The Institute of Space and Astronautical Science
Report No. 664, March 1996

An Arc-Heated High Enthalpy Test Facility for Thermal Protection Studies

By

Motoki HINADA, Yoshifumi INATANI
Tetsuya YAMADA and Koju HIRAKI

(February 15, 1996)

ABSTRACT: A high enthalpy flow facility primarily for the high-temperature-resistant material research and for experimental studies on high temperature gas dynamics is built in ISAS, taking into account the demand for the application to the reentry vehicles. The facility is composed of Huels-type arc heater and necessary subsystems for power supply, water cooling, evacuation and operation/control. After briefly describing the facility, characterized facility performance and flow conditions for the heating test purposes are presented. It demonstrates the planned simulation capability, in terms of heating and impact pressure, which ranges 0.1 to 5 MW/m^2 of heat flux and 10 to 100 kPa of impact pressure by two operation configuration of vacuum and open-to-air condition. Equipped measurement instruments for various needs both for material testing and studies of aerothermodynamics including state-of-the-art optical and laser diagnostics are also outlined.

1. INTRODUCTION

Since no similarity law is valid in the flow in total and flow-wall interaction in terms of thermal and chemical kinetics and response of the material contacting the flow, particularly for the application to estimating the aerodynamic heating, and to the thermal protection materials and systems of the vehicles which fly with hypersonic speed in the atmosphere, flight conditions in terms of the flow enthalpy, temperature of the wall surface, impact pressure, and so on, are to be simulated by the ground-based test facilities as close as possible to those of the real flight.

Flow enthalpy necessary for the hypersonic aerodynamics of the reentry application, for example, is as high as 30 MJ/kg and more for the entry flight from earth circular orbit. This value is never obtained by giving heat into the working gas by combustion or electrically resistant heating[1,2]. Thus, among many existing high enthalpy flow test techniques, arc-heater is the unique solution for the evaluation of the material's durability for the thermal protection purposes, simply because of its continuous flow generation capability and higher enthalpy. Hypersonic shock tubes and / or tunnels gives much more ideal flow condition than that, however the high speed flow by

* Permanent address:

these techniques does not last long as it is by the arc-heater. These are used primarily for the detailed aerodynamic analysis of the flow quality such as thermal and chemical non equilibrium processes, validation of reaction kinetics and so on.

An increasing demand for the planetary exploration in the Institute of Space and Astronautical Science (ISAS) lately provides aerodynamicists and material researchers with flight opportunities of high speed atmospheric flight such as planetary entry flight and returning flight to the earth from outer space. New launch system M-V of ISAS[3] dedicated to these scientific exploration makes it possible to conduct these missions in the late 1990s and beyond the year 2000. In these new ventures, both the better understanding of flight environment and flow characteristics, which these vehicles encounters and being surrounded, are called for. In addition, the materials, which covers the vehicle, durable under these extreme flight condition particularly from the thermal protection point of view, are crucially needed.

Micro-gravity environment utilization and various experiments utilizing space environment require to take these space products back to the ground. It also offers the opportunity to conduct atmospheric reentry flight of these returning vehicle. EXPRESS[4] is one of the example of the mission pioneering and establishing the autonomous in-orbit experiment flight facility. The flight condition and environment of the returning flight of these vehicles are different by their mission requirements, the size, weight and shape of the vehicle and so on, however, for the sake of simplicity in building these vehicles together with those designed for the planetary missions, the vehicles sometimes employ the simple axisymmetric capsule geometry which performs ballistic entry flight. The flight environment encountered by these capsules is inherently harder in terms of the heat flux on its surface and impact pressure during its returning flight than those encountered by the lifting entry vehicles.

Figure 1 summarizes the variety of the flight conditions of these vehicles' stagnation point for the missions mentioned above, where these mission studies were assuming that the spacecraft is launched by the M-V equivalent launch system. Therefore this presentation is not always valid for any other mission, however, it is seen that the flight condition varies widely in terms of the heat flux and impact pressure at the stagnation point.

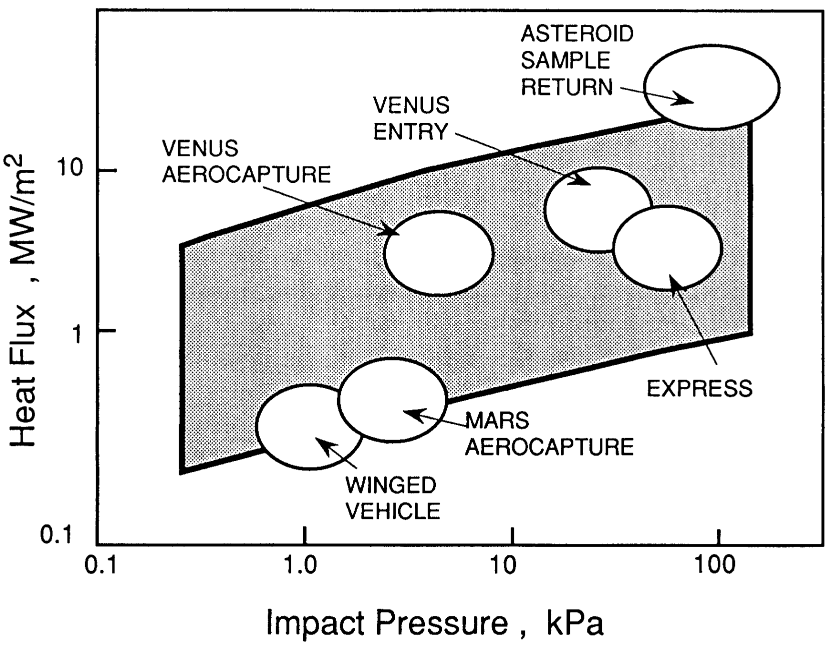


Fig. 1 Flight Environment Summary

From view point of the heat shield or thermal protection materials used for these vehicle, requirement for demonstrating its durability differs each other with respect to the selection of the type of the heat shield material, such as ablative ones, reusable radiation cooling ones, and so on. The ablative materials which are primarily used for the returning capsule from the orbit or planetary entry capsule are those composed of either the phenolic, epoxy or silicon resin with the reinforcement by high-temperature-resistant fiber or fabric materials. The response of these materials under the reentry heating is dominated by the heat flux and the temperature of the surface itself. However, when talking about the surface recession, for instance, which is the critical design parameter of these ablative materials, two types of the recession mechanisms; chemical and mechanical ones, must be taken into consideration. Therefore, the importance of simulating the impact pressure, which sometimes would be a driving parameter for the mechanical recession, should be recognized together with simulating the heat flux.

On the other hand for testing the reusable thermal protection materials, like a carbon-carbon composite and ceramic materials, for example, simulation difficulties on the gas composition for estimating the surface chemical reaction and/or catalytic effects would take place and would play a dominant role other than simulating the heat flux and the surface temperature of the material. As is seen by these examples, any kind of ground-based test facility never satisfies a perfect simulation requirement, and giving the priority in choosing a set of essential and the most influential simulation parameter is a key issue in planning these tests.

Even an arc-heated high enthalpy gas source never gives a perfect simulation test environment, too, because of its mechanism in giving energy to the working gas in which the gas molecules are highly dissociated and ionized already before applying it to the test piece of these materials. This is not a special character of the arc-heater and all the high enthalpy test facility can not avoid it, except the ballistic range which accelerate the test piece itself instead of giving heat into the working gas. Thus, for the application of the high enthalpy gas sources to the high-temperature-resistant material's evaluation for the thermal protection purposes, so many design considerations must be taken. In the selection of the heater type and design of the present facility, to simulate heat flux and impact pressure which will be encountered by the missions presented above was conducted.

In addition to these material's studies, reentry aerodynamics and/or high temperature aerothermodynamics view point is another important issue both for the design of the entry vehicles and for the estimation and measurement of the test environment. As stated above, the environment of the real flight and the test conditions by these high enthalpy facilities can never be the same, and knowing this difference is quite important. On the one hand, recent advancement in the numerical prediction technique has made it possible to "simulate" numerically the nonequilibrium high temperature gas flow such like an expanding nozzle flow and flow around the body with strong shock wave near its stagnation region[5]. Optical diagnostics and/or laser diagnostics technique is to be matured, on the other hand, and it also make it possible to "measure" some of the important flow characteristics such as species concentration, temperature of vibrationally excited species and many other state variables of the high enthalpy flow[6,7] A comparison between these results will lead to the enhancement of the knowledge about the phenomena taking place in the flow of concern and giving correct information about the test environment applied to the material to be tested.

Although one facility can never cover up all the experimental requirement from the related study activities, the arc-heated test facility primarily for the purpose of the material studies were built, and necessary studies for the high temperature gas dynamics of the present concern described above and studies for related state-of-the-art measurement technique is underway by utilizing this facility in ISAS. In the following part of this report, description of arc-heater, whole facility and equipment' outline and a summary of the measured and characterized facility performance and equipped measurement systems are presented, as an introductory information of the facility.

2. HIGH TEMPERATURE GAS SOURCES

Various types of high temperature gas sources are existing for the reentry flight simulation purpose. There are many possibilities in the arrangement and the shape of electrode in DC arc-discharge heater and others. Figures 2 and 3 summarizes four of typical high enthalpy flow generators and their simulation envelope in this category which are capable of generating enthalpy high enough for the reentry application; segmented heater , constrictor-type heater, Huels type,

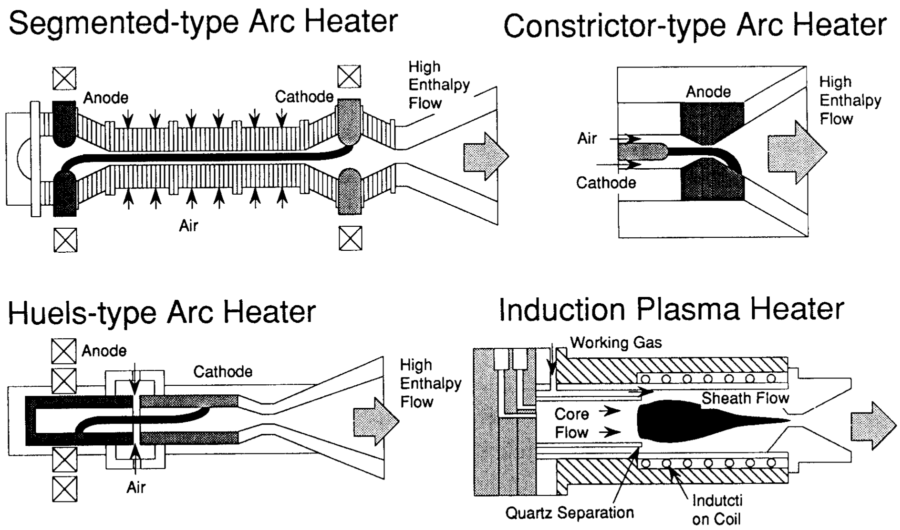


Fig. 2 Various Types of High Enthalpy Flow Generators

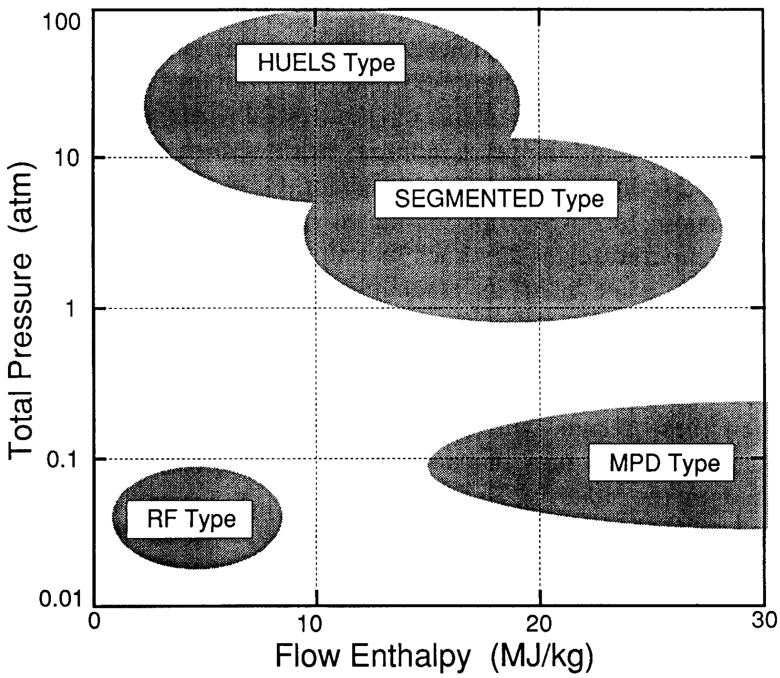


Fig. 3 Operation Envelope of Various Types of Arc Heaters.

and high-frequency induction heater. There are also many derivatives from these types of heater.

