ISAS HIGH ENTHALPY FLOW FACILITY FOR THERMAL PROTECTION MATERIAL TESTS

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Abstract

A 1-MW segmented-type arc heater is installed in the ISAS high enthalpy flow facility. The facility has been conducting heating tests of the thermal protection material used for reentry capsules and for sounding rockets. The aerothermodynamic flight environment for the vehicles, generally speaking, can not be duplicated in the ground facility. In this meaning, the simulated flow environment needs to be well-characterized for heating test in addition to understanding of its effect on the thermal behavior of the materials. The high enthalpy flow is characterized not only by conventional sensors, but also by laser induced fluoresece technique. This paper describes the performance and flow characterization of the ISAS high enthalpy flow facility and its activities in relation to the thermal protection material tests.

1. Introduction

ISAS has several reentry missions for the present. In the final phase of the MUSES-C mission[1] , a small capsule with asteroid sample conducts reentry flight directly from interplanetary transfer orbit. In DASH mission[2] , a capsule enters the earth atmosphere from geosynchronous transfer orbit as " a demonstrator of atmospheric reentry system with hyperbolic velocity" which is an origin of the mission name. High enthalpy flow facility is indispensable to not only development of thermal protection material but also functional verification of components of the thermal protection systems. The aerodynamic heating load the capsules will encounter in these high velocity reentry missions is estimated to be beyond $10MW/m^2$. In heating test for the high heat load mission, simulation of the heat flux is the crucial issue more than simulating any other parameters. Mach number for example should fall into of secondary priority in comparison with the heat flux according to the issue to be tested. On the other hand, flight environment of the ascent phase of sounding rocket is low enthalpy and high impact pressure. Since the excessive heat flux tends to prevent proper evaluation of thermal protection materials, heating condition with low enthalpy needs to be simulated in the ground test. For the heating test of materials or components, thus, the environment needs to be well-characterized and carefully conditioned taking account what is essential to thermal behavior of the material. In characterizing high enthalpy flow, conventional sensors such as heat flux sensor and pressure probes are valid for macroscopic feature of the flow, and optical technique such as LIF (laser induced fluorescence) technique is advantageous to measurements of flow velocity, temperatures, and chemical species composition.

This paper describes the performance and flow characterization of the ISAS high enthalpy flow facility and its activities in relation to the thermal protection material tests.

2. Arc Wind Tunnel Facility

Figure 1 shows a block diagram of ISAS arc wind tunnel facility subsystems; The facility is divided into 6 major subsystems ; 1) arc heater, 2) power supply system, 3) gas supply system, 4) exhaust system, 5) cooling water system, and 6) measurement system. The facility has two sets of arc heaters; one is Huels type arc heater and the other is a segmented-disk type arc heater. Although common subsystems are so designed that heaters can be exchangeable in accordance with the required enthalpy level, the segemted-disk type is now eagerly in use. It is because enthalpy range of the segmented-disk type covers that of Huels by changing its disk configuration. The specification of each heater is shown in Table-1.

Segmented-type arc heater

ISAS segmented-disk type arc heater consists of the rear anode part, the converger part, constrictor disk parts, diverger part, and front cathode part as shown in Fig. 2. Each disk is made of oxigen-free copper, and is electrically insulated each other by ceramic insulator. The working gas, normally air, is supplied into each segmented disk through gas supply tubing connected to the mixing bottle which diminishes pulsatory supply. And the gas enters the boa inside through 4 swirl injection ports connected to the slot-gap along the ceramic heat shield. The arc discharge is stabilized between the two electrodes located at the end of converger/diverger part respectively where the flow decelerated by area expansion effect takes not a small part in stabilization of the arc. In order to minimize the electrode erosion due to the current concentration, an axial magnetic field is applied to the arcfoot by a magnet coil built inside each electrode segment. The arcfoot rotates in radial plane under the influence of the Lorentz force. Each disk is independently water-cooled by demineralize water with conductivity below 20 μS. Constrictor disks are arranged together into 4 constrictor disk packs, with 14 constrictor disks per pack. The number of installed constrictor packs can be changed in accordance with the required enthalpy level as will be described in the following section. Since the segmented-disk type arc heater is fixed-arc length type heater, the variable range of discharge current is limited by the arc stability in a given disk configuration.

Radiative Heating Simulation

In case of reentry with hyperbolic velocity, namely reentry velocity beyond 10 km/s. In case of MUSES-C asteroid sample return capsule, radiative heat flux of 3 MW/m^2 estimated while the maximum convective heat flux is 15 MW/m^2.The ISAS arc wind tunnel can simulated the radiative heat flux up to 5 MW/m^2 on the area of 1 cm^2 by means of 500W continuous YAG laser system. The wavelength is 1064nm. Intensity distribution in a irradiation plane of the YAG laser is homogenized by an optical rectifier. Laser radiation is lead into the test chamber through quartz window.

Facility subsystems

The power supply is switching regulator type which converts 2500 VAC max. current to DC. Three rectifiers are connected in series to this circuit diminish the current ripple.

The working gas heated and expanded into the test section is first pressure-recovered by diffuser and is evacuated through the heat exchanger by vacuum pumps. After slightly pressurized by the exhaust fan, the exhaust gas is lead to the air cleaner to remove toxic nitric oxide, and finally ejected to atmosphere. Vacuum pump system is composed of 3 mechanical booster pumps and 2 oil rotary pumps. This evacuation system enables to dump out the working gas flow rate of 20 g/s keeping the test cabin pressure as low as 0.3 Torr.

