

Consolidating NASA's Arc Jets

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The paper describes the consolidation of NASA's high powered arc-jet testing at a single location. The existing plasma arc-jet wind tunnels located at the Johnson Space Center were relocated to Ames Research Center while maintaining NASA's technical capability to ground-test thermal protection system materials under simulated atmospheric entry convective heating. The testing conditions at JSC were reproduced and successfully demonstrated at ARC through close collaboration between the two centers. New equipment was installed at Ames to provide test gases of pure nitrogen mixed with pure oxygen, and for future nitrogen-carbon dioxide mixtures. A new control system was custom designed, installed and tested. Tests demonstrated the capability of the 10 MW constricted-segmented arc heater at Ames meets the requirements of the major customer, NASA's Orion program. Solutions from an advanced computational fluid dynamics code were used to aid in characterizing the properties of the plasma stream and the surface environment on the calorimeters in the supersonic flow stream produced by the arc heater.

I. Introduction

IN 2011 a feasibility study pointed to consolidating all of NASA's high powered arc-jet testing into one location. NASA Headquarters supported the facility consolidation which was completed in 2014. The project replicated at Ames Research Center (ARC) the arc-jet hardware and test conditions from the Johnson Space Center (JSC), while decreasing NASA's overall facility infrastructure, thereby lowering the costs associated with maintaining and operating two arc-jet complexes. The TP1 and TP2 arc jet facilities at JSC were removed and relocated into one existing modular test bay in the arc-jet complex at ARC, (the arc heater relocated to ARC is referred to as "TP3"). Special support systems were designed and installed to maintain the unique test capabilities, including delivery systems for pure oxygen and pure nitrogen as components of the test gas, future carbon dioxide test gas storage and delivery, and a duplicate set of the TP2 water-cooled conical nozzles.

Calibration tests are reported from the recently installed 10 MW arc heater, which will be used to develop and qualify thermal protection systems (TPS). A new control system was developed giving a level of automation needed to improve control of the test gas flow into the arc heater. Experimental data are given from a series of tests completed in 2014 in which the capabilities of the arc heater and some of the new family of conical nozzles were calibrated using pitot and stagnation point heat flux probes. Computational results from the Data Parallel Line Relaxation (DPLR) reacting gas code are compared with these experimental data, and detailed flow field results are presented. Computational simulations were performed to estimate the shear and heat flux levels onto test articles. This paper summarizes the consolidation process, the design of new systems, a comprehensive set of experimental data from the community acceptance test (CAT), and a short overview of computational results of the high enthalpy flow field.

II. Consolidation

NASA evaluated the nation's arc-jet testing capabilities (Calomino)¹, and concluded that maintaining existing arc-jet test capabilities was critical for NASA's missions into the foreseeable future. The Agency, facing limited budgets, therefore decided to preserve all of its unique arc-jet test capabilities, while cutting long term costs, by transferring the arc heaters from the Johnson Space Center to Ames Research Center, and then closing the JSC arc

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jet facility. The two 10 MW arc-heated wind tunnels in the Atmospheric Reentry Materials and Structures Evaluation Facility² (ARMSEF) at JSC, test positions 1 and 2, (TP1 & TP2), were removed, and one of the arc heaters was installed at ARC as TP3. Since TP1 and TP2 used identical arc heater configurations, both facilities could be implemented in a single location at ARC with only a nozzle change.

III. Technical Requirements

The technical requirements for operating the 10 MW arc heaters at ARC were chosen to reproduce existing capabilities at ARMSEF. New controls for gas delivery and arc heater operation were needed at ARC. Test personnel at JSC and ARC documented the ranges of ARMSEF system performance including test gas composition, dynamic response, operating sequence, and operating limits, to maintain these core capabilities upon transferring the arc heaters to ARC. The following unique test capabilities of JSC's arc jets were preserved: (1) simulating time-varying profiles to represent the heating, pressure and enthalpy variations experienced during a spacecraft's atmospheric flight, (in lieu of applying to test articles a steady "flat-top" heating pulse); (2) achieving necessary low heat flux and low stagnation pressure conditions without significant concentration (<10% mass) of argon gas in the test stream mixture; (3) a test gas mixture with a flexible ratio of oxygen to nitrogen; (4) a test gas mixture with a flexible ratio of carbon dioxide to nitrogen; (5) testing to very large diameter stagnation test bodies, of the order of 68 cm (27 in) diameter. Each of these was demonstrated, except for the fifth, which is constrained at ARC by the smaller diameter (122 cm, or 48 in) of the existing exhaust duct. To verify the installation at ARC, the Orion Multi-Purpose Crewed Vehicle, MPCV, program requested a comprehensive series of tests (CAT) consisting of specific sets of flight-profile and steady-state conditions to measure the surface environment to bodies in stagnation and on two wedge-shaped bodies. The successful CAT results, summarized here, together with the CFD simulations, proved that the 10 MW TP3 arc heater relocated at Ames will continue to support Orion-MPCV testing requirements.

IV. Facility

Currently the arc-jet complex at Ames has four operating arc jets operating between 10 MW and 60 MW input power, used to test samples of heat shield materials in high-enthalpy free jet flow fields. One of them is the Aerodynamic Heating Facility (AHF). Apart from this work, the AHF possesses two interchangeable plasma arc heaters, both rated to 20 MW, (one constricted arc heater, and one Huels arc heater). But due to inherent design differences these arc heaters did not reproduce all of the necessary test characteristics of the 10 MW arc jets at JSC. The AHF test location was modified through the consolidation project to include a third interchangeable arc heater relocated from JSC's ARMSEF. The 10 MW unit is a constricted arc heater with dual bore of both 3.8 and 6 cm and variable length from 100 cm to 240 cm. Similar to JSC, this arc heater operates at Ames with test gas mixtures of pure nitrogen, or variable ratios of oxygen-nitrogen, (or future variable ratios of nitrogen-carbon dioxide), all without argon gas. This paper focuses on the 10 MW TP3 constricted-arc heater in the AHF bay.