The segmented heater is often used for the heating facility with relatively higher enthalpy. It is a fixed-arc-length operation heater and arc-column between cathode and anode on both ends of the heater assembly is maintained by a series of electrically insulated cylindrical segmented disks in which each unit disk keeps about 30 to 40V of voltage potential gradient, and a several tens of disks in line enables a high voltage operation of the heater system. Working gas is injected through insulators between disks and each segmented disk is water cooled individually. It is normally giving heat into gas as much as 20 to 30 MJ/kg of enthalpy [8]and several tens of Mega-watt facilities have been built and operated for the reentry vehicles' heating objectives in the US.[9]

The magnetoplasmadynamic (MPD) generators are developed as a derivative of those for the application to the electric propulsion.[10,11] The arc discharge is stabilized between the tip of the cathode rod and the anode nozzle throat called "constrictor". Although the arc attachment point at the cathode is fixed, that at the anode is still free with diffusive mode. Since the working gas is expanded through the nozzle soon after heated, the specific enthalpy is extremely high over 30 MJ/kg. The plenum pressure is, however, much lower than any other heaters. In order to decrease the contamination due to the electrode erosion, several methods are tried such as tangential argon injection at the diverging section of the anode.

Huels heater[12] is that of free length arc-column between tube shaped cathode and anode facing each other. Working gas is injected into the arc chamber formed by these two electrodes from the gap between them. The anode side arc end is rotated and stabilized by magnetic field. The length of the arc-column becomes its electrically balanced length automatically with respect to the operating conditions such as the pressure inside the arc chamber and the discharge current, e.g. the higher the pressure is, the longer the arc column is. The highest pressure facility ever built reported is that of 20 MPa[13]. Thus, this type of heater could have a wider range of operation envelope and higher pressure operation is possible by relatively simple assembly configuration as compared with the segmented heaters, however the flow enthalpy of the Huels heater is lower than that. A derivative of electrode arrangement such as two anode and cathode facing in triangular accommodation is existing, and a combination of Huels / segmented ones (hybrid type) is also proposed.

Instead of giving heat into working gas by DC arc discharge, an induction heating technique by high frequency current circuit or micro-wave heating is used and studied. [14,15]These types of high enthalpy gas sources would have a potential to produce contaminant-free high temperature gas which is not achievable by DC discharge arc heaters due to the erosion of its electrodes. This could be beneficial to those who studies detailed surface chemistry under highly heated conditions on the material surface. In addition, the heating itself is made in wider region of the space inside the coil for induction, a peaky heating as it is done in the DC arc column could be avoided, and the heated gas composition might be expected to be identical to those estimated by simple equilibrium flow assumption. For the same reason, it is also expected that it could be maintenance free while those in the rest of the heaters presented here needs replacement of some parts frequently. As far as reported performance of these heaters are concerned, it has relatively low thermal efficiency including that of electrical energy conversion for high frequency and the achieved enthalpy is lower than those of DC arc heaters.

Since the present concern is to simulate the various combination of flight condition of heat flux and impact pressure as stated in the previous section, an in-line-arrangement Huels heater is chosen for the facility, primarily due to its wide range of operational capability in terms of pressure and heat flux to the model to be tested, and due to the simplicity in its construction, operation and maintenance.

3. OUTLINE OF THE FACILITY

3-1. Facility Subsystems

In the construction of present heating facility, 500 kW class of Huels-type heater and associated subsystems such as DC power supply, evacuation systems, cooling systems, working gas supply systems, and operation / control systems were designed. This was done by the requirement for the heating demand presented previously; a range of test condition in Fig. 1 to the front surface of 30 mm-diameter cylindrical-shaped test piece to be heated. Since one nozzle set up in terms of its expansion ratio can not afford the whole simulation range presented in Fig. 1, a low expansion nozzle for the high heating and high impact pressure test condition, and a high expansion nozzle for the lower heating and impact pressure condition is planned to be prepared. When operated with the smaller nozzle, heating test is done at one atmosphere. Table 1 summarizes the facility subsystems.

Figure 4 shows the whole facility system block diagram. The primary input power is converted from standard 6600V AC to 1000V DC to be supplied to the heater. The working gas is supplied directly by standard bottles, regulated by the control console in the operation room and is injected into the heater. Evacuation system is composed of jet catcher and diffuser, heat exchanger for cooling down the heated gas and vacuum pump systems. The heater and other subsystems are water-cooled. Demineralized closed cooling loop for the arc-heater is equipped and the heat exchanger extracts the heat from the demineralized water cooling loop and dump it by cooling tower together with the heat from other subsystems. All the subsystems are capable of continuous operation. From the control console in the operation room, the operation of all the subsystems together with the measurement and record is to be made.

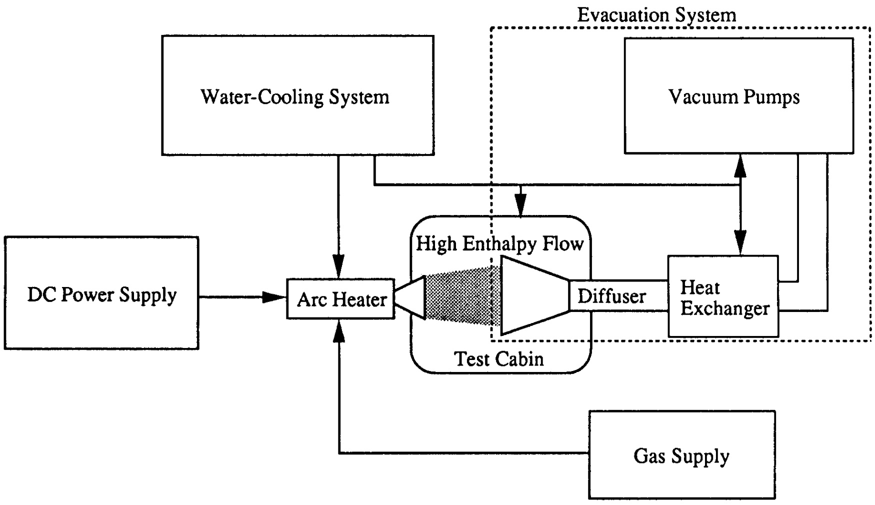
3-2. Arc-Heater

Figures 5 and 6 present the cross sectional view and the outlook photograph of the present Huels-type arc heater. As described briefly in the previous sections, it has two facing electrodes made of oxygen-free copper. Internal diameter of the cathode is 11 mm and 17 mm for anode. At the down stream of the cathode, a throat and small expansion nozzle block, which alone is used for the open-to-air operation, is fixed. Nozzle extension for highly expanded flow is added for the vacuum operation. Each part such as two electrodes, nozzle throat and nozzle extension is individually cooled by demineralized water and fixed up by the outer body cylinder.

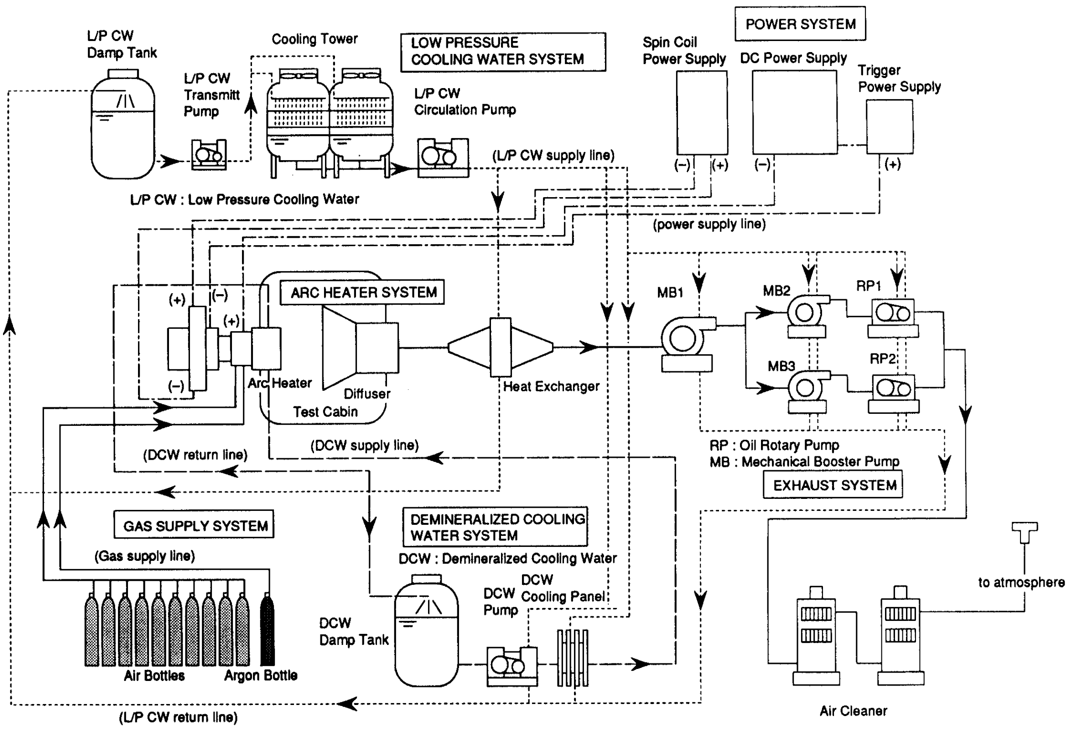
The working gas to be heated is injected through the gap between two electrodes as shown in the figure. Gas injection ports are tangentially tilted to form the swirl flow in the arc chamber. Spin

Table 1 Facility Subsystems

Arc Heater Systems	Demineralized Cooling Water System
• Huels-type Arc Heater	• Demineralizer
• Nozzle Options	• Circulation Pump
	• Damp Tank
	• Radiation Panel
Evacuation Systems	Low Pressure Cooling Water System
• Diffuser	• Transmission Pump
• Heat Exchanger	• Circulation Pump
• Vacuum Pumps	• Cooling Tower
• Air Cleaner	• Damp Tank



(a) System Block Concept



(b) System Block Diagram

Fig. 4 Arc Wind Tunnel Facility

coil is assembled at anode part. It fixes the anode-side end of the arc-column position and rotate the foot of the arc to make even the damage by erosion on the inner surface of the anode. At the ignition of the heater, the initial arc discharge occurs at the gap between two electrodes, as its detail is described in the later sections. Therefore, in order to avoid the damage by unexpected discharge onset at the parts and elements around the gap, heat insulating ring made of ceramics is fixed at the open end of the anode. A set of major dimensions and specifications of the heater is presented in

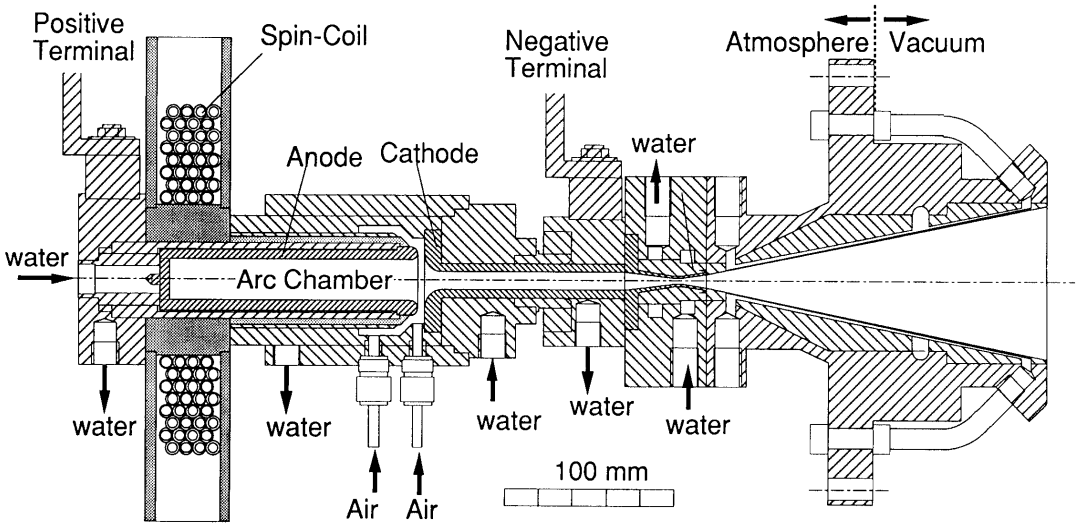


Fig. 5 A Cross Sectional View of the Huels-type Arc Heater Assembly

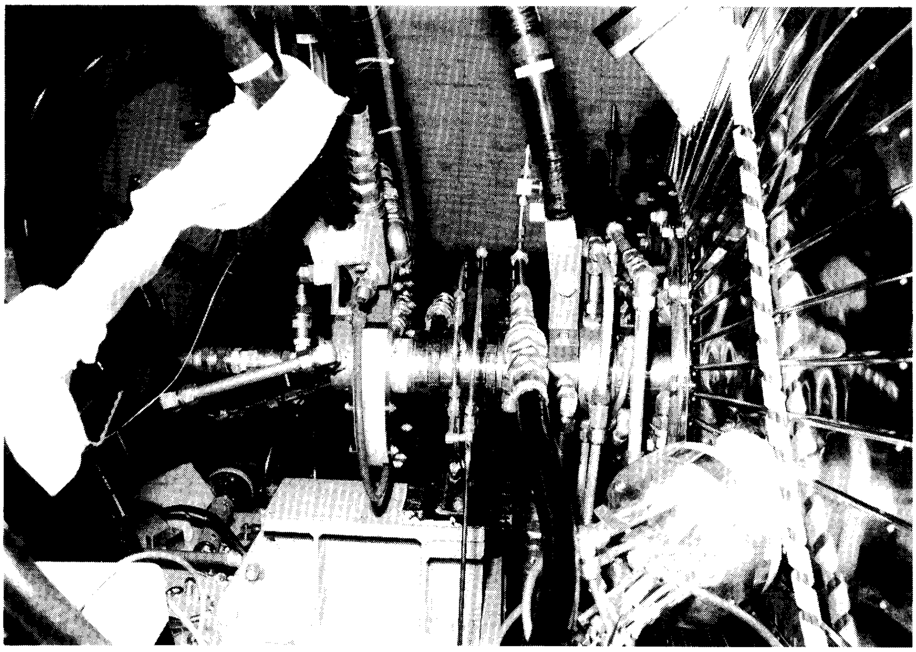


Fig. 6 Photograph of ISAS Huels Arc Heater

Table 2.