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. The closed-loop DCW line is used for primary cooling of the arc-heater. In order to keep the desired electrical resistance between the electrodes of the heater, the conductivity of the cooling water is usually maintained below 10 μS. When the conductivity excesses the upper limit of 20 μS, the demineralizer supply new DCW into the line.

The arc jet is expanded through the nozzle into the test chamber. The test chamber is 1.5 m in diameter by 1.5 m long. Entire surface of the cabin is water-cooled by L/P cooling water line. For the optical measurement purposes, seven major windows toward the test section are installed by taking into account of various application for diagnostics purposes. Since 300 mm side windows can cover the all the plum radially expanded, absorption spectroscopy with Abel's inversion can be easily conducted. In order to measure the surface temperature of the test piece by a pyrometer or to radiatively heat up the surface by YAG laser, front surface can be seen directly though the front window at the sight angle of 53 deg.

Table-1 Specification of ISAS Arc Heater

Type	Segmeted-disk Type
Discharge Current	300 - 700 amperes
Discharge Voltage	- 2000 Vdc
Maximum Input Power	1 MW
Mass Flow Rate	10 - 30 g/s
Constrictor inner diameter	25 mm
Throat Diameter	10 mm
Nozzle Exit Diameter	25, 40, 110 mm
Inter-Electrode Distance	750mm (4-pack) 325mm(1-pack)
Total Length except Nozzle	930mm (4-pack) 500mm (1-pack)
Flow Enthalpy	3 - 20 MJ/kg
Impact Pressure	0.05 - 0.7 kg/cm^2

Model Injection System

Duration required for the heating test of TPS material such as heat shield especially used for the ballistic entry probes 30 to 60 sec. Maintenance labor is required for the next test run after several operational runs mainly due to decline of the electrical resistance between each segmented-disk. For efficient operation of the arc heater, it is desirable to conduct several tests in one operation run. Reciprocating motion table is installed in the test cabin which enables heating test of five test pieces including heat flux sensor etc. Test piece can be inserted into the arc jet within 1 second of transient motion. While a test piece is under heated in the arc jet, temperature rise of the next piece in the stand-by position is about 10 °C. In most case, this temperature rise can be negligible as long as it is recognized as initial bias, otherwise "one test piece for one operation run" is conducted.

Heater Operation and Control

The segmented-type arc heater is ignited by high voltage breakdown with argon gas filled in the arc chamber. The argon gas supply is terminated and followed by the air toward main discharge within one second after the arc ignition. The discharge current and the plenum pressure are set to the target operational condition that realizes required heating environment. When the heater reaches thermally equilibrium state, normally 30 sec is required judging from temperature rise of the cooling water, the heat flux sensor and impact pressure tubes are injected into the arc jet to confirm the heating environment. After having accomplished the target condition, the test model is injected into the test section.

3. Operation Envelope

Operational Characteristics

Independent operational control parameters are the discharge current and plenum pressure; The discharge voltage is determined spontaneously on the basis of conductivity of the high enthalpy gas and the arc length. The bulk enthalpy of the arc jet is measured by the energy balance method.

$$h = \left(I \cdot V - \Sigma f_i \cdot C \cdot \Delta T_i\right) / \dot{m}$$

where h is the bulk enthalpy, mdot: mass flow rate, I : discharge current , V: discharge voltage, C: specific heat of the water, ΔTi: temperature rise due to operation of i-th cooling water supply tubing., and fi: flow rate.
Since temperature rise due to the flow friction is not negligible this effect is corrected. The operation envelope is shown in Fig. 3. The envelope is not maximum envelope in the exact literal meaning of it, but normal operation envelope in which loads on all systems is relatively light. The lower current boundary is determined by the arc instability due to power supply system and the boundary in the higher current is due to electrode erosion limit.

Figure 4 shows thermal efficiency, defined as ratio of the total flow enthalpy to the input power, vs. gas enthalpy characteristics with parameter of the plenum pressure or arc chamber pressure. It is recognized that the thermal efficiency is higher with higher plenum pressure. At a given plenum pressure, the thermal efficiency decreases with increasing the specific enthalpy. Since the convective heat transfer to the wall is proportional to the temperature gradient at the boundary, the increase of the enthalpy enhance the thermal dissipation at the wall.

Low Enthalpy Operation

As for sounding rockets in the ascent phase, generally speaking, maximum aerodynamic heating occurs at the altitude of 30 to 40 km when the velocity is below 3 km/s. Thus enthalpy for simulating rocket flight environment is much lower than that for reentry vehicles. Heating test with excessive high enthalpy flow make the surface phenomena of the thermal protection material different from that in real flight. Simulating enthalpy level is of great importance for appropriate heating test.

ISAS arc heater can be operated with various number of segment disk packs in accordance with the required enthalpy and the heat flux, impact pressure in the mission as shown in Fig.5. The configuration of 1-pack operation consists of 1 segment pack installed between the diverger and converger. The flow enthalpy in 1 or 2-pack operation ranges 7 to 10 MJ/kg; This is half of the enthalpy in normal 4-packs operation, because the arc heating length is shorten. In order to obtain lower enthalpy without arc instability, it is good to install the cooling extension pack downstream of the front (cathode) electrode, which reduces the gas enthalpy down to 3 MJ/kg. The configuration of 1 constrictor pack with the cooling extension is appropriate for heating test of TPS material for sounding rocket; It is true that the configuration fails to simulate maximum impact pressure but can simulate the impact pressure at maximum heat load.

