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Jupiter Entry Simulation Using a High-Performance Arc Heater

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Abstract

THE NASA Galileo mission includes entry into the Jovian atmosphere at 49 km/s. Simulation of the high radiative and convective heat flux to the probe's heat shield requires heating mixtures of hydrogen and helium to 16,000 K at pressures to 1 MPa. In order to obtain these severe stagnation gas properties, a new high-performance arc heater (HIPERARC) that immerses the sample heat-shield material inside the arc core is being developed by the McDonnell Douglas Research Laboratories. Initial testing of this device has been completed, and is discussed herein.

Contents

The arc heater used in this work was originally designed to operate on air for simulating Earth entry of advanced strategic vehicles. The original heater utilized long interelectrode segments in the constrictor section, a centripetally cooled forward electrode, and a flared low Mach number nozzle for high-impact pressures and hypersonic pressure distributions on the nosetips being tested. In order to simulate a Jovian entry, it was necessary to modify the heater to: 1) operate on a much lower mass flow mixture of hydrogen-helium, 2) eliminate the small throat-nozzle module to increase the model size and reduce radiative decay and cold gas infusion of the central arc core, 3) sustain the high axial voltage gradient without a strong shroud gas flow, i.e., shortened segments for the reduced mass flow rates, and 4) envelop the model in the central arc core, i.e., in-stream electrodes. The resultant configuration creates a high-radiation (HIRAD) test stream; hence the name HIPERARC-HIRAD. The resulting arc heater is shown in Fig. 1. The constrictor section between electrodes consists of 39 highly cooled segments, each 6.3 mm long and electrically isolated. The end of the constrictor section is the throat of the nozzle, and a 2.5-cm long expander accelerates the flow to either Mach 4 or 1.4.

A mixture of hydrogen and helium is fed into the heater through injection slots at the upstream end of the constrictor (60%) and between each constrictor segment (40%). The rear electrode is a centripetally cooled torus with a magnetic field coil causing the arc termination to rotate rapidly around the inner rear quadrant. The forward electrode is the sting of the model or probe being tested. Thus, the central arc core totally envelops the model and minimizes radiative decay.

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Index categories: Radiation and Radiative Heat Transfer; Research Facilities and Instrumentation; Entry Vehicle Testing, Flight and Ground.

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Each constrictor segment is cooled using a cusp-shaped passage to impart a centripetal acceleration to the flow which sweeps vapor bubbles away from the wall when boiling occurs. This technique significantly increases the allowable constrictor heat flux.

Electrical isolation of the constrictor segments prevents axial current flow and allows each segment to float near the column potential, thereby eliminating performance degradation caused by arc shunts to the wall.

A nominal 50/50 volumetric mixture of hydrogen and helium was selected for the initial tests to enhance the radiative heat flux. The arc heater exhausted into an evacuated test cabin where the pressure was 350 MPa. The initial nozzle was the inner downstream quadrant of a toroidal expander having a 2.5-cm radius flare. The expanding gas accelerated to approximately Mach 4 under these conditions. The current-carrying plasma in the central core also expanded and then attached to a grounded sting in the test stream. The intense central core conducts the arc current flows along the insulated conical holder and then forms the cathode attachment region on the grounded sting. Part of the current-carrying gas remains in the expanding flowfield until it reaches the compression shock in back of the sting. The current is then conducted along the shock to the symmetrical cathode region on the sting. The net effect is that the model is immersed in the highest enthalpy region in the flow, i.e., the arc region where temperatures of the gas mixture are high enough to qualify as a plasma. This yields the highest possible radiative heat flux to the model surface. Later tests were made using a conical expansion section that limited the exit Mach number to 1.4.

Figure 2 illustrates the range of conditions tested in terms of arc current and arc pressure. The measured impact pressures for the two nozzles tested are also shown. The arc current was varied from 800 to 1800 A, which increased the arc pressure from 280 to 420 kPa. The predicted impact pressure for the Mach 4 nozzle agrees favorably with the experimental values measured on the test stream centerline. The lower Mach nozzle yields higher pressure recovery and thus increased

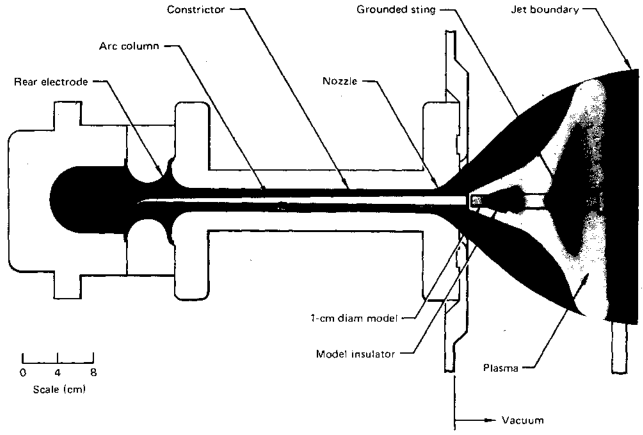

Fig. 1 HIPERARC-HIRAD.