Electrode erosion is also one of the concerns from the standpoint of the endurance of the heater itself and of the contamination of the high enthalpy flow. Since erosion rate is reduced by diffusing the current density at the arc spot, the spin coil is equipped with the heater in order to rotate and diffuse the arc spot azimuthally by induced magnetic field. The axial current distribution, in other word the location of the anode attachment point of the arc, has turned out to be controllable owing to the interference between the Hall current in the arc plasma and the magnetic field. Since the anode attachment point of the arc is moved downstream with increasing the spin coil current, the optimal operation current of the spin coil is determined according to such emphasized conditions as the thermal efficiency maximum or the operational safety.

Table 2 Arc Heater Specification

Length	350 mm
Diameter	150 mm
Spin Coil Current	400 A
Spin Coil Turn Number	5.5 turn/cm
Gas Injection	6 swirl ports
Cooling Water Conductivity	< 10 μS
Mass Flow Rate	10 - 20 g/s
Nozzle Expansion Ratio	10, 40, 300
Nozzle Throat Diameter	6.35 mm
Thermal Efficiency	50 - 65 %
Specific Enthalpy	8 - 15 MJ/kg

3-3. Power Supply

The powers for the arc heater, the subsystems and the spin coil are supplied independently through each power line respectively as shown in Fig. 7. The primary 6,600 V AC is transformed into 1080V for the arc heater power and into 210 V for subsystems. Spin coil power is supplied from 200 V AC power line.

For the power supply to the arc heater, 1080V-maximum AC current is converted DC current through the DC power supply unit. In parallel to this power supply unit, the trigger high voltage power supply is installed for the ignition of the arc heater as will be described in detail in the later section. First, the trigger power supply adds high voltage of 2,500 Vdc between the electrodes of the heater. As soon as the breakdown has been occurred, the circuit is switched to the main power supply by the thyrister and the arc discharge is stabilized between the electrodes.

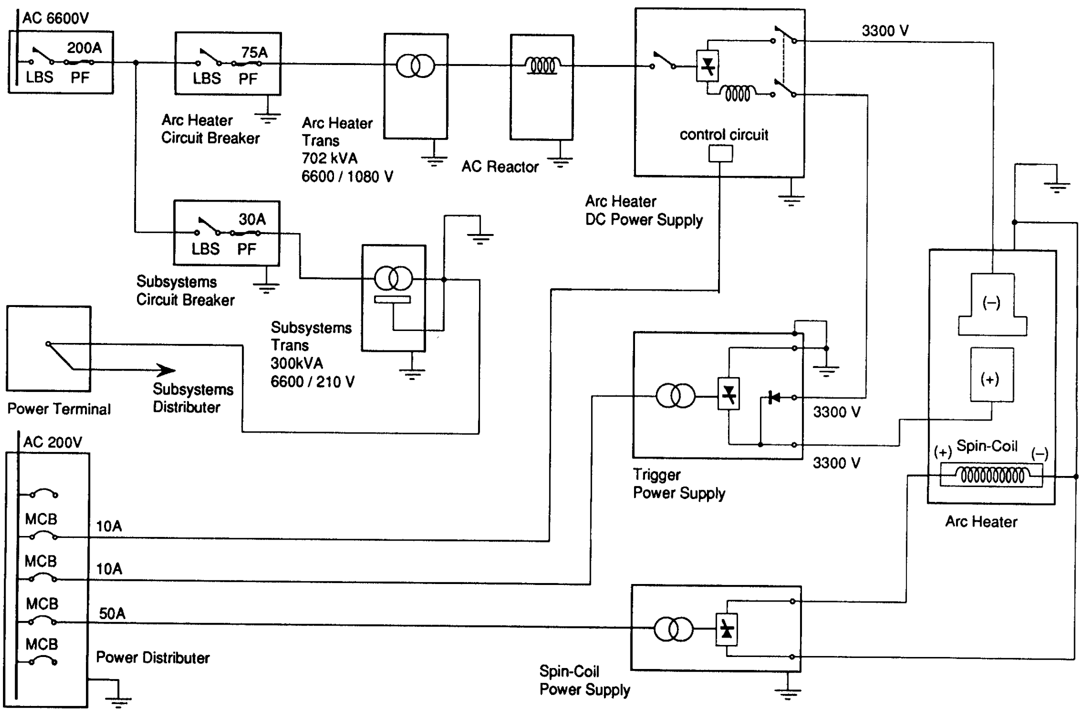


Fig. 7 Power Supply System Block Diagram

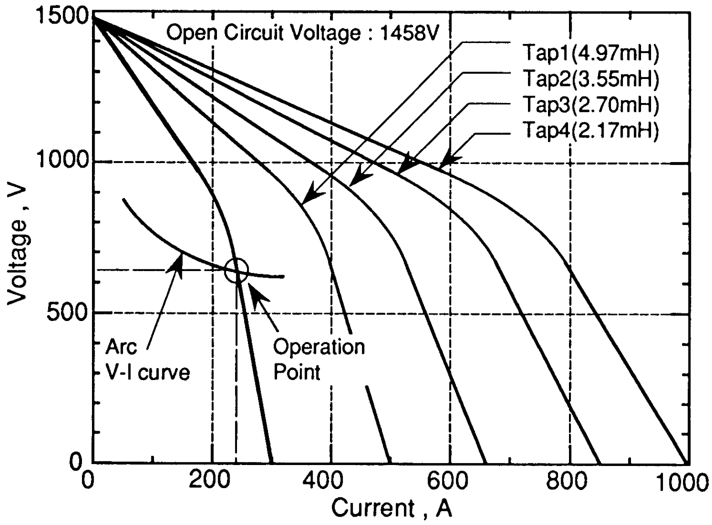


Fig. 8 Voltage-Current Characteristics of the DC Power Supply

For the stable operation of Huels-type heater in relation to the electrical characteristics of the arc-column itself, perturbation of the arc discharge must be negatively fed back by the power supply V-I characteristics to cancel the perturbation; Since the voltage of the arc discharge has drooping curve as a function of the discharge current, the power supply needs to increase the input voltage when the arc current is perturbed to be small, and vice versa. Figure 8 shows the power supply characteristics in relation to the AC reactor inductance. Corresponding the required operation range, the stable discharge region can be selected by changing the inductance value. The inductance value can be changed by selecting terminal taps in the power transformer.

3-4. Air/Working Gas and Control Air Supply

The gas supply lines together with major valves are also shown in Fig. 9. The working gas (normally the air) to be arc-heated is supplied from standard high pressure bottles of 150 kg/cm^2. Taking account of the pressure drop between the bottles and the arc heater plenum chamber where over 10 kg/cm^2 is needed, the pressure of the working gas is regulated about 50 kg/cm^2 and led to the control room. The mass flow rate is controlled here in the control room, and finally the working gas is injected into the arc heater with swirl injection. The mass flow rate is determined as follows; As previously described, the discharge current and the plenum pressure are the independent control parameters. The pressure controlling valve installed in the control console reduces the supply air pressure so that the plenum pressure is equal to the target value. At the point, the pressures both at the inlet and the throat of the venturi orifice installed in the line is measured, and the mass flow rate is calculated based on the flow temperature and this pressure at the orifice by the data acquisition system (DAS) as will be described later. By this arrangement, gas composition needed with respect to the various test purposes is easy to change. Argon gas needed for the ignition is also supplied by the bottles in parallel to the working gas supply line. Ignition sequence is controlled automatically from operation console.

The valve control of the lines mentioned above are conducted by solenoid valves and numatic valves controlled from the operation console. The control air line for the numatic valves are established in parallel to the above working gas supply lines. The air of about 5 kg/cm^2 is generated by the compressor and fed for the numatic valve control. As will be described later, extraction and retraction operation of the test piece strut into the arc jet is also conducted numatically by the control air led inside of the test cabin.

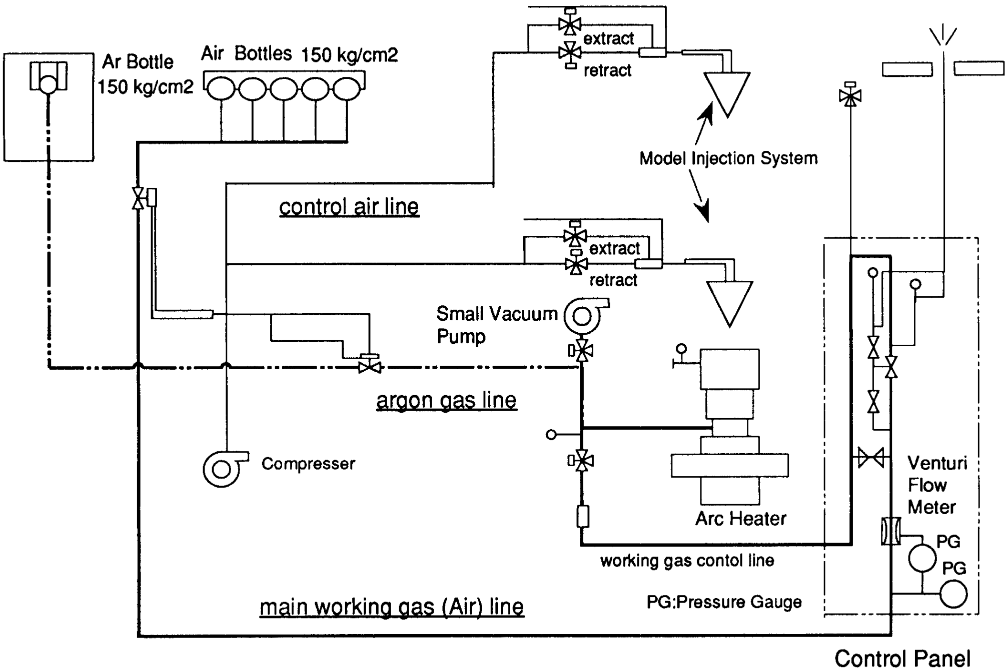


Fig. 9 Air / Working Gas Supply System Block Diagram

3-5. Evacuation System

The working gas heated and expanded by the arc-heater is first pressure-recovered by diffuser and is evacuated through the heat exchanger by a raw of vacuum pumps. After slightly pressurized by the exhaust fan, the exhaust gas is sent to the air cleaner to remove toxic nitric oxide, and finally ejected to atmosphere. The whole evacuation systems are already shown in Fig. 4 and the specification is in Table 3.

The diffuser catch cone and parallel part of it are water-cooled for the protection against the high enthalpy flow ejected from the arc heater nozzle. A detailed diffuser inlet dimensions are presented in the section of test cabin. The heat exchanger is that of three stages of water cooled array of tubing.