4. Simulation Environment

For designing of the thermal protection system (TPS) of the hypersonic vehicles, TPS material data and its thermal behavior need to be obtained in the ground high enthalpy facility. Ablator is used for the heat shield of MUSES-C and DASH capsule. For example, ablation blocking effect is empirically expressed as a function of the flow enthalpy, cold wall heat flux, surface temperature, and gas mass flow rate from the ablator surface. Thus, for the development work of the thermal protection material these parameters need to be measured in addition to the flow enthalpy for each heating test.

Convective Heat Flux

Cold wall heat flux is measured by circular foil water-cooled heat flux sensor (Gardon gauge)[3] as shown in Fig. 6. The sensing foil is connected at its perimeter to a heat sink having a thermoelectric potential different from that of the foil material, thus forming thermocouple junction. When the sensor is exposed to a heat source, thermal equilibrium is rapidly established, and the equilibrium thermoelectric potential between center and edge of the foil will be vary in proportional to the heat flux. Injection of the heat flux probe into the arc jet flow durates 1 second which is enough of thermoelectric equilibrium.

Cold wall convective heat flux is expressed as

$$q_c = C \cdot h \cdot \sqrt{P_{02}} / R_n$$

where P02 is the impact pressure, Rn the effective nose radius of the test model and h the specific enthalpy of the flow. In order to attain high heat flux, small diameter of the test piece, higher enthalpy, and higher impact pressure is required. Thermal analysis of the heat shield material is usually conducted under the assumption of one-dimensional heat conduction problem. The minimum diameter of the test piece is determined comparing the heat penetration depth or decomposition depth of the material with the test piece radius. About 25 mm diameter of test piece is minimum from the standpoint of the assumption of one-dimensional heat conduction. Since the variation of the enthalpy as for the discharge current is relatively small as shown in Fig. 3. The variation of the impact pressure as for the distance from the nozzle exit is large as shown in Fig. 7. Thus the heat flux can be changed by distance from the nozzle exit. As shown in Fig. 8, the heat flux on 50mm diam. flat face test piece ranges from 1.0 MW/m^2 at 200 mm from the nozzle exit to 6 MW/m2 at 80 mm in 4-pack configuration. Heat flux of 12 MW/m^2 can be obtained with 25 mm diam test piece at 25 mm from the nozzle. The simulation environment is summarized in Table-2.

5. Laser Diagnostics

Figure 9 shows heating test of MUSES-C Aftbody ablator and a fin component of S-520 sounding rocket, respectively. Heating test of the flat plate requires special treatment, since the the thickness of the boundary layer, the viscous stress at the surface and so on have greater effect on thermal behavior of heat shield material than in the case of stagnation point heating. The heat flux distribution along the flat plate differs as for the distance from the leading edge, it can be measured by heat flux sensors installed on the measurement plated of the same configuration as shown in Fig.10. Conventional sensors are of great use, it is true, but more sophisticated diagnostics, non intrusive optical diagnostics is advantageous for further understanding of high enthalpy flow. Laser diagnostics system has been established in ISAS high enthalpy flow facility as as shown in Table-4.

Velocity Distribution measured by Cu LIF

By using the previously described LIF (laser induced fluorescence) spectroscopy instrumentation, a Doppler shift measurement of these LIF signal gives and ideal non intrusive distribution velocimetry. Fig. 11 is a typical example of 2D image of the expanded flow out of the arc heater in which fluorescence form copper atoms of 578 nm was detected and processed[4]. 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 crosses the vector is virtual extension line of the nozzle wall. It is recognized that the flow direction near the boundary is along this virtual nozzle extension line. The velocity along the radial distance in the flow as shown as hatched line in the upper side of Fig. 11. These results show that the difference of the velocity at the center and at the edge of the arc jet is about 85 %. Then the flow uniformity is satisfiable as long as the diameter of the model is as large as 30 to 50 mm. The velocity measured by LIF and those calculated by corresponding non equilibrium nozzle flow was compared with good agreement. Roughly 80 to 90% of the bulk enthalpy turned out to be converted into the flow kinetic energy.

Flow Temperature Measurement

Nonequilibrium temperatures of nitric oxide has been measured experimentally by multi-line LIF thermometry[5]. NO molecules in a given rotational and vibrational state in γ-band has been selectively excited by laser irradiation. Since the relative intensity of LIF signals are so selected that LIF intensity is proportional to the population distribution of selectively-excited molecules in a given different energy state, nonequilibrium temperatures (rotational and vibrational) can be deduced independently by comparing the intensity under the assumption that Boltzman distribution is applicable to each energy state. In an operation condition

Table-2 Heating Environment of 4-pack

Flow Enthalpy (MJ/kg)	14 - 20 MJ/kg
Heat Flux on φ25 flat face	- 13 MW/m^2
on φ50 flat face	1 - 6 MW/m^2
Impact Pressure	0.05 - 0.7 kg/cm^2
Repetition Frequency	10 Hz

Table-3 Heating Environemnt for Oblique Flat Plate

		Configuration	
	Flight	High*1	Low*2
Flow Velocity (km/s)	2.7	5.5	2.6
Flow Enthapy (MJ/kg)	3.6	15	3-3.5
Recovery Temp (K)	3000	8000	3000
Heat Flux (kW/m2)	200	300	23
dynamic Pressure*3 (kg/cm2)	0.4	0.4	0.06
Mach number	9	no data	no data

*1 High : 4 constrictor disk pack configuration
*2 Low : 1 pack + cooling extension configuration
*3 heat flux measured at 40mm from Leading Edge.

