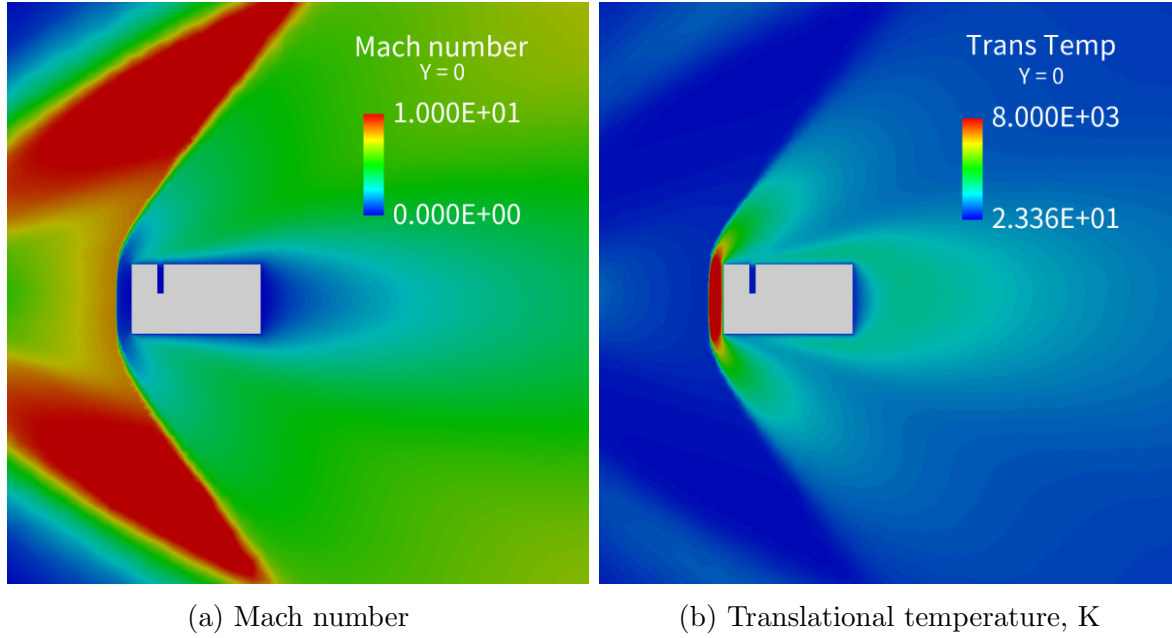


Figure 14: Flow distribution without injection

at the front of the equipment experienced an increase in temperature caused by the gas compression. Additionally, a minor temperature increase was observed behind the experimental model. This is caused by gas recompression. Furthermore, an emission phenomenon was observed at this location during the wind tunnel experiment. These findings suggest that the distinctive flow field of the arc-heated wind tunnel chamber can be replicated numerically.

4.4. CFD analysis with gas injection

The flow field near the wall of the equipment is shown in Fig. 15 for a gas injection of $\text{MFR} = 1.00 \text{ g/s}$. The mass fraction of N_2 in the channel was 1, which means that only N_2 was distributed inside the injection channel, whereas the surrounding arc flow and plasma were not distributed. The Mach number inside the channel was lower than 1 and increased toward the channel outlet, reaching 1 near the outlet. The gas injected from the equipment then rapidly expanded adiabatically, accompanied by the shock wave. This suggests that under-expansion occurred in the flow inside the nozzle. The Mach number, translational temperature, and density changed rapidly in front of the expanding jet gas, indicating the generation of a shock wave. This was due to the compression of the expanding jet gas by the high-speed arc flow. The present wind tunnel experiments confirmed the presence of emission phenomena at the shock wave location in front of the jet gas as well as in the frontal high-temperature region associated with the bow shock in the front of the experimental model. A large density gradient was observed before and after the gas injection area, which is consistent with the results of Schlieren imaging. The jet gas continued to expand adiabatically backward under the