A raw of vacuum pumps are composed of 3 mechanical booster pumps and 2 oil rotary pumps. In order to match the ambient pressure to the nozzle exit pressure for appropriate expansion, the pumps can be operated in three configuration; Configuration 1) Two oil rotary pumps,

Table 3 Type and capacity of Diffuser, Heat Exchanger, Pumps

Vacuum Pumps		Diffuser	
Ambient Pressure	> 0.1 Torr	Distance from the Nozzle	300 mm
MB1 Exhaust Velocity	12,000 m^3/h	Catch Cone Diameter	300 mm
MB1 Input Power	22 KW	Catch Cone Half Angle	5.8 deg
MB2 & 3 Exhaust Velocity	1,350 m^3/h	Catch Cone Length	540 mm
MB2 & 3 Input Power	5.5 kW	Parallel Part Diameter	190 mm
RP1 &2 Exhaust Velocity	900 m^3/h	Heat Exchanger	
RP1 &2 Input Power	22 kW	Type	3-stage
		Cooling Panel Number	3
* MB : Mechanical Booster Pump		Cooling Flow Rate	9.8 m^3/h
* RP : Oil Rotary Pump		Maximum Diameter	1,250 mm

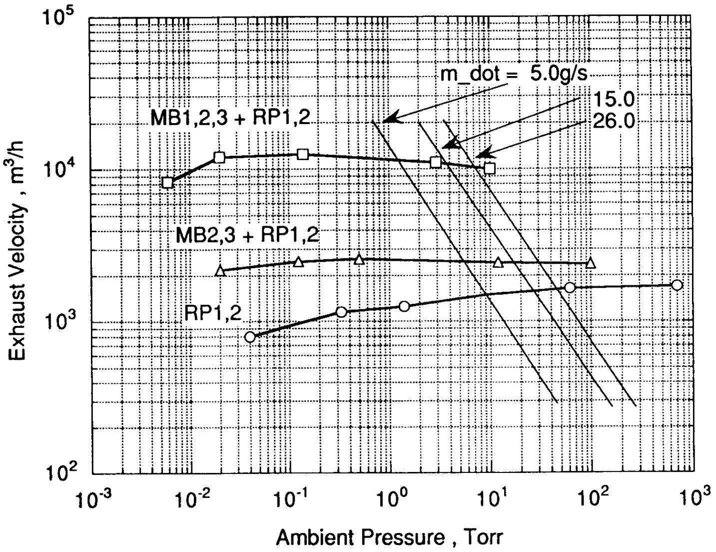


Fig. 10 Vacuum Pump Operation Characteristics

Configuration 2) Two mechanical Booster pumps evacuated by two oil rotary pumps respectively, and Configuration 3) Operation of total pumps system. This evacuation system makes it possible to dump out the working gas flow rate of 20 g/sec keeping the test cabin pressure as low as 0.3 Torr, continuously in the Configuration 3 operation. The vacuum pump operation characteristics are shown in Fig. 10.

The air cleaner is two-staged and removes nitric oxide from the exhaust gas by NaOH solvent in the catalysis bed. The pH value of the NaOH is monitored by control console during the operation, and is maintained below pH 11.0.

3-6. Test Cabin and Model Injection System

A test cabin is connected both to the arc-heater and diffuser. For both open-to-air and vacuum operation, arc-heated gas is injected into test cabin and dumped out by the evacuation system. The diameter and the axial length of the cabin are 1.5 m and 1.5 m, respectively as shown in Fig.11, and the whole cabin surface is water-cooled, too. The gas entrance arrangement for both the operation is also shown in the figure, and it keeps atmospheric pressure and low pressure for each operation. Inside the cabin, a model injection device, cooling water supply and electrical terminals for measurement are equipped.

For the optical measurement and laser diagnostics purposes, seven windows altogether toward several directions are fixed by taking into account various future applications for diagnostics purposes. Since the 300 mm side windows can cover the all the plume radially expanded, absorption spectroscopy with Abel's inversion can be easily conducted. As will be described in the later section, the laser beam can be inserted from different windows of 53 degrees with to the axis for the Doppler velocimetry. Moreover for the detection of the laser induced signal emitted for homogeneous direction is detected through the ceiling window perpendicular to the plane determined by the two laser beams.

Two model support is normally equipped and injected into the hot gas plume by pneumatically driven actuators for its quick injection and extraction requirement. The cooling water supply to the model to be mounted is prepared through the injection support structure. . For the sake of its easy access in the model preparation and handling from a workmanship view point, the cabin is divided into two at its cylindrical part; into the forward part to which arc-heater is fixed and rearward part

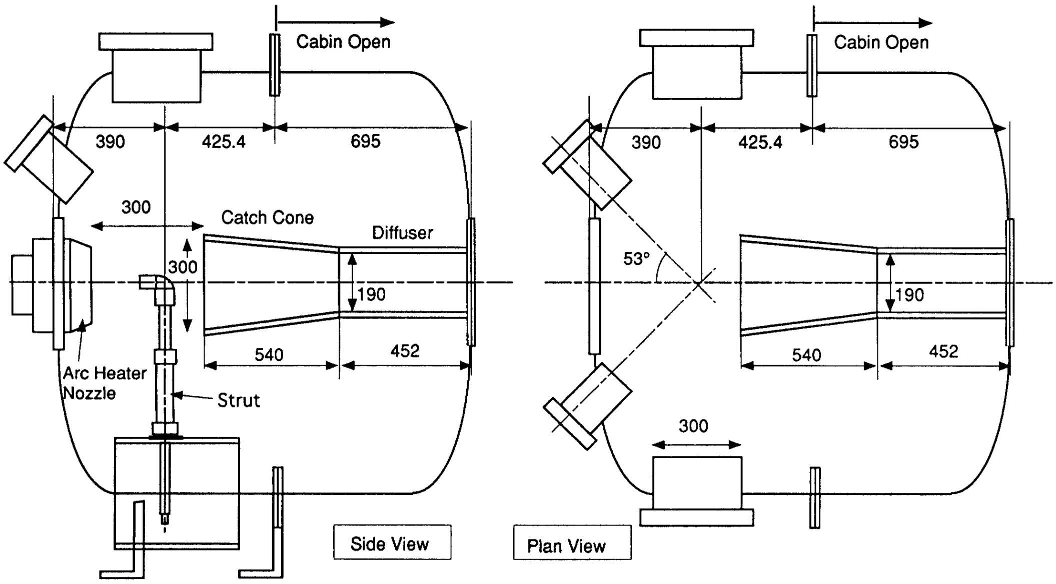


Fig. 11 A Schematic View of the Test Cabin and Model Injection System.

with diffuser. The forward half is fixed to the ground base and the rear half is to slide in the axial direction by removing a part of diffuser piping out side the cabin.

The test section extends from the nozzle exit plane to the diffuser catch cone plane: The axial length of the test section is 300 mm all of which can be observed from the 300 mm diam. side window.

3-7. Cooling System

There are two water-cooling loops in the facility: One is a closed-loop demineralized cooling water (DCW) line and the other is open-looped low pressure (L/P) cooling water line as shown in Fig. 4 and the specification is in Table. 4.

The closed-loop DCW line is used for primarily cooling of the arc-heater. In order to keep the desired electrical resistance between the electrodes of the heater the conductivity of the demineralized cooling water is maintained below 10 μS for normal operation. When the conductivity excesses the upper limit of 20 μS, the demineralizer supply new demineralized cooling water into the line. The flow rate values to each part of the arc-heater such as two electrodes, throat, and nozzle are independently tuned and are carefully monitored for giving an appropriate temperature rise during the operation of the heater. Each flow rate for cooling the

Table 4 Cooling Water System Specifications

DCW Cooling System		L/P Cooling System	
Total Flow Rate	200 l/min	Total Flow Rate	200 l/min.
DCW Conductivity	< 10 μS	Conductivity	normal
Input Power	31 kW	Input Power	
Damp Tank Volume	2.5 m³	• Transmission Pump	38 kW
Operation Temperature	< 60 °C	• Circulation Pump	8 kW
Input Power	31 kW	• Cooling Tower	4 kW
Damp Tank Volume	1.9 m³	Damp Tank Volume	1.9 m³

DCW : Demineralized Cooling Water L/P : Low Pressure

Table 5 DCW Flow rate / delta T for Heater Cooling

Components	Flow Rate (l/m^3)	Temperature rise
Body	11	3.0 deg
Cathode	60	5.0 deg
Anode	50	7.5 deg
Throat / Nozzle	50	14.0 deg
Spin Coil	15	–
Total	184	–

values for the typical operation (PT0 : 10 Pa, I = 250 A)

heater and water temperature rise for the normal operation condition is listed in Table 5.

The open-loop L/P cooling water system is used for the cooling of the rest of the facility such as vacuum pumps, working gas heat exchanger, and DCW radiation panel as shown in Fig. 4. The heat of DCW is exchanged in the DCW radiation panel where L/P cooling water is flown. The heat of the L/P cooling water is dissipated to the atmosphere through the cooling tower.

3-8. Operation, Control and Monitoring

All the operation function and monitoring important variables for operation and safety is concentrated to the console in the operation room neighboring to the test room, as shown in Fig. 12. Operational conditions monitored by data acquisition system (DAS) is listed in Table 6. Before operation of the arc heater, subsystem health check is conducted on the basis of the these monitored data such as flow rates and temperatures of cooling water. In case that a condition-indicating values are excessively below/over the nominal value, all the systems are not activated or shut down by the interlock. Not until all the condition-indicating parameters are set with nominal value, next start-up sequence can be followed.

The independent variables for operating Huels-type heater are the plenum pressure and the discharge current. They are manually set both before and after starting the operation. The ignition

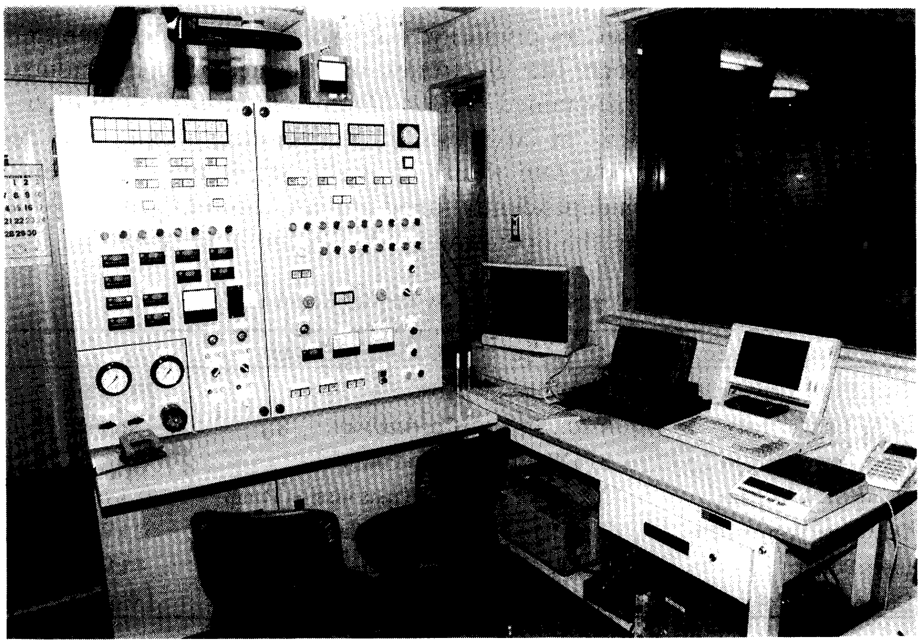


Fig. 12 Operation Console

Table 6 Data Acquistion and Calculation Lists

Real Time Data Acquisition	
• DCW Temperatures	Inlet, Body, Anode, Cathode, Throat
• DCW Flow Rate	Inlet, Body, Anode, Cathode, Throat
•Pressures•	Plenum Pressure, Cabin Pressure
• Air Flow Meter	Inlet temperature, Inlet Pressure, Orifice throat Pressure
• Discharge Current	
• Discharge Voltage	
• Experimental Measurements	Heat Flux, Impact Pressure, Thermocouples installed on Test Piece

Calculated Data Display	
Items	Data required for Calculation
• Input Power	Discharge Current, Discharge Voltage
• Flow Enthalpy	DCW Temperatures, DCW Flow Rates Discharge Current, Discharge Voltage
• Mass Flow Rate	Air Flow Meter Variables
• Thermal Efficiency	Input Power, Flow Enthalpy

sequence both for switching argon gas to the working gas to be heated and for switching trigger power supply to steady-state arc discharge is automatically controlled by the console with respect to the predetermined time sequence as presented in the next section.

During the operation of the facility, micro-computer-based monitoring system displays and records the major operation variables such as input current and voltage, cooling water flow rate and temperature rise, important pressure levels and so on. The model injection sequence control is made by the console, too. For the safety reason, critical state variables are real-time monitored and interlocking operation is activated automatically to avoid danger and keep the system safer, when the values of arc current, voltage, and cooling flow rate etc. are deviated from the predetermined allowable ranges.

3-9. Equipped Measurement Systems

Data Acquisition System

Operational conditions listed in Table 6 are converted into the digital data at a given sampling frequency through A/D converter. These data are stored by the personal computer. During the operation of the arc heater, some of the data are displayed on the monitor of the DAS. Figure 13 shows a quick-look display image of the DAS. In addition to the operational conditions, extra 16 channels are allocated for each experiment data. In these channels, the sampling rate is 20 Hz.

System diagram of the measurement utilities is shown in Fig. 14.