Table-4 Laser Dagnostics System Spefication

Excimer Laser (Lumonics PM-882)	
Laser Medium	XeCl (308nm)
Band Width	1 nm @300nm
Pulse Width	20 ns
Laser Energy	600 mJ /Pulse
Repetition Frequency	10 Hz
Dye Laser (Lumonics HD-500S)	
Wavelength	300 - 800 nm
Band Width	1 cm^{-1} @300nm
Conversion Efficiency	10 - 20 %
ICCD Camera (Hamamatsu C-4077)	
Gate Width	7ns - 14 μs
Wavelength Range	160 - 850 nm

with enthalpy of 10 MJ/kg, the measured vibrational temperature is about 1000 K higher than rotational temperature by 300 K.

6. Concluding Remarks

ISAS arc wind tunnel facility for thermal protection material research and development work was outlined. In parallel with the facility characterization study described here, the segment-disk type arc heater has been extensively used for the development of ablator materials for reentry missions and rocket related applications for thermal protection purposes.

Regardless of the flow chemistry and the nonequilibrium flow characteristics, it is difficult to conduct a correct and detailed estimation of material reaction under highly heated condition by high enthalpy flow. Therefore, studies on diagnostics using optical technique 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 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

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3) Standard Test Method for Measuring Heat Flux using a Copper-Constantan Circular Foil, Heat-Flux Gauge, ASTM E 511-73.

4) K Itagaki, T. Yamada, Y. Inatani, "Measurement of 2-dimensional Velocity Distribution of Arc-Heated Flow by Cu-LIF", ISTS-96-d-18, Proc. International Symposium on Space Technology and Science, Gifu, Japan, 1996.

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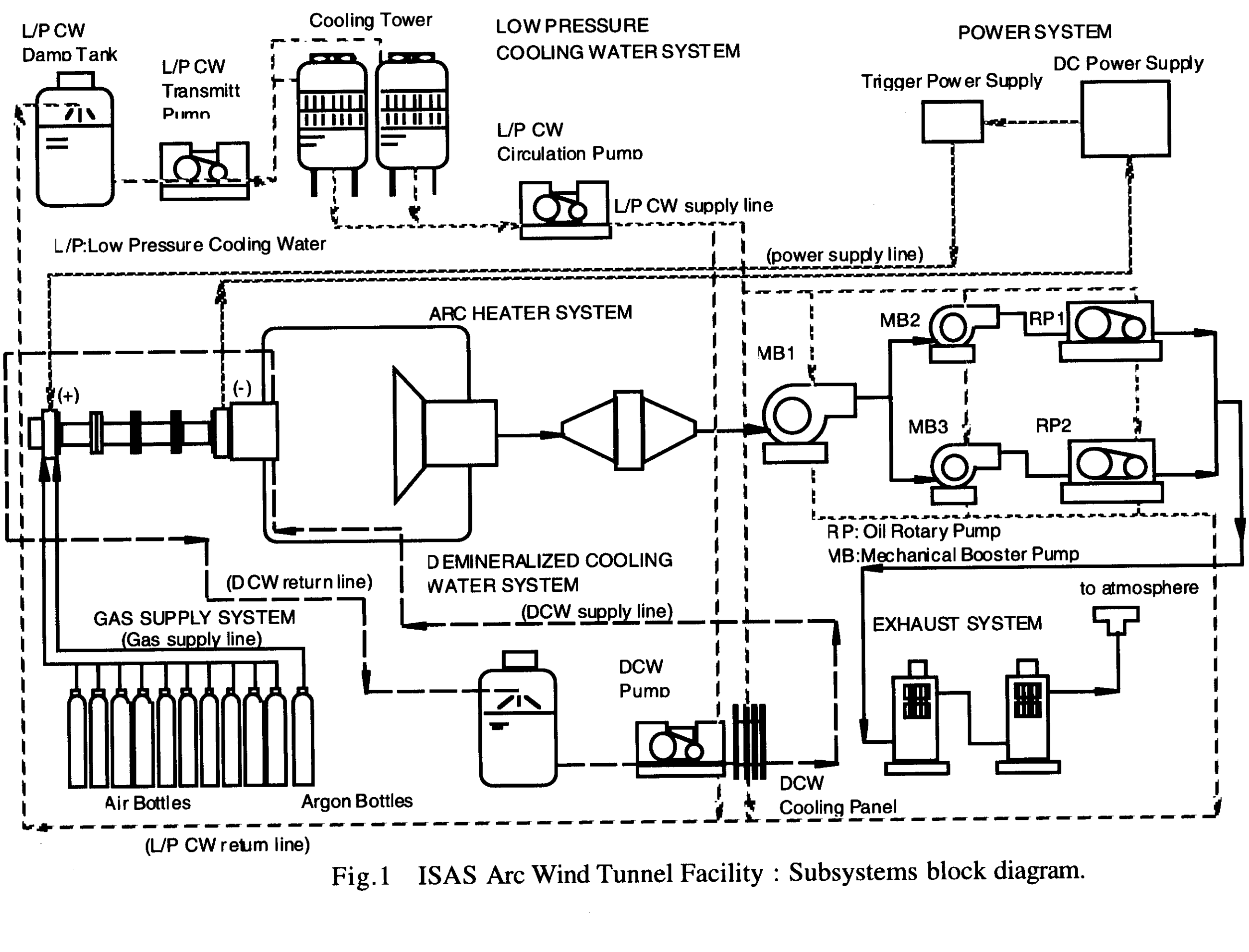