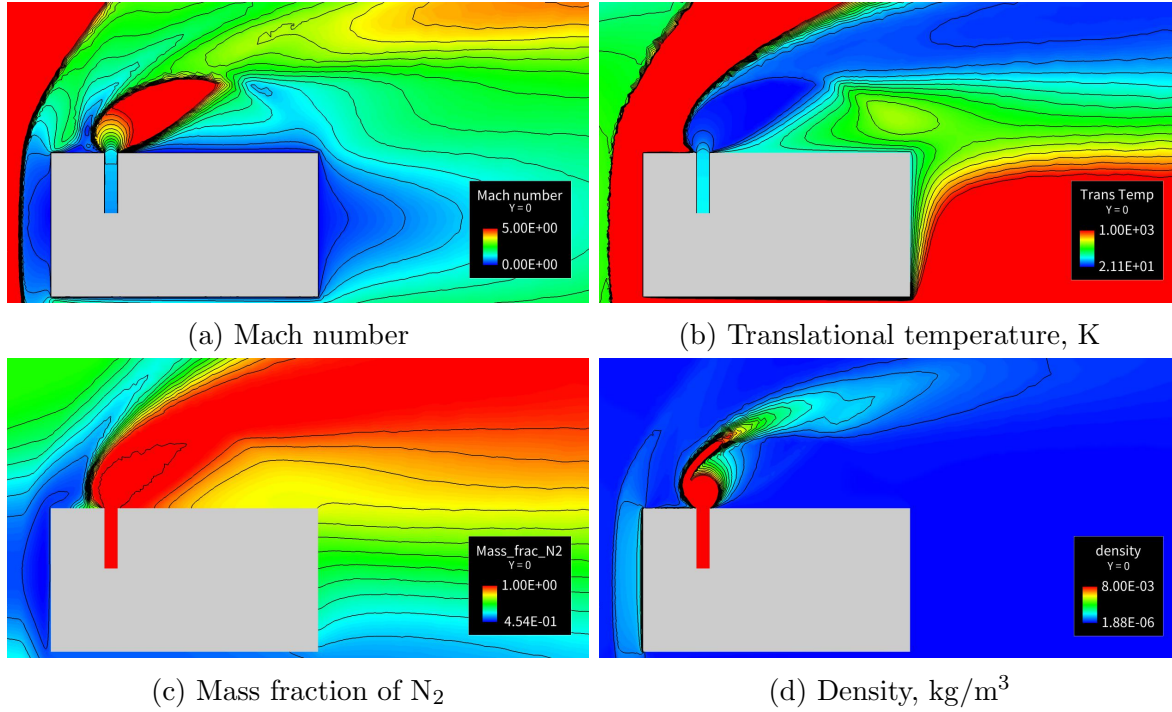


Figure 15: Flow distribution for 1.00 g/s injection rate.

The injected gas rapidly expands into the low-pressure chamber environment, creating a region of low temperature and a high fraction of nitrogen flow.

influence of the mainstream, resulting in a decrease in translational temperature and density observed in the wake. The local translational temperature was approximately 20 K, while the low pressure of N_2 means that it can be classified as a gas.

The temperature of the injected N_2 decreased owing to rapid expansion, and a low-temperature region was widely distributed above the model. Because the temperature of the injection gas remained low in the wake flow, chemical reactions were less likely to occur in this region. Therefore, it is concluded that the ionization reactions do not almost proceed even if the ratio of the injected gas, N_2 in our case, increases.

The distribution of electron number density is shown in Fig. 16 to evaluate the mitigation of communication blackout. The critical value expressed in Eq. 2 is the upper limit in the legend. When the electron number density exceeded this critical value, electromagnetic waves were reflected and could not propagate, resulting in the communication blackout represented by the red region of the figure. This figure demonstrates that gas injection gave rise to an electromagnetic propagation layer on the surface. Additionally, it confirms that the area where electromagnetic waves can propagate expands with an increase in mass flow rate.