Heat Flux and Impact Pressure Measurement

For the heating test of the material, to know its test condition is so important that one must be careful in each test. Since the nature of the DC arc-discharge, reproducibility in flow enthalpy, for example, is poorer than that of pressure. It is partly because the operation condition, even in the steady-state operation, is slightly time varying with respect to the surface condition of electrode,

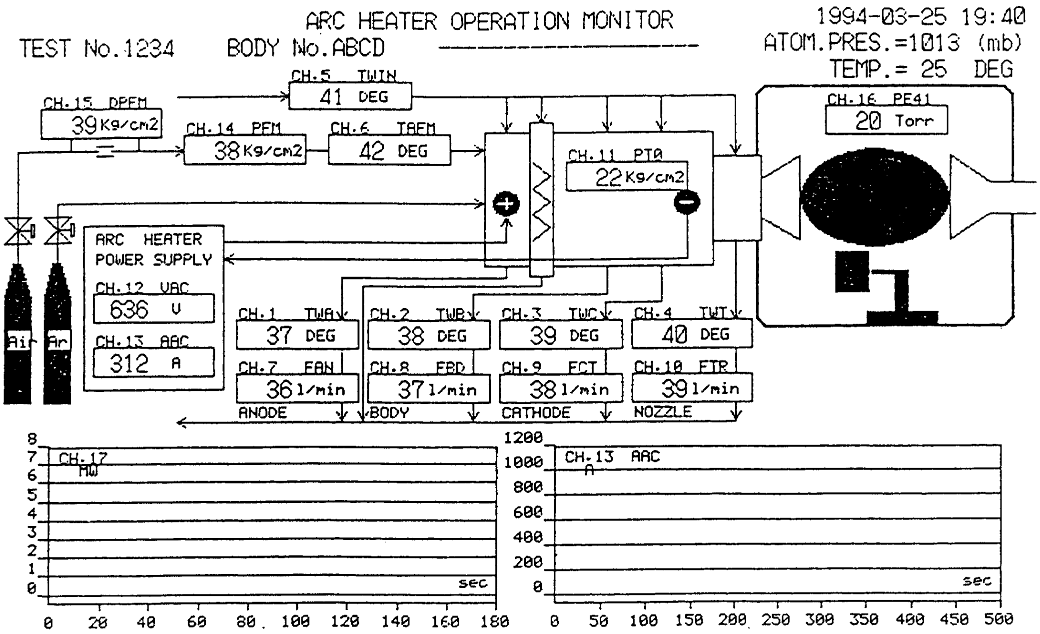


Fig. 13 Quick Look Display of the Data Acquisition System

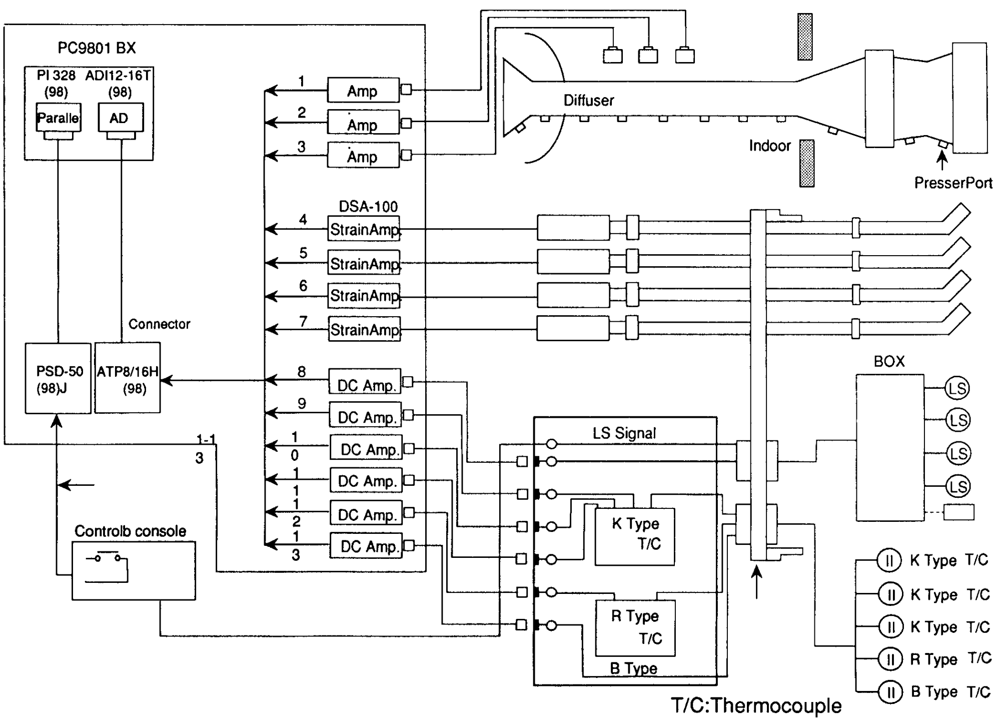


Fig. 14 Data Measurement Utilities Block Diagram

particularly of the anode due to its recession in the Huels-type heater. As a result, heat flux at the material surface to be tested varies to some extent from one test to another. Then in the present facility, heat flux is measured by water cooled Gardon gauge for its benefit of quick response and of direct reading proportional to the cold wall heat flux. Normally it is accommodated in a copper body as shown in Fig.15, and mounted on one of the model injection strut presented in the previous

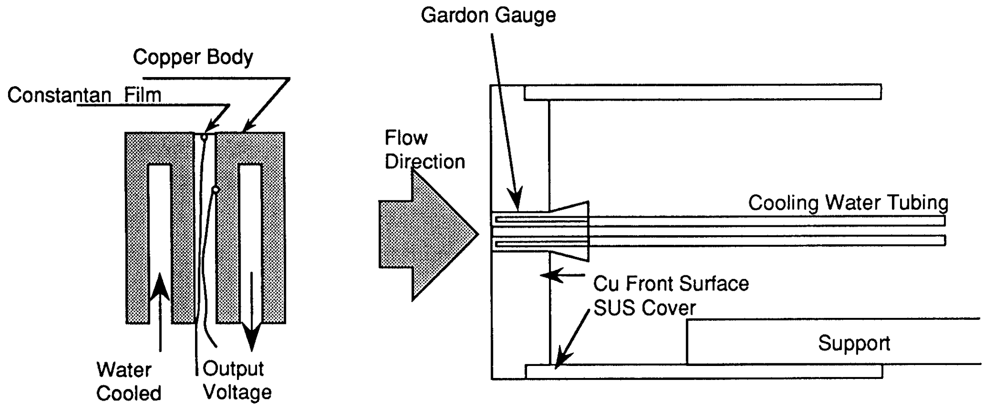


Fig. 15 Gardon Gauge and its Accommodation to the Probe Body

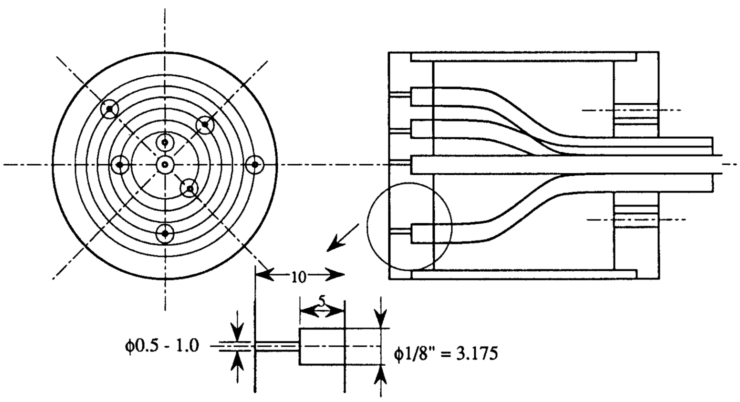


Fig. 16 ϕ50 mm Pressure Probe for the Impact Pressure Measurement

section.

Impact pressure and other body surface pressure is measured by a normal pressure transducer installed on the pressure probe as shown in Fig. 16, and temperature measurement for various purposes by thermocouples are prepared. Electrical terminals are provided at the wall of test cabin connected to the multi-channel strain and DC amplifiers and PC-based monitor / record system in the operation room.

Laser Diagnostics System

In addition to the measurements of heat flux and impact pressure on the test piece, characterization of the heater itself as a high enthalpy gas sources and flow measurement is to enhance the understanding of the flow produced by these heaters. For example in the arc heater, flow enthalpy is measured by a total energy balance between electrical power input and heat dumped out into the water which cools the corresponding parts of the heater assembly. A flow velocity measurement by a pitot tube in the flow is somewhat difficult, because of the unknown flow variables such as specific heat, Mach number and so on. A laser diagnostics technique will give us an opportunity to nonintrusively measure the state variables of the flow. A recent high power laser technique makes it possible to measure two dimensional image of the flow velocity, temperatures (electronic, vibrational, and rotational temperature), and concentration of each specie.[16][17]

The instruments and their specifications of the laser diagnostics system is presented in Table. 7. The two sets of dye lasers pumped by excimer lasers are equipped with for the excitation of the target species. This combination is designed for various laser diagnostics application, it can excite

Table 7 Laser Diagnostics System Specifications

Excimer Laser		I/I-CCD Camera	
(Lumonics PM-882)		(Hamamatsu C-4077)	
• Laser Medium	XeCl	• Gate width	7 ns - 14 μs
• Wavelength	308 nm	• wavelength range	160 - 850 nm
• Bandwidth	1 nm		
• Pulse width	20 ns		
• Laser Energy	600 mJ	Spectrometer	
• Repetition Frequency	10 Hz	(Hamamatsu PMA-100)	
• Repetition Frequency	10 Hz	• Monochrometer type	Tzelny-Turnar
		• Focusing Length	500 mm
Dye Laser		• Resolution	0.2 Å
(Lumonics HD-500)		• Detector	I/I CCD Camera
• Wavelength	330-800 nm		
• Bandwidth (@300nm)	0.04 cm^{-1}		
• Conversion Efficiency	10 - 20 %		

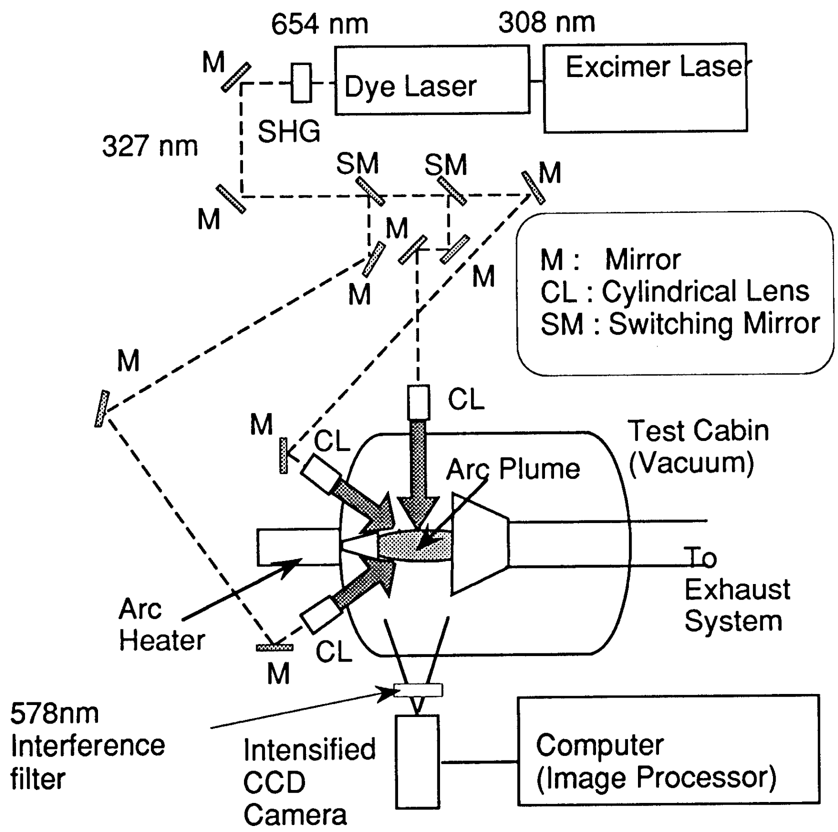


Fig. 17 Copper Atom LIF Doppler Velocimetry ; Experimental Setup

the species whose absorption lines lie from 211 nm with a certain frequency doubling crystal such as BBO to 650 nm. The emission or scattering from the target specie can be detected through the ceiling window for the homogeneous signal such as the laser induced fluorescence (LIF), Raman, Rayleigh scattering, and through the window opposite to the laser insertion for the absorption spectroscopy. The 2-dimensional image of the optical signal is obtained by the image-intensified CCD camera, and the spectroscopic data of the optical signal can be analyzed by the spectrometer through the optical fibers installed on the window.

As will be described in the later section, the velocity distribution of the high enthalpy flow is obtained Cu LIF Doppler velocimetry. Figure 17 shows this Cu LIF velocity measurement apparatus.