Fig.1 ISAS Arc Wind Tunnel Facility : Subsystems block diagram.

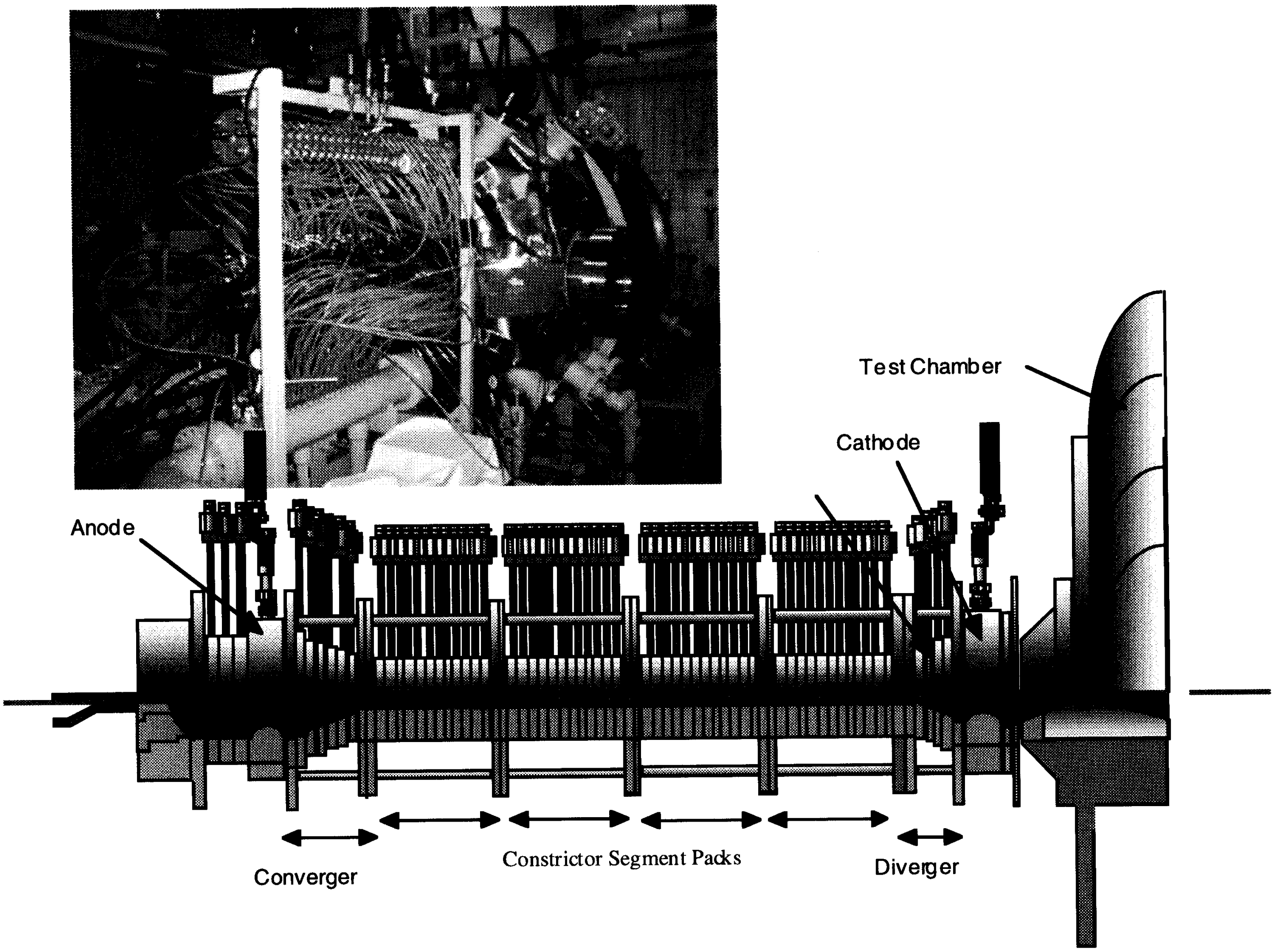

Fig. 2 A Schematic View of ISAS Segmented-disk type Arc Heater.