Figure 17 shows the isosurface of the electron number density at the critical electron number. This figure shows that the electron number density on the side surface of the experimental model was reduced to less than the critical electron number density and that the electron number density was distributed three-dimensionally. This plasma-

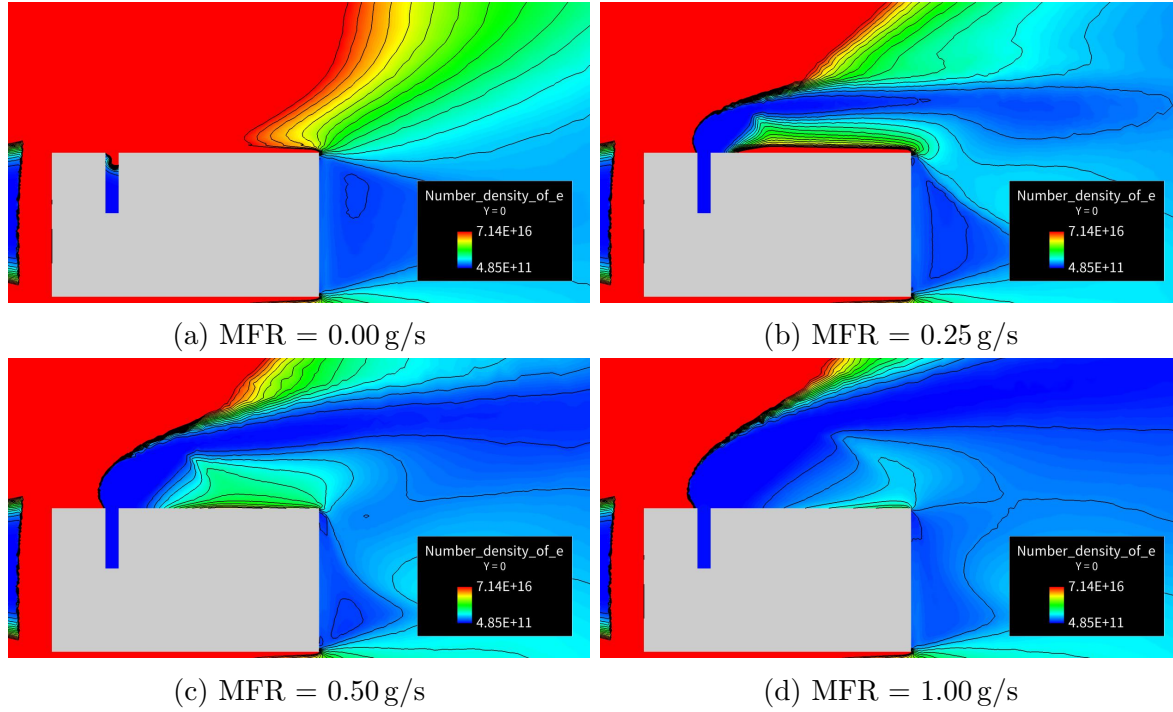


Figure 16: Distribution of electron number density, m^{-3} .

The injected gas is plasma-free, providing an electron-depleted path above the payload for the transmitter.

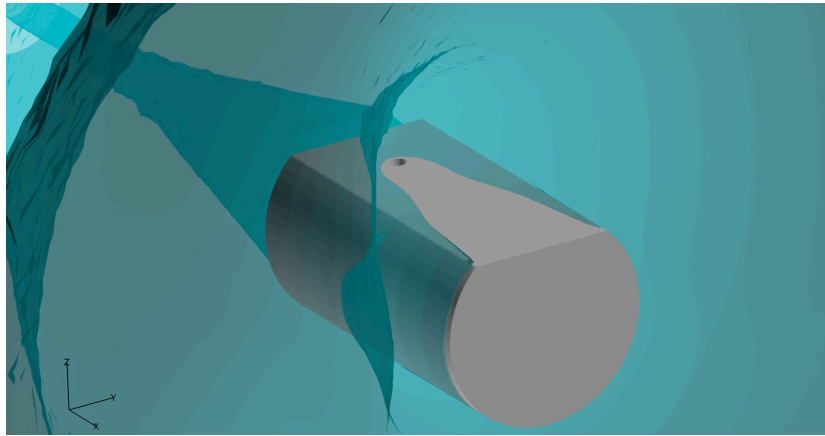


Figure 17: Isosurface of $n_{\text{ele, crit}}$ (MFR = 1.00 g/s)