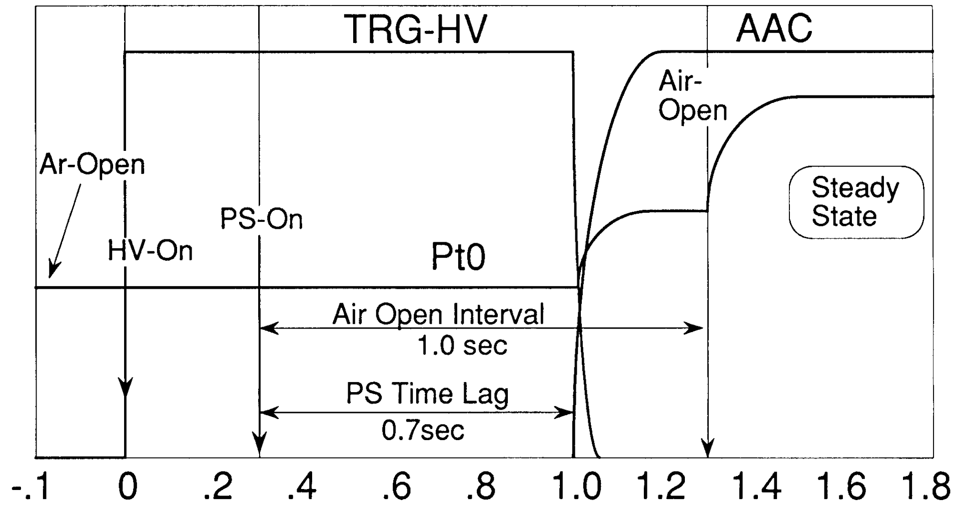
4. HEATER CHARACTERISTICS AND TEST CONDITIONS

4-1. Ignition

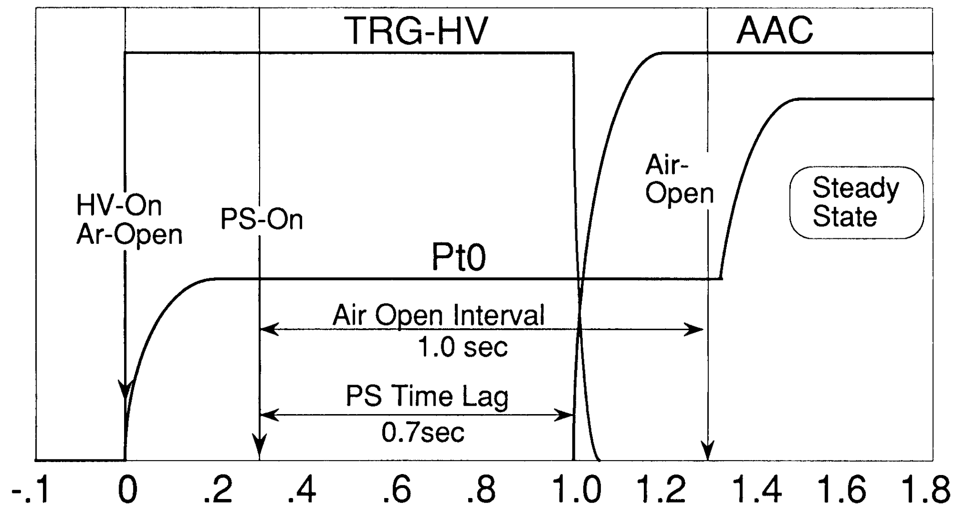
The arc heater is ignited with argon for the ignition gas at 2,500 Vdc trigger voltage. After the breakdown, the trigger voltage is followed by the discharge voltage peculiar to the arc discharge and the argon gas is automatically transferred to the air within one or two seconds. All experimental data are obtained in several minutes in the steady-state operation. As will be described in the following section, there are two ways of operation; One is the vacuum operation mode in which relatively low impact pressure and heat flux are attained in the vacuum ambient pressure and the other is the open-to-air operation mode in which the exhaust plume is directory injected into the atmospheric pressure to attain relatively high impact pressure and heat flux on the test piece. Corresponding to the two operational modes, there are two ways of ignition.

The argon gas start is an ignition sequence used for the vacuum operation mode as schematically shown in Fig. 18. After the test cabin is evacuated to 0.1 Torr, simultaneously the plenum chamber itself is also in 0.1 Torr, high purity argon gas (99.999%) is injected into the plenum chamber. The argon flow is easily choked by the nozzle throat in several seconds about 300 Torr. Then the trigger command is manually sent to the trigger power supply system. After this ignition command, all ignition sequence are controlled automatically by the control console sequence. After 0.7 sec of time lag for power supply safety, the step-function high voltage up to 2,500 Vdc is added on the gaps between the anode and the cathode. On sensing increasing arc discharge current due to the Paschen breakdown, the thyrista switches current path from the trigger power supply to the main DC power supply unit. One second after sensing the breakdown, the gas supply is switched from argon to the test working gas, normally the air. Moreover, two second after the air injection, the argon supply valve is closed and the arc discharge is stabilized in steady state. The breakdown voltage in steady argon flow is plotted in Fig. 19 with varying plenum pressure by controlling argon mass flow.

The vacuum start is an ignition sequence used for the open-to-air operation mode. Since the ambient pressure in this operation is atmospheric pressure, the plenum pressure must be higher than the atmospheric pressure to fill the chamber with the pure argon gas ; otherwise the air will flow inversely from the atmosphere into the plenum chamber through the nozzle. As shown in Fig. 19, the breakdown voltage is monotonously increased with the increasing plenum pressure. Then the arc heater cannot be ignited with 2,500 Dc trigger voltage in such high plenum pressure over 1 atm. This was solved by triggering in vacuum. At first the plenum chamber is maintained in vacuum pressure below 2 Torr sealed by a rubber ball attached to the nozzle throat. By sending the trigger command, the trigger high voltage is added to the electrode gap and simultaneously the argon supply valve is opened. The small vacuum arc discharge established in several mili-seconds is enlarged with increasing argon pressure. On sensing increasing arc discharge current due to the Paschen breakdown, the thyrister switches current path from the trigger power supply to the main



(a) Argon Start Sequence



(b) Vacuum Start Sequence

Fig. 18 Arc Heater Ignition Sequence

DC power supply unit. The following sequence is same as that for the vacuum operation described previously. From the stand point of electrode erosion, argon start is more desirable compared with the vacuum start where the arc erodes copper electrodes for maintaining arc plasma.

4-2. Performance Characterization

Operation Envelope

Performance characterization of the arc heater has been conducted in order to clarify the possible operation range experimentally as shown in Fig. 20. The discharge voltage vs. current characteristics at the constant plenum pressure show drooping curves, and the value of the voltage at a given current increases with increasing the plenum pressure, namely the mass flow rate. Reduction limit of the discharge current is about 150 A because of the arc instability. Several factors determine the operation envelope of the heater, and the static instability of the arc due to the interaction with the power supply characteristics is one of the dominant factors. The range of

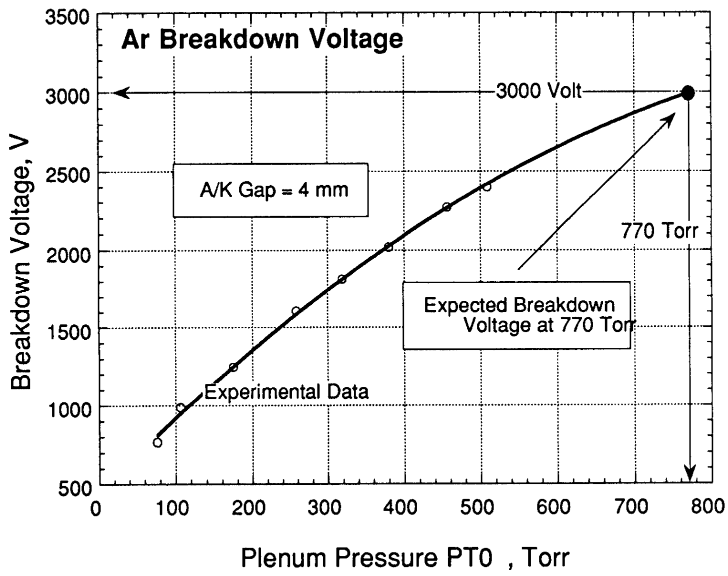


Fig. 19 Paschen Breakdown Voltage Characteristics of the Present Arc Heater

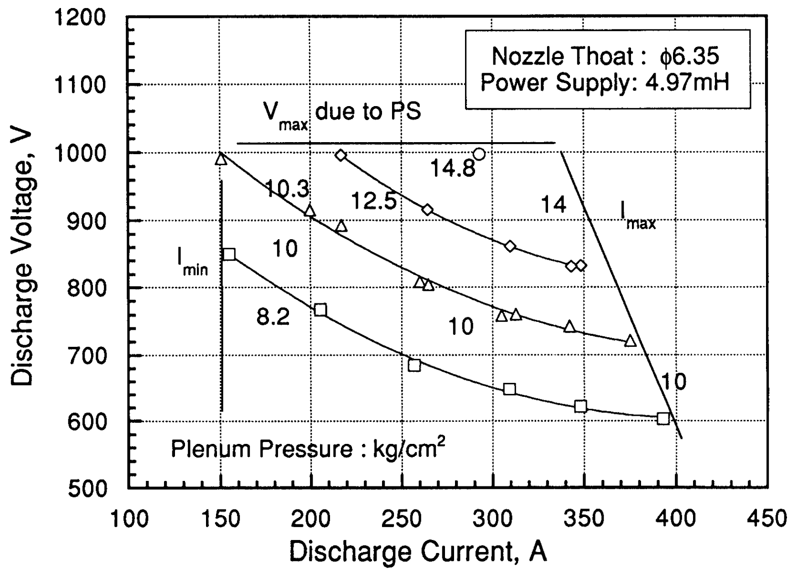


Fig. 20 Operation Envelope (Voltage vs. Discharge Current Characteristics)

discharge current variation is from 150 A to 400 for the low power operation mode of 4.97 mH AC reactor inductance and 220 A to 500 for the high power operation of 2.17 mH.

Air Enthalpy and Thermal Efficiency

Thermal efficiency, defined as ratio of the total flow enthalpy to the input power, and gas enthalpy are calculated on the measured temperature and mass flow rate of the cooling water. Temperatures and flow rates of the cooling water are measured both at the inlet and the outlet of the supply tubes. A typical energy balance measured with this method is shown in Fig. 21. About 60% of the total input power is transferred to the working air, and the rest of it is almost dissipated into the cathode and nozzle throat block.

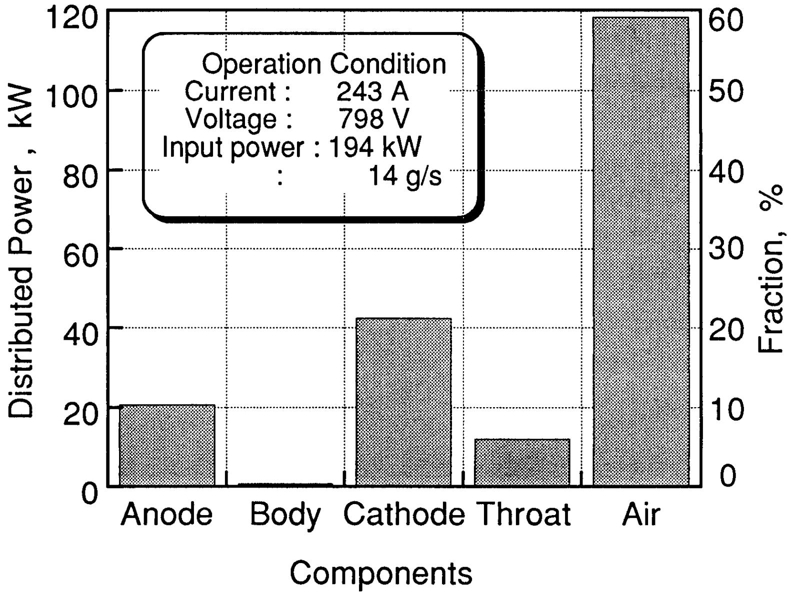


Fig. 21 Energy Balance in typical Operation

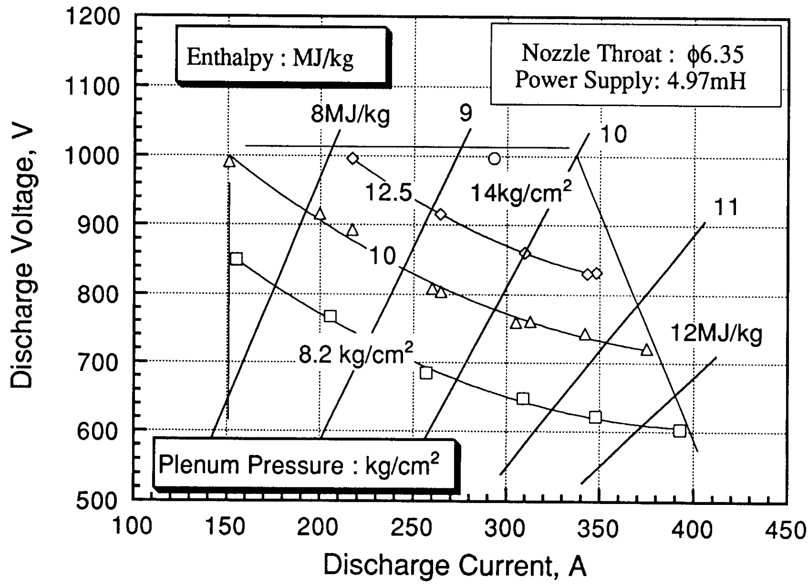


Fig. 22 Operation Envelope (Specific Enthalpy Characteristcs)