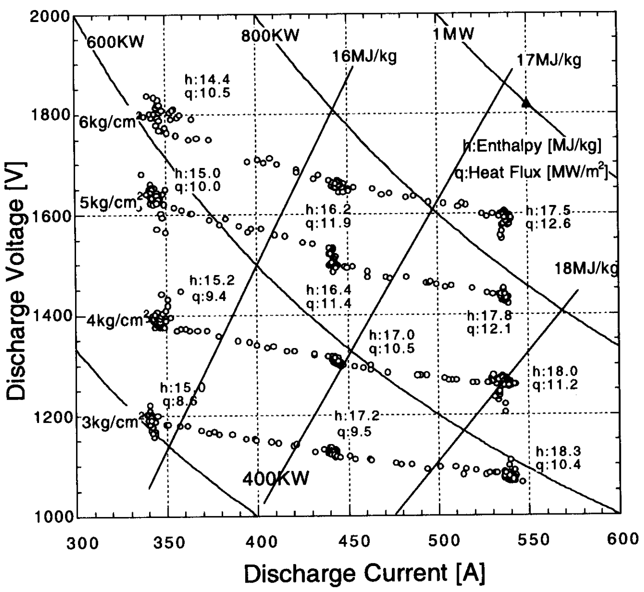

Fig. 3 Operation Envelope of the Segmented-disk type Arc Heater.