free region was large enough to allow electromagnetic waves to pass through. Thus, communication blackouts were reduced via gas injection in the arc-heating facility.

The distribution of mole fractions of each chemical species on the upper wall of the experimental unit is shown in Fig. 18. The solid lines represent the results without gas injection, whereas the dotted lines represent the results with gas injection at MFR = 1.00 g/s. The port locations of the gas injection are represented by the gray areas. Ionic species and electrons increased at 140 mm from the nozzle exit, indicating the

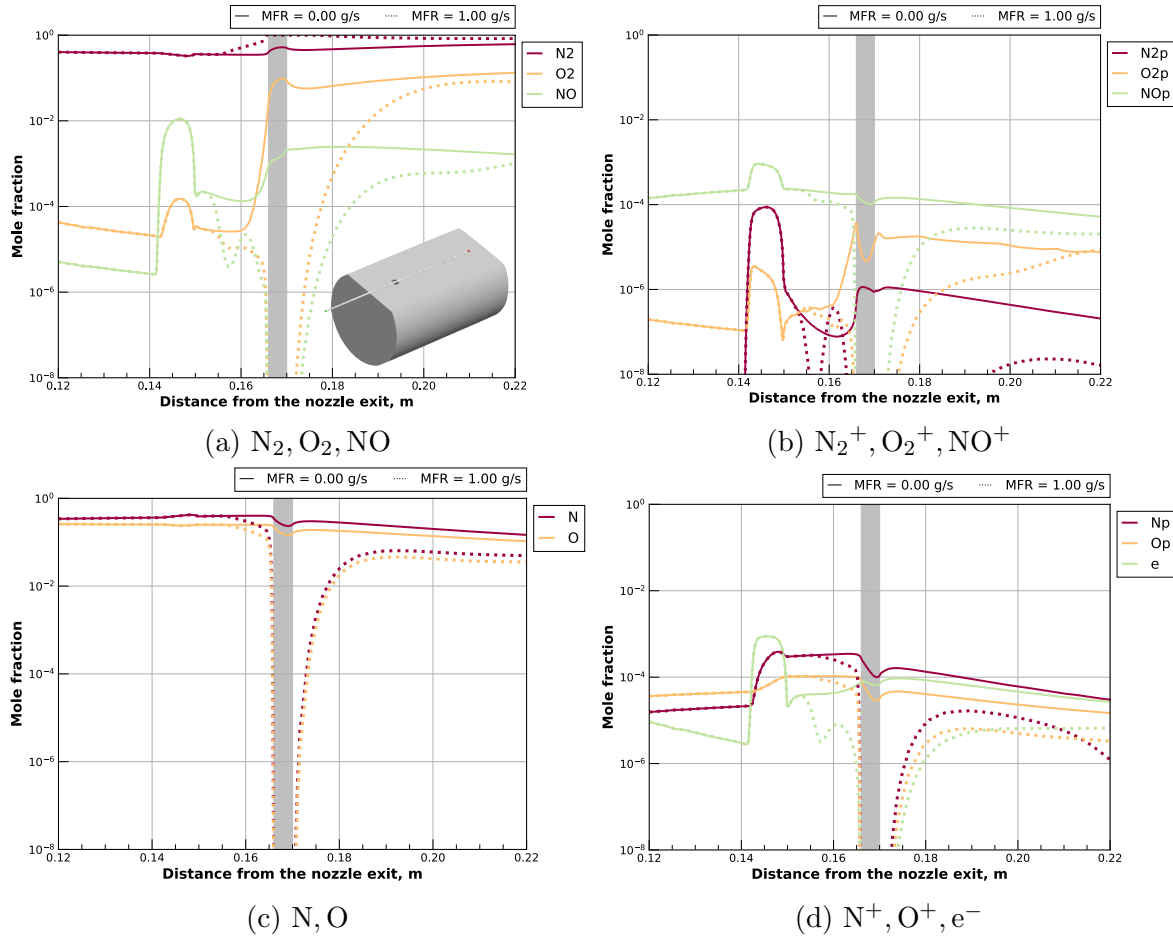


Figure 18: Molar fraction of chemical species

effect of ionization reactions behind the shock wave. In the vicinity of the gas injection area, the fraction of N_2 increased owing to the gas injection, while the fractions of other chemical species decreased. The effect of the gas injection was more pronounced in the region after 150 mm, where N_2 increased and the other chemical species decreased. A low plasma density region was formed near the experimental model due to the injected N_2 , which