Under the consolidation project, the AHF test bay and control systems were modified to support the 10 MW arc heater, while retaining the interchangeability in AHF for either of the two 20 MW arc heaters. After removing the 20 MW arc heater, the 10 MW constricted arc heater and nozzle family can be installed and operated using the new test gases and new controls, (the older gas systems and controls are temporarily placed in standby for use with the 20 MW arc heaters, as needed). Changing the arc heater configuration requires removal of the arc heater by an overhead crane, lifting in the desired arc heater, reconnecting interfaces (vacuum chamber, cooling water, dc power, instrumentation, & nozzles), and reconfiguring the control systems. All of the three arc heaters use much of the same infrastructure: test chamber, vacuum pumping, cooling water distribution, dc power distribution, dc power control, model support, and instrumentation systems. All of these systems were in place prior to the consolidation project. The photograph in Figure 1 shows a portion of the 10 MW arc heater and nozzle installed onto the AHF test chamber.

A new family of conical nozzles was fabricated at Ames using the same internal geometry as the TP2 nozzles at JSC. All conical nozzles use the same throat section having an interchangeable copper liner of inside diameter 5.7 cm (2.25 in) surrounded by a cooling-water jacket to provide high speed water cooling to maintain low wall temperatures and structural integrity. The 15-degree half-angle conical expansion of the nozzle is extended by bolting additional conical frusta sections in series producing the following nozzle exit diameters: 12.7, 19.05, 25.4, 38.1, 50.8, 63.5, 76.2, 88.9, or 101.6 cm (5, 7.5, 10, 15, 20, 25, 30, 35 or 40 in). The first two nozzle expanders are constructed of water-cooled aluminum, while the larger expanders are of water-cooled steel construction for

continuous operation. Each nozzle seals to the vacuum test chamber with adapters designed to keep the exit plane of every nozzle visible within the viewing windows of the test chamber, such that the TPS heat shield samples are visible to external cameras. The arc heater mounts to a wheeled cart to adjust its location relative to the nozzle exit plane for all of the varying length nozzles. The throat section of the channel nozzle from the TP1 at ARMSEF was transferred to ARC, but not yet the expander sections.

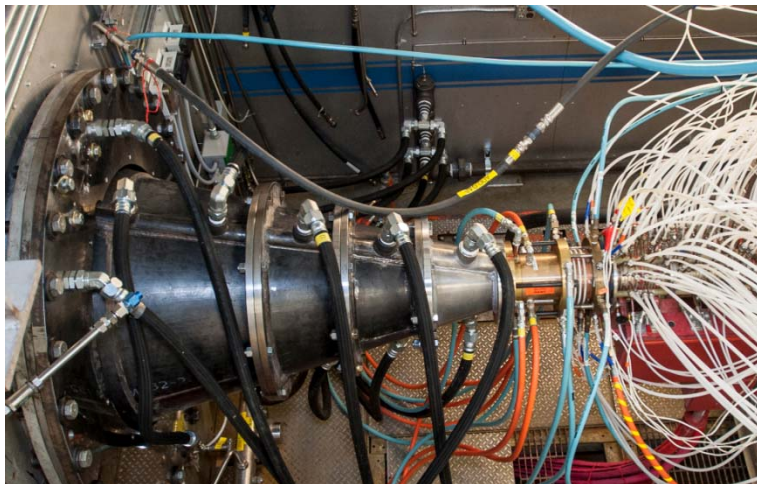


Figure 1. The 10 MW arc heater installed in the AHF with the 102 cm (40 in.) diameter conical nozzle. Flow is right to left.

V. Control System

The control system design for the consolidation focused on the requirements for the range of test gas flow rate, the stability of the gas flow, and the rate of change of gas flow rates. NASA created detailed functional specifications of the control system using symbolic logic diagrams, which was critical to the success of the consolidation. Having the logic diagrams streamlined both the creation of the necessary software commissioning test plans and the troubleshooting that occurs during testing and operations. The system controls the flow rates of start argon, main nitrogen gas flow, main oxygen gas flow, and an optional cold-gas flow (add-gas) that can be injected in a plenum upstream of the aerodynamic throat of the supersonic nozzle to reduce the overall temperature of the test gas stream, if needed. Currently two options for the test gas include: (1) pure nitrogen, or (2) nitrogen plus mixed oxygen, with or without plenum gas injection (add-gas) of room temperature nitrogen gas. Later in 2015 the system will be upgraded to add a third optional mixture: (3) CO₂ and N₂, with or without cold gas injection of CO₂. The control system allows the operator to select the gas mixture for a test, and, during a test, to vary the following: gas flow rates, ramp rates between flow rate set points, and relative concentrations of gases in the O₂-N₂ mixture, and future CO₂-N₂. The system monitors various measured parameters such as the gas flow rates and arc current, and will automatically alert the operator or perform emergency shut down upon detection of out-of-tolerance conditions.

VI. Stagnation-Point Calibration Tests

From September 2013 to August 2014 a calibration test series was conducted to commission the AHF with the 10 MW arc heater. Its objectives, set by