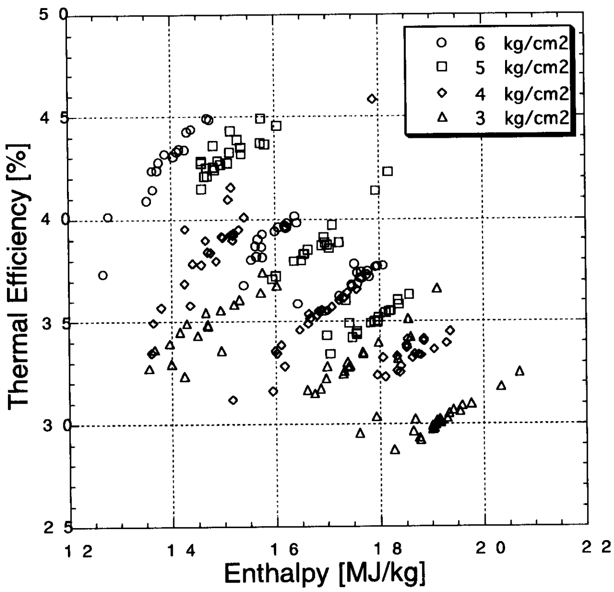

Fig. 4 Thermal Efficiency vs. Discharge Current Characteristics

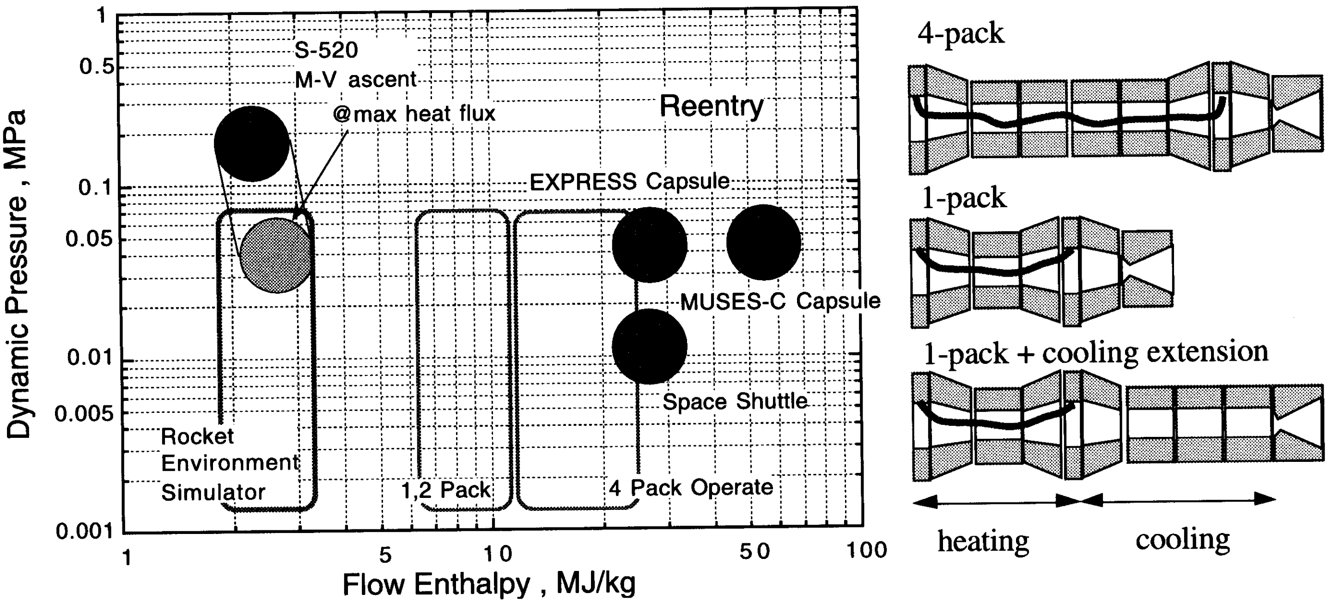

Fig. 5 Impact Pressure vs. Distance from the Nozzle Exit Characteristics

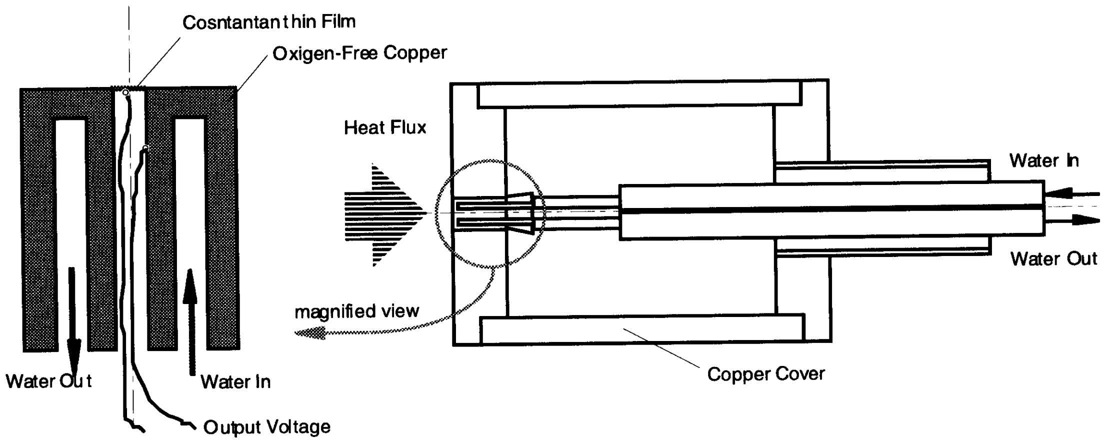

Fig. 6 A schematic View of Heat ϕ50mm diam. Flux Probe (Gardon Gauge Installed)

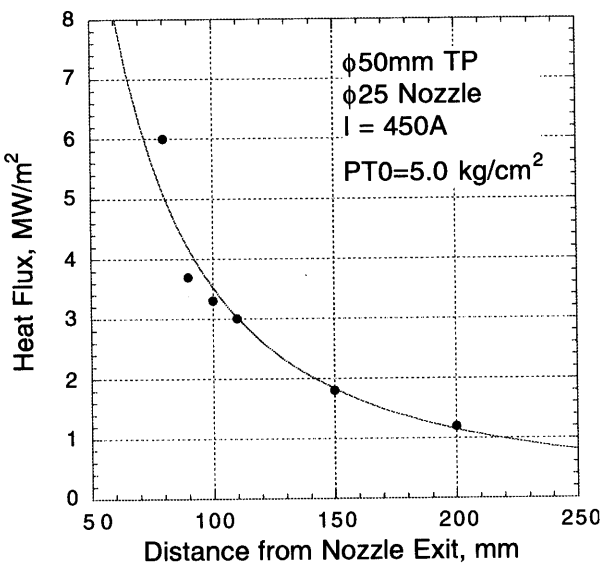

Fig. 7 Heat Flux vs. Distance from the Nozzle Exit Characteristics

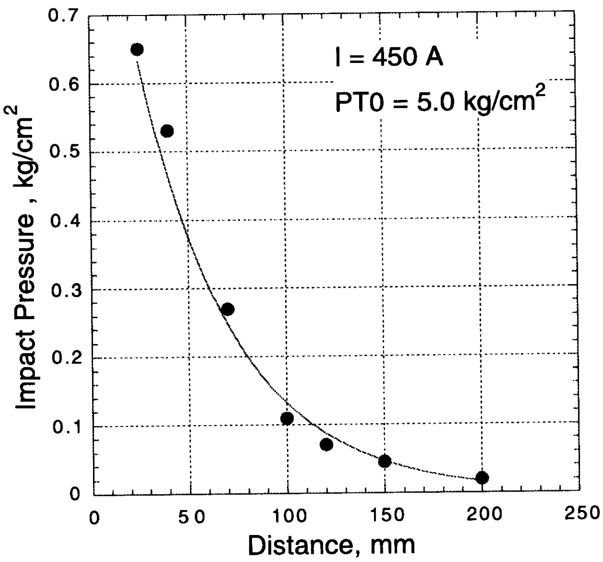

Fig. 8 Impact Pressure vs. Distance from the Nozzle Exit Characteristics

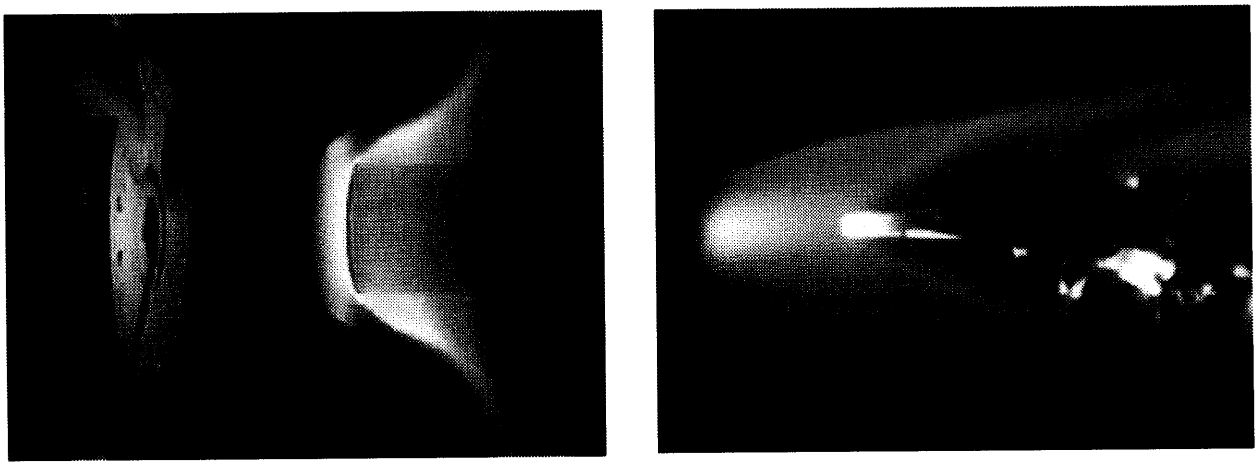

Fig. 9 Thermal Protection Material Heating TestAblator Heating Test.
MUSES-C aftbody Ablartor (left) and S-520 Sounding Rocket Fin (right)