appeared to cover the model without ionization, as observed around 200 mm, where the communication antenna was located. In this region, the ratio of injected N_2 gas was approximately 1, indicating that the region where the ionization reaction did not occur extended to the wake. This was because the temperature inside the injection gas remained low, as shown in Fig. 15. The low temperature prevented the chemical equilibrium from shifting toward the generation of electrons as the mole fraction of N_2 increased, creating a plasma-free space inside the air film. This region constitutes a propagation path for communication.

It can be observed in Fig. 19 that the heat flux was reduced by the backward gas injection in the injection area. Given that the injection gas flowed at a low temperature owing to rapid expansion, an insulating layer was formed near the model wall. This thin layer of N_2 widely covered the upper surface of the equipment and kept the high-density

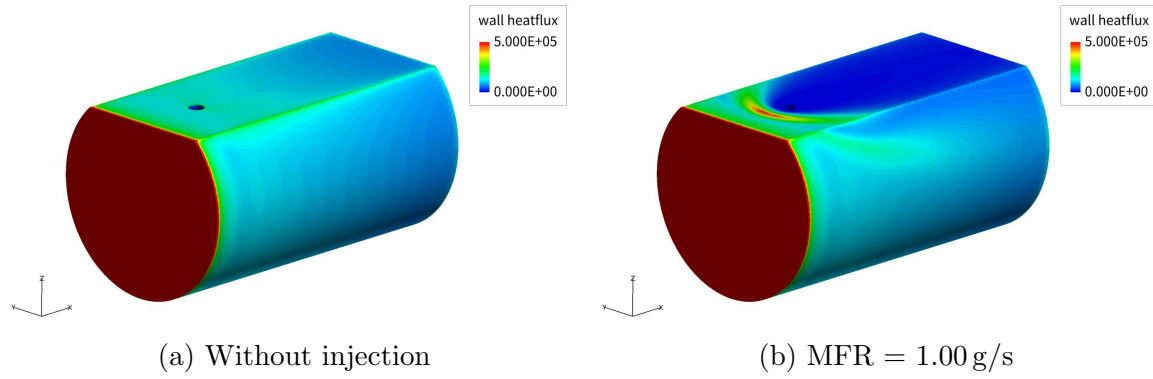
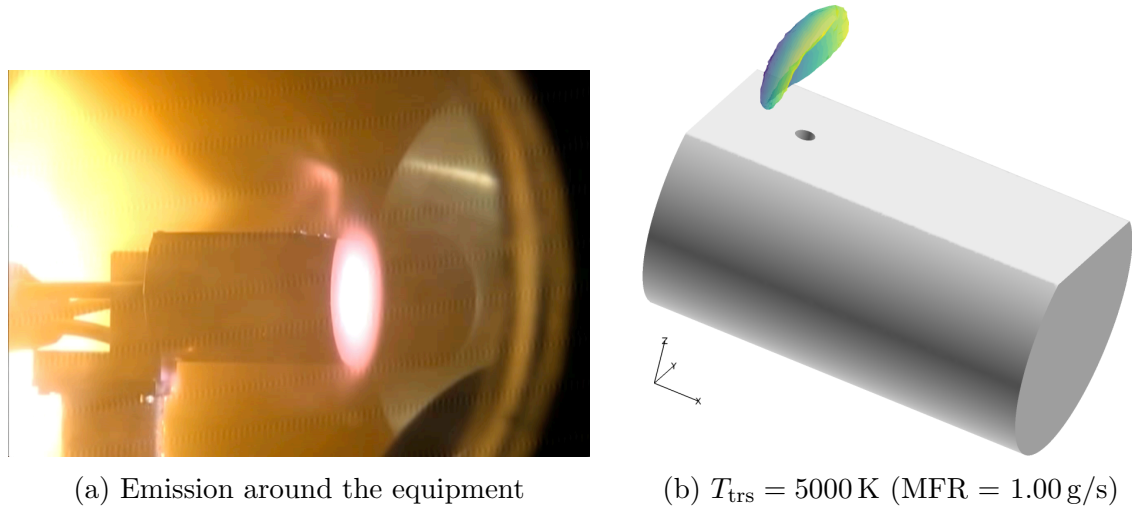
Figure 19: Insulating effect resulting the gas injection expressed in W/m²