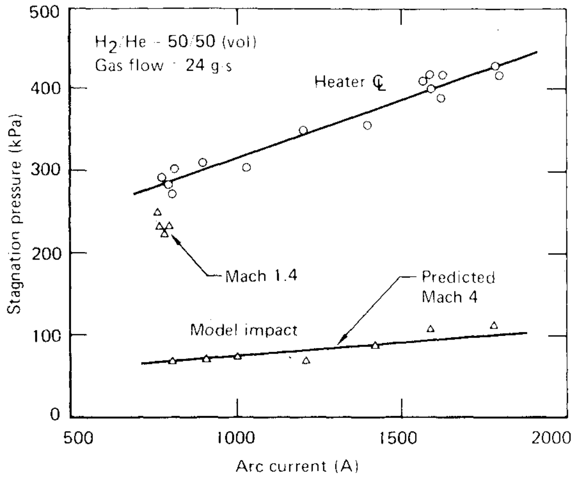

Fig. 2 Arc heater and impact pressures.

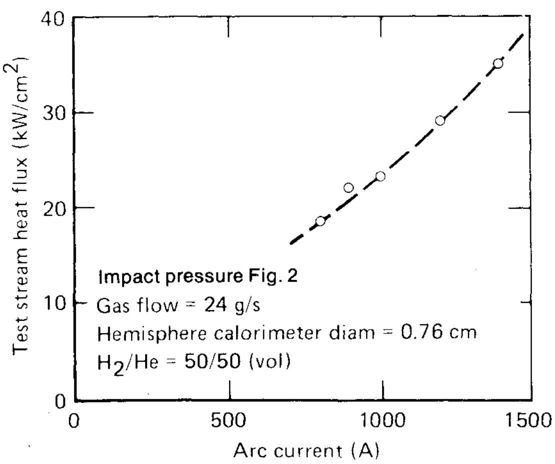

Fig. 3 HIPERARC test stream heat flux.

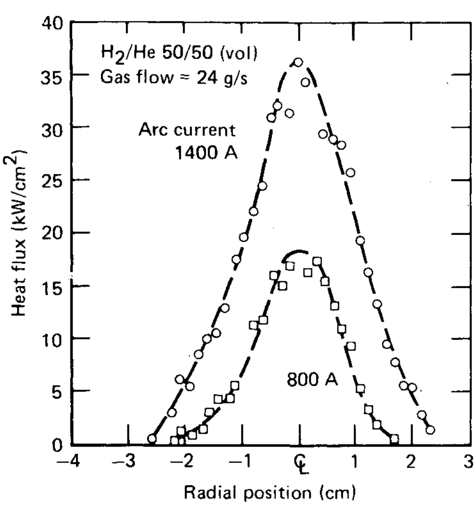

Fig. 4 HIPERARC heat flow profiles.

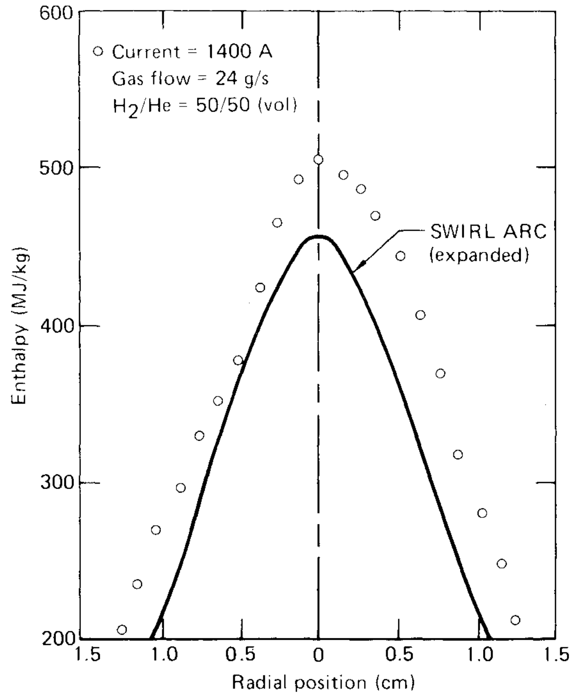

Fig. 5 HIPERARC predicted and computed enthalpy.

gascap density and radiative heat flux. A factor of four increase in impact pressure was realized by reducing the test stream Mach number.

Null-point calorimeters (0.76-cm-diam hemisphere) sweeping at 1.65 m/s were used to document the Mach 4 test stream heat flux profiles. Figures 3 and 4 illustrate these measurements. At arc currents above 1400 A, the calorimeters were destroyed by the high heating rates. The centerline heat flux (Fig. 4) increased from 18 to 36 kW/cm^2 as the arc current was increased from 800-1400 A. The broadened core can be seen in Fig. 4, where the heat flux profiles are shown for two arc current levels. The advantage of high-current operation is apparent.

The measured heat flux and impact pressure profiles were used to calculate the stream enthalpy profile. Figure 5 compares the inferred enthalpy profile with that predicted by the SWIRL ARC code. The SWIRL ARC prediction was expanded from the contstrictor diameter to a diameter consistent with the test stream Mach number. The agreement is good, but more importantly, the enthalpy level is 500 MJ/kg on the stream centerline, which exceeds any published data to date and provides the enthalpy levels needed for Jovian entry simualtion. This enthalpy is in a 50/50 by volume mixture of hydrogen and helium. Higher enthalpies are attainable in hydrogen-rich mixtures. The enthalpy profile indicates that a 1-cm diam flat-face model can be tested at the 450 MJ/kg enthalpy level, and that the test stream is nearly symmetrical.

Acknowledgment

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