Fig. 22 shows the enthalpy characteristics simultaneously mapped in the operation envelope. The air enthalpy ranging from 7 MJ/kg to 13 MJ/kg has been obtained. Fig. 23 shows the thermal efficiency characteristics as a function of specific enthalpy in the typical operation envelope with varying the plenum pressure. It is recognized that the thermal efficiency is higher (>60%) in the operation with higher plenum pressure and lower input power. At a given plenum pressure, the thermal efficiency decreases with increasing the specific enthalpy. Since the higher enthalpy gas corresponds to the higher temperature, heat dissipation to the chamber wall is larger in the higher enthalpy gas. This reduces the thermal efficiency at higher specific enthalpy region. At a given specific enthalpy, the central hot core is thermally confined and heat dissipation to the wall is

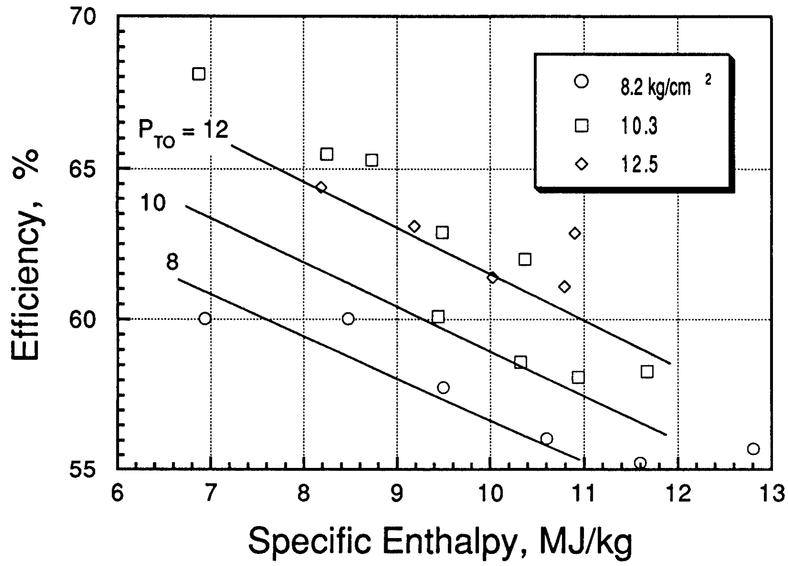


Fig. 23 Thermal Efficiency vs. Specific Enthalpy Characteristics

restricted. Since this effect is remarkable at higher plenum pressure, the thermal efficiency increases with increasing the plenum pressure.

Electrode Erosion

After the several typical operations with duration of 20 minutes, erosion rate of the anode has been measured as difference between the weight before and after the operation. Operation sequences are almost same for each operation; 350 A for the preset discharge current followed by 230 A within ten seconds. The plenum pressure is 10 kgf/cm^2. The duration of one run is about After the experiment anode is removed from the arc heater and cut into two half pieces as shown in Fig. 24. Since the spin coil current remained constant within an operation, axial position of the arc

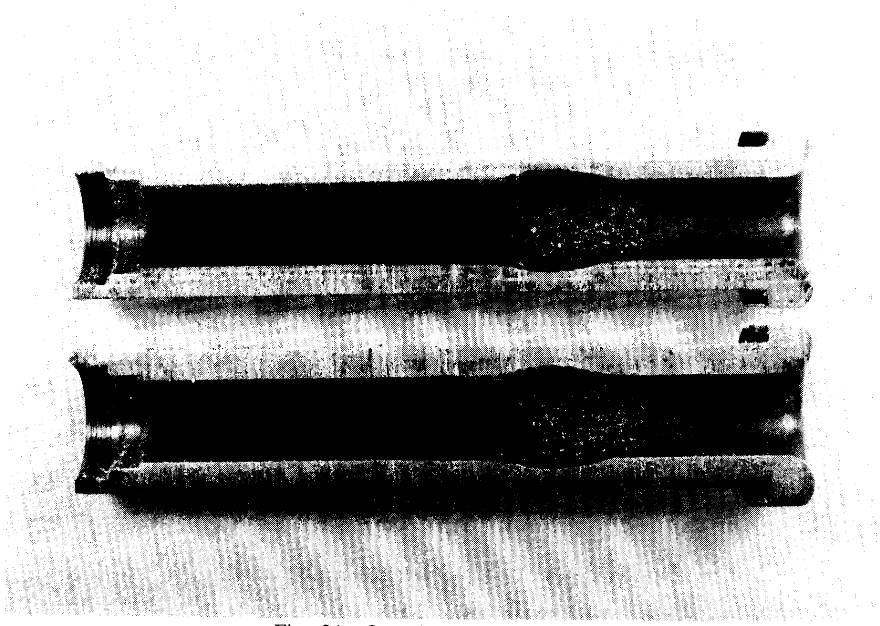


Fig. 24 Cut-off View of the Anode

foot is almost same with the result that the anode is scraped at the given axial position. The total electricity is calculated through the integral of the time history of the discharge current. Erosion rate is 30 mg/C or 7 mg/s. Since the mass flow rate is 13 g/s in this operation, the copper is included 400 ppm by weight fraction or 180 ppm by mole fraction in the high enthalpy air as an contaminant.

4-3. Simulation Environment

Operational conditions of the arc heater described above are correlated with basic characteristics of the flow such as the heat flux and impact pressure incident on the ablator materials. In order to cover the wide range of the environment as previously shown in Fig. 1, the arc heater is designed to be operated in two configuration; open-to-air configuration and vacuum operation configuration.

Open to Air Configuration

Relatively higher heat flux up to several MW/m^2 and impact pressure over 10^4 Pa can be attained in Open-to-Air-Operation, where the exhaust plume is directly injected into the atmospheric pressure in constricted plume. Distribution of the heat flux and impact pressure is obtained in typical operation of 10 kgf/cm^2 plenum pressure and 230 A discharge current.

The impact pressure was measured with pressure-measurement model injected in the exhaust plume, which is ϕ50 mm cylinder made of SUS. Obtained impact pressure distribution is shown in Fig. 25. Impact pressure is high in the center axis, and gradually decrease toward outside: The central 10 mm diameter is pressure-flat region regardless of the distance from the nozzle exit.

Heat transfer rate is measured by a ϕ40 mm heat flux measurement model installed with Gardon gauge. The model is injected in the exhaust plume in the same operational condition as the impact pressure model. Heat flux distribution has 20 mm diameter flat region from the center axis as also shown in Fig. 25. In a normal operation in the atmospheric pressure, heat flux level is from one to several MW/m^2.

Although the operation with high plenum pressure (>15 kgf/cm^2) and lower current is difficult to be achieved through the present configuration of the nozzle throat of 6.35 mm in diam., preliminary tests demonstrate that the operation with the plenum pressure of 30 kgf/cm^2 can be achieved through other nozzle throats of below 6 mm in diam. In the higher plenum pressure and

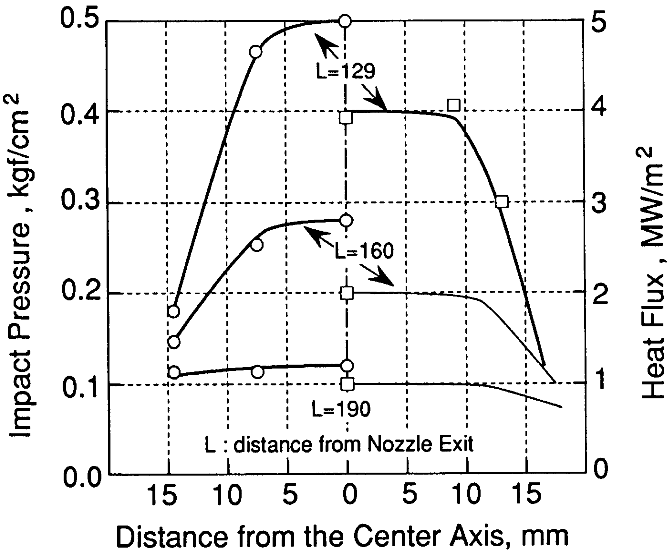


Fig. 25 Heat Flux and Impact Pressure Distribution in typical Open-to-AirOperation

the smaller distance from the nozzle exit (80 mm), heat flux of 15 MW/m^2 has been obtained.

Expanding Nozzle / Vacuum Configuration

Data of the impact pressure and the heat flux are also obtained in the expanding nozzle configuration with area ratio of 300. Since electrodes with different time history were used in this preliminary experiment, discharge voltage vs. discharge current characteristics varies in each experiment. Then arranging the impact pressure and the heat flux as a function of the discharge current brings us only a little information. We here restrict our discussion in the order of them; The heat flux vs. the discharge current characteristics are shown in Fig. 26, and ranges from 0.8 MW/m^2

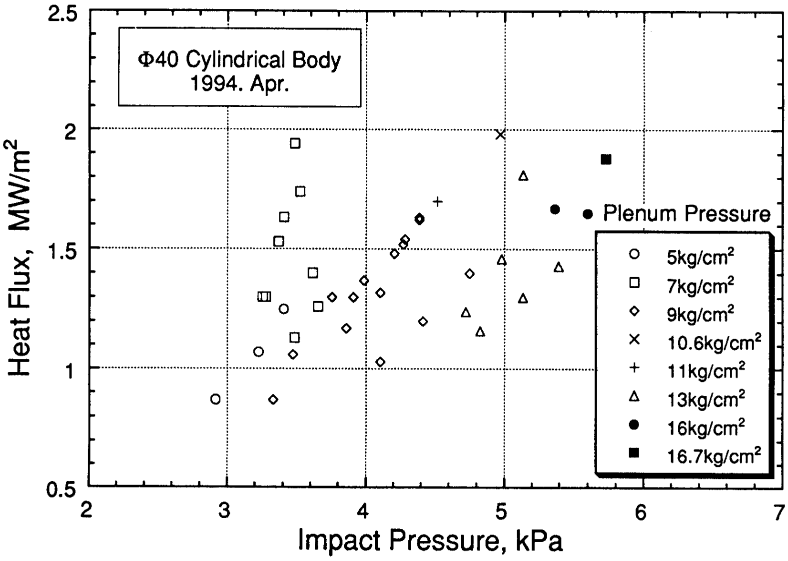


Fig. 26 Environment Simulation Envelope in typical Expansion Nozzle Operation

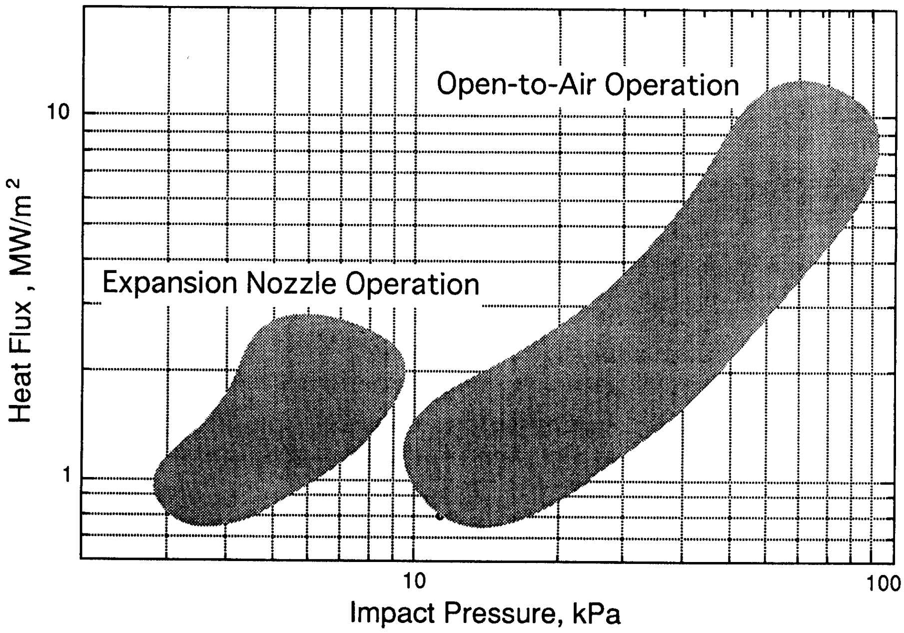


Fig. 27 Environment Simulation Envelope of the Present Arc Wind Tunnel Facility

to 2 at maximum. The impact pressure ranges from 0.03 to 0.06 kgf/cm2. These values are somewhat small in comparison with those in the open air configuration. This is due to the shock wave loss.

Impact pressure ranging 0.03 kgf/cm^2 to 0.7 and heat flux of 0.5 MW/m^2 to 10 are demonstrated. Thus the Huels-type arc heater has accomplished to cover the wide range of the entry/reentry environment in the open to air configuration and in the expanding nozzle configuration.

The whole simulation environment is summarized in Fig. 27. Relatively low heat flux and impact pressure is obtained in vacuum operation (expansion nozzle operation), and relatively higher heat flux and impact pressure is obtained in open-to-air operation. Totally the present arc wind tunnel simulated heat flux ranging several hundred kW/m^2 to 15 MW/m^2, and impact pressure ranging from 1kPa to 60 kPa.