Figure 20: High-temperature region at the front of the injection outlet

plasma away from the equipment. The antenna was located inside this layer, enabling electromagnetic waves to travel through the ambient.

4.5. Verification of computational results

A region with increased N_2^+ and electrons can be observed around 160 mm in Fig. 18d. This is the region where the main flow and jet flow interfered with each other. Both experiments and CFD confirmed that high temperatures occurred in this region, as shown in Fig. 20. This effect is also visible in the wall heat flux distribution of the experimental model. The large heat flux region in front of the gas jet was distributed in a bow shape by the gas injection; this is considered to be caused by the shock wave in front of the injected gas, as described above.

To further validate the numerical analysis results, the wall heat flux at the stagnation point of the experimental model was simultaneously measured using a Gurdon gauge during a communication test in the 1 MW arc wind tunnel. The results are shown in Fig. 21. Given that the nozzle flow was axisymmetric and the experimental

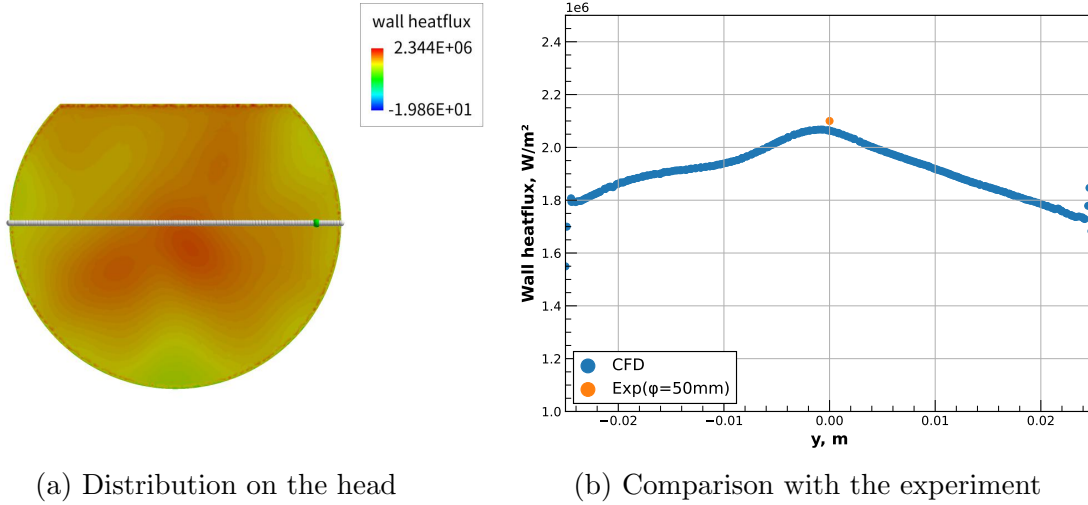


Figure 21: Wall heat flux obtained by CFD analysis, W/m^2

model was located on the nozzle center axis, the axisymmetric nozzle flow should have resulted in an axisymmetric distribution with a maximum value at the center. However, owing to numerical errors, the heat flux distribution was not smooth. The numerical analysis was conducted without gas injection. The maximum heat flux obtained from the numerical analysis and the experimental results are in good agreement.