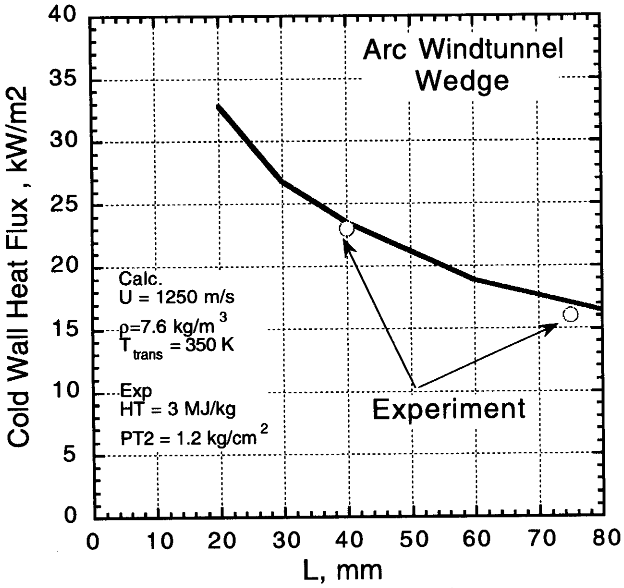

Fig. 10 Heat Flux Distribuion on the plate shown in Fig. 9 (right) behind the oblique shock.

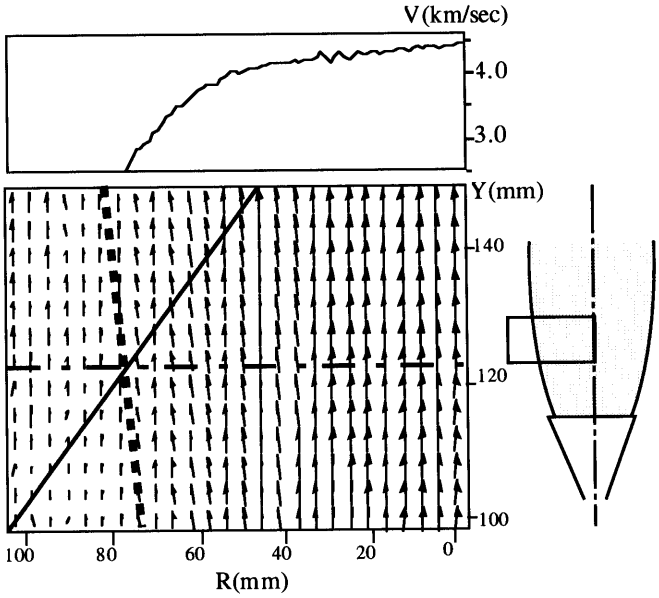

Fig. 11 Velocity Distribution of the High Enthalpy Flow measured by Cu-LIF Technique.
(h = 10 MJ/kg, Nozzle area ration = 300)

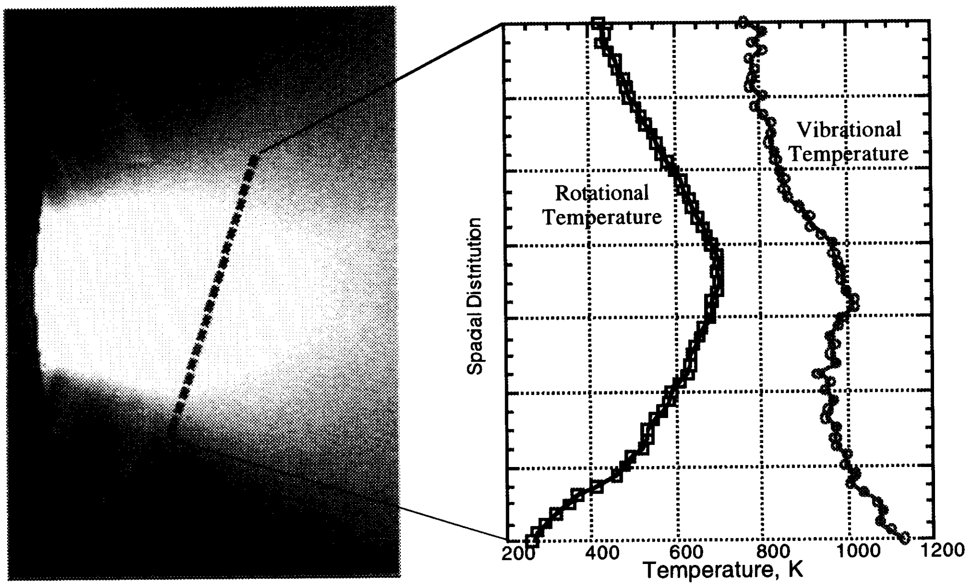

Fig. 12 Nonequilibrim Temperature Distribution of the high temperature expansion flow.