Velocity Distribution

By using the previously described LIF instrumentation of the present facility, a Doppler shift measurement of these LIF signal gives an ideal nonintrusive distribution velocimetry[18]. Fig. 28 is an example of 2D image of the expanded flow out of the arc heater in which fluorescence from copper atoms of 578 nm was detected and processed. The measurement was made by laser wave length of 327 nm by excimer-pumped dye laser and second harmonic generator. This result demonstrates the velocity distribution and the uniformity of the expanded flow out of the nozzle. The line which cross the vector is virtual extension line of the nozzle wall. It is recognize that the flow direction near the boundary is along this virtual nozzle extension line.

Fig. 29 shows the velocity along the radial distance in the flow as shown as hatched line in the Fig. 28. These results show that the difference of the velocity at the center and at the edge of the plume is about 85% and the influence to the model injected in the plume is easily seen. Then the flow uniformity is satisfiable as long as the size of the mode! is as large as 30 to 50 mm on its front

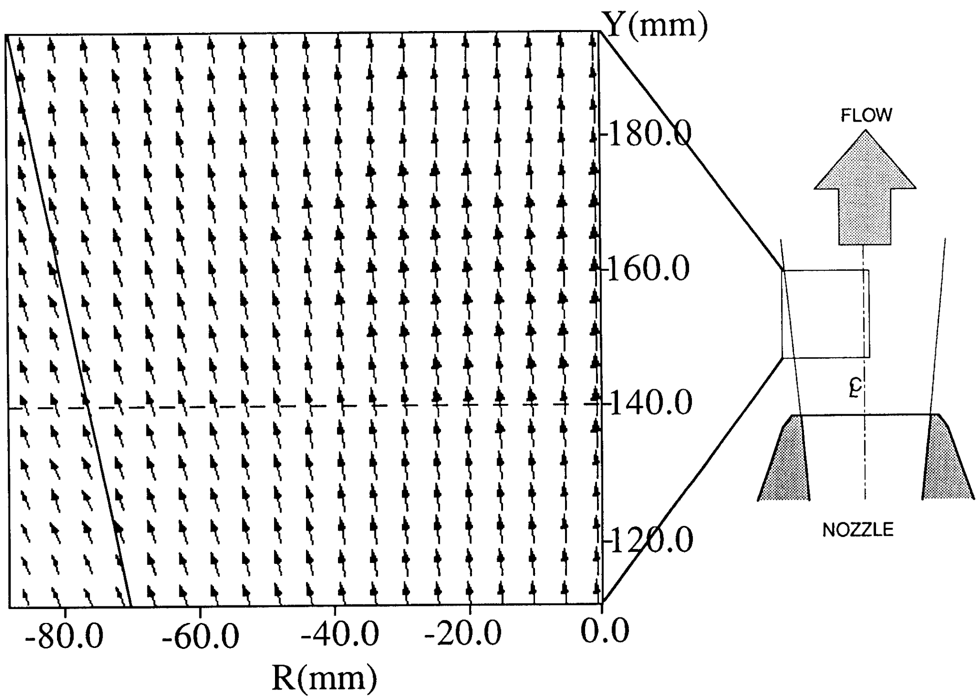


Fig. 28 Flow Velocity Distribution of the Arc Jet obtained by Cu LIF

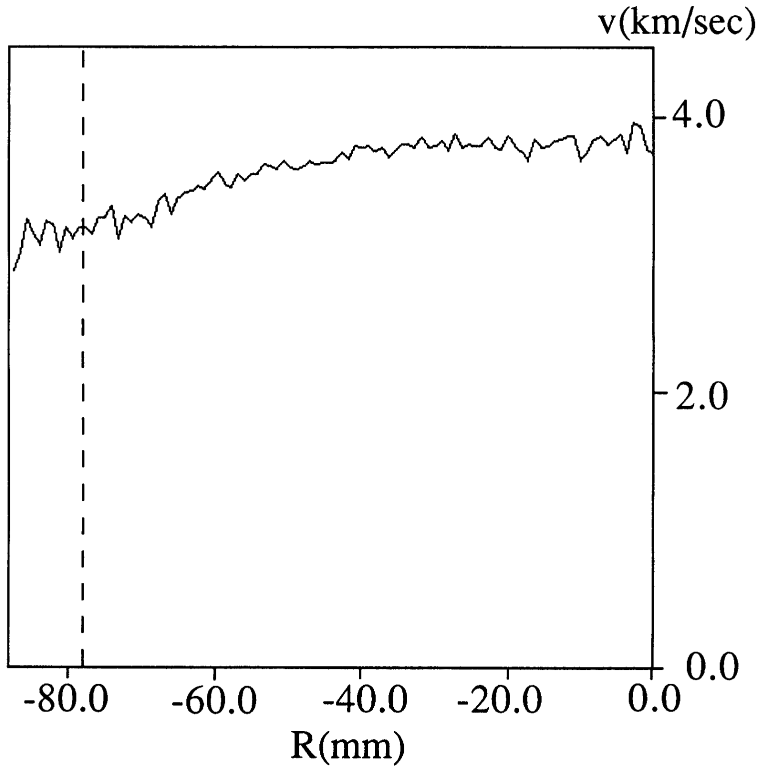


Fig. 29 Flow Uniformity from the standpoint of Velocity

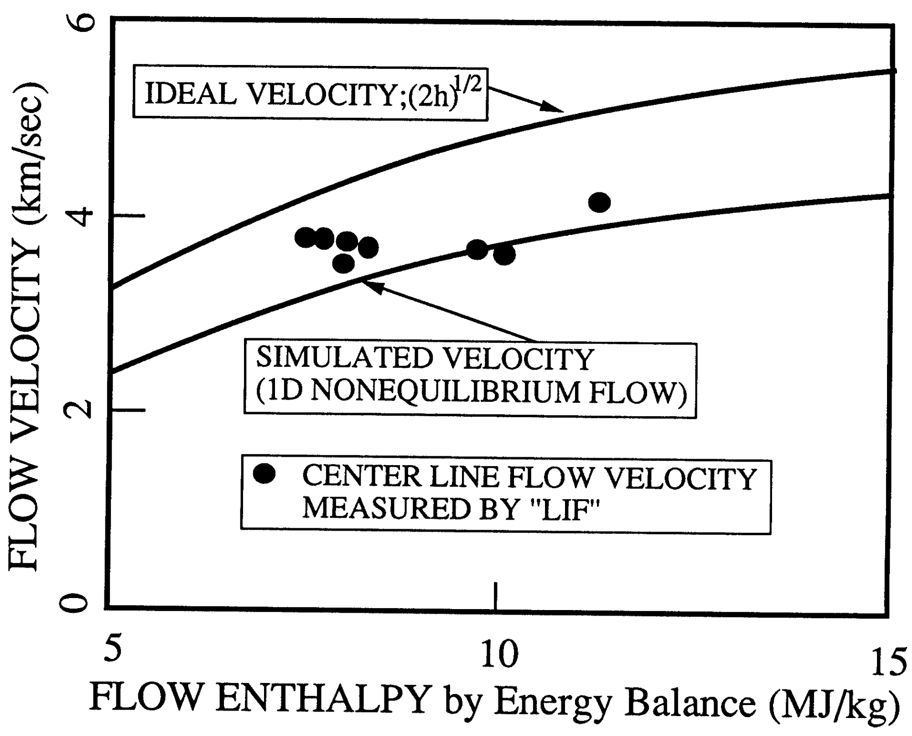


Fig. 30 Flow Velocity vs. Specific Enthalpy Characteristics

surface.

Figure 30 is comparison between the velocity values measured by LIF and those calculated by corresponding nonequilibrium nozzle flow[19]. The flow enthalpy on this figure is that measured by a energy balance of the heater, which is defined by the difference between the power input to the heater and the heat extracted by the cooling water. The agreement among them is observed, however, the scattering of the measured velocity might be improved from several point of view such as an accuracy of the energy balance technique, time varying characteristics of the heater operation where it takes about five minutes for scanning the laser wave length and changing the direction of laser injection in this LIF measurement in order to get a good signal to noise ratio.

5. CONCLUDING REMARKS

A facility for the high-temperature-resistant material research and for experimental studies on high temperature gas dynamics was outlined. Huels-type heater of 500 kW input power was chosen, and its operation envelope and performance characteristics were demonstrated as 20 MJ/kg of enthalpy and about 60% of thermal efficiency in maximum, respectively. For the simulation of reentry flight conditions, planned envelope is calibrated in terms of heating and impact pressure, which are ranging 0.1 to 5 MW/m^2 of heat flux and 10 to 100 kPa of impact pressure by two operation configurations of vacuum and open-to-air condition. In parallel with the facility characterization study presented here, it has been used extensively for the development of ablator materials for reentry missions and rocket related applications for the thermal protection purposes.

Regardless of the flow chemistry and the nonequilibrium flow characteristics, one can never conduct a correct and detailed estimation of material reaction under highly heated condition by high enthalpy flow. Therefore, studies on diagnostics using optical and laser media is vital to enhance the knowledge about flow characteristics and flow-wall interaction in the heating test. Instruments for these non intrusive diagnostics equipped in the present facility together with the arc-heated high enthalpy flow are expected to contribute to bridging simulation results by up-to-date numerical simulation and measurement results which will be produced out of the present facility. A preliminary laser-induced-fluorescence-based velocimetry demonstrates the direct nonintrusive measurement of the velocity distribution of the highly expanded high enthalpy flow, and it corresponds to the enthalpy results derived from the energy balance of the heater.

REFERENCES

[1] J. Lukasiewicz, "Experimental Method of Hypersonics", Gasdynamics vol. 3, Marcel Dekker, Inc., New York, 1973.
[2] D.A. Wagner, M.O. Verner, R.R. Williams, B.J. Griffith, "Hypersonic Facility Requirements and Design Considerations", AIAA-88-1991, AIAA 15th Aerodynamic Testing Conference, San Diego, 1988
[3] R. Akiba, "Japanese Space Program Part 1", ISTS-NSP-11, Proceeding of 19th Internatinal Symposium on Space Technology and Science, pp. 1071–1080, Yokohama, 1994.
[4] Y. Inatani, and T. Abe, "RTEX-Reentry Technology Experiment of EXPRESS Capusule", ISTS-94-g-07, Proceeding of 19th Internatinal Symposium on Space Technology and Science, pp. 573–580, Yokohama, 1994.
[5] C. Park, "Fully Coupled Implicit Method for Thermochemical Nonequilibrium Air at Suborbital Flight Speed", J. Spacecraft & Rocket, vol. 28, no. 1, JAN-FEB, pp. 31–38, 1992
[6] C.D. Scott, "Survey of Measurements of Flow Properties in Arc Jets", AIAA-90-1765, AIAA/ASME 5th Joint Thermophysics and Heat Transfer Conference, Seattle, 1990.
[7] R.L. McKenzie, "Progress in Laser Spectroscopic Techniques for Aerodynamic Measurements: Overview", AIAA Journal, vol. 31, no. 3, pp. 465–477, March 1993.
[8] Y. Watanabe, T. Matsuzaki, K. Ishida, K. Yudate, T. Yoshinaka, "Characteristics of the 750 kW Arc Heated Wind Tunnel", ISTS-94-d-36, Proceeding of 19th Internatinal Symposium on Space Technology and Science, pp. 377–382, Yokohama, 1994.
[9] W. E. Bruce, D. D. Horn, E. J. Felderman, L. M. Davis, "Arc Heater Development at AEDC", AIAA-94-2591, 18th AIAA Aerospace Ground Testing Conference", Colorado Spring, June 1994.

[*10*] H. A. Harbigar, M.Auweter Kurz, S. Faoulas, S. Laure, A. Schöemann, "Investigation of a High Enthalpy Air Flow within a Plasma Wind Tunnel", AIAA-94-2037, AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Colorado Springs, June 1994.
[*11*] M. Ishii, et. al. "Development of the Stabilized 20 kW Arc Heater using Simulated Air", J. Japanese Mech. Society, B-59, pp. 344–347, 1993.
[*12*] Knud Kindler, "The Arc Heated Wind Tunnel (LBK) of DLR", DLR Cologne Internal Report, April 1989.
[*13*] J.H. Painter, R.J. Ehmsen, R.B. Helm, "Development of the MDC 200 Arc Air Heater", McDonnel Douglas Research Laboratories Report MDC Q0432, 1972.
[*14*] Peter H. Dundas, "Induction Plasma Heating: Measurement of Gas Concentrations, Temperatures, and Stagnation Heads in a Binary Plasma System" NASA CR-1527, 1970.
[*15*] Merle L. Thorpe, "Induction Plasma Heating", NASA CR-1143, 1968.
[*16*] Alan C. Echbreth, "Laser Diagnostics Technique for Combustion Temperature and Species". Abacus Press, 1984.
[*17*] Franz Mayinger (Ed), "Optical Measurement —Technique and Application—", Spinger-Verelag, 1992.
[*18*] Copper LIF velocimetry of the Arc Heated High Enthalpy Flow (to be published).
[*19*] Inatani, Y.," One Dimensional Nonequilibrium Flow", Internal Report, IRS University of Stuttgart, 1991.