5. Conclusions

The experimental demonstration of the effectiveness of gas injection in reducing communication blackouts was conducted using a large-scale arc-heated wind tunnel. Additionally, plasma flow analysis was performed inside the chamber. Compressible flow analysis software was used to investigate the effect of gas injection on the surrounding flow field assuming a steady and laminar flow.

In the wind tunnel experiments, a transmitter was placed in the test model, which was in turn placed in the arc flow, and communication was established with a receiver outside the wind tunnel. When gas injection was not applied, communication was interrupted in the section where the model was exposed to the arc flow, resulting in a communication blackout. However, communication was maintained when gas injection was applied. The experimental results indicate that gas injection is an effective method for reducing communication blackouts in an arc-heated wind tunnel. The Schlieren method was used to visualize the jet shape formed by the injected gas, and the Gurdon gauge was used to measure the wall heat flux at the stagnation point. These results were consistent with the CFD analysis.

The wind tunnel experiment was simulated using numerical analysis to clarify the effects of the gas jet on the surrounding flow field and to reduce the communication blackout. The temperature of the arc flow entering from the nozzle exit increased behind the impulse layer in front of the experimental model. Additionally, the plasma

density increased owing to the ionization and dissociation reactions of the gas. The experimental model was covered by high-density plasma, resulting in a communication blackout: the 2.4 GHz communication electromagnetic wave could not propagate. By injecting gas, a region of low plasma density was formed near the experimental model. In this region, the ratio of injected gas, N_2 , was close to 1, and the ionization reaction did not occur, extending to the wake. The mass flow rate of the injected gas affected the propagation path of electromagnetic waves. When the gas flow rate was increased, the communication intensity improved, indicating that the communication blackout could be reduced if a sufficient amount of gas was injected. The flow path of the injection gas inside the experimental model had a ratio of 1 for N_2 , preventing the backflow of the surrounding plasma flow. The gas jet expanded with a shock wave and was compressed where it interfered with the main flow, causing an increase in ion species due to the temperature rise. In the wind tunnel experiment, an emission phenomenon indicating high temperature was observed directly above the gas jet. The position and shape of the emission phenomenon were consistent with the high-temperature region observed in the numerical analysis. The gas that was injected continued to expand while being transported, resulting in the formation of a low-temperature gas layer on the sides of the experimental model.

The results suggest that implementing an air film can effectively decrease communication blackouts by providing a channel for the electromagnetic waves to propagate. Furthermore, it reduces local temperature increases. The numerical results are consistent with the experimental findings. In conclusion, both numerical analysis and wind tunnel experiments demonstrate that gas injection in arc wind tunnels can mitigate communication blackouts.

Acknowledgments

This study was supported by JSPS KAKENHI (Grant No. 17KK0123). The wind tunnel experiments were conducted at the arc wind tunnel facility provided by the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency as an inter-university research institute facility (Project ID: WA21-05, WA21-06, WA22-04, WA23-11). Numerical analysis was conducted using a compressible fluid analysis solver for unstructured grids (FaSTAR) developed by the Japan Aerospace Exploration Agency. This work used the computational resources of the supercomputer Fugaku provided by the RIKEN Center for Computational Science through the HPCI System Research Project (Project ID: hp210097, hp220007). The computations were performed using the computational facilities at the Research Institute for Information Technology, Kyushu University.

REFERENCE

- [1] Lehnert R and Rosenbaum B 1965 *NASA Technical Reports*

- [2] Rao Q, Xu G, Wang P and Zheng Z 2021 *Sensors* **21** 263
- [3] Rao Q, Xu G, Wang P and Zheng Z 2021 *International Journal of Antennas and Propagation* **2021**
- [4] Ouyang W, Jin T, Wu Z and Deng W 2021 *IEEE Transactions on Plasma Science* **49** 460–465
- [5] Belov I, Borovoy V Y, Gorelov V, Kireev A, Korolev A and Stepanov E 2001 *Journal of Spacecraft and Rockets* **38** 249–256
- [6] Kim M, Keidar M and Boyd I D 2008 *Journal of Spacecraft and Rockets* **45** 1223–1229
- [7] Kim M and Gülhan A 2011 Plasma manipulation using a mhd-based device for a communication blackout in hypersonic flights *Proceedings of 5th International Conference on Recent Advances in Space Technologies - RAST2011* pp 412–417
- [8] Steffens, L, Koch, U, Esser, B and Gülhan, A 2017 Characterization of weakly ionized argon flows for radio blackout mitigation experiments *EUCASS Book Series – Advances in Aerospace Sciences* vol 9 ed Array pp 335–348
- [9] Jung M, Kihara H, Abe K and Takahashi Y 2017 Numerical simulation of plasma flows and radio-frequency blackout in atmospheric reentry demonstrator mission *47th AIAA Fluid Dynamics Conference, 2017* (American Institute of Aeronautics and Astronautics) ISBN 9781624105005 (Preprint <https://arc.aiaa.org/doi/pdf/10.2514/6.2017-3308>)
- [10] Takasawa H, Takahashi Y, Oshima N and Kihara H 2021 *Journal of Physics D: Applied Physics* **54** 225201
- [11] Takahashi Y, Yamada K and Abe T 2014 *Journal of Spacecraft and Rockets* **51** 430–441
- [12] Good R E and Rossi J J 1966 An injection system for alleviation of radio blackout during re-entry Tech. rep. National Aeronautics and Space Administration URL <https://api.semanticscholar.org/CorpusID:91542131>
- [13] Lee J I, Kim C and Kim K H 2007 *Journal of thermophysics and heat transfer* **21** 67–76
- [14] Takahashi Y, Enoki N, Koike T, Tanaka M, Yamada K and Shimoda T 2021 *AIAA Journal* **59** 263–275
- [15] Esser B, Gülhan A and Kuhn M 2007 Thermal qualification of transpiration cooling for atmospheric entry *Proceedings of the 1st CEAS European Air and Space Conference* pp 3205–3210
- [16] Gülhan A and Braun S 2011 *Experiments in Fluids* **50** 509–525
- [17] Miyashita T, Takasawa H, Takahashi Y, Steffens L and Gülhan A 2024 *AIAA Journal* **62** 437–448 (Preprint <https://doi.org/10.2514/1.J063254>) URL <https://doi.org/10.2514/1.J063254>
- [18] Takahashi Y, Kihara H and Abe K 2010 *Journal of Physics D: Applied Physics* **43** 185201
- [19] Takahashi Y, Kihara H and Abe K 2011 *Journal of Physics D: Applied Physics* **44** 085203
- [20] Yamada T and Inatani Y 2003 *The Institute of Space and Astronautical Science report. SP: Aerodynamics, Thermophysics, Thermal Protection, Flight System Analysis and Design of Asteroid Sample Return Capsule* **17** 147–163 ISSN 0288-433X URL <https://cir.nii.ac.jp/crid/1050848249892146816>
- [21] Takahashi Y 2015 *Journal of Physics D: Applied Physics* **49** 015201
- [22] Hashimoto A, Murakami K, Aoyama T, Ishiko K, Hishida M, Sakashita M and Lahur P R 2012 *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition* 1075
- [23] Papamoschou D and Hubbard D 1993 *Experiments in Fluids* **14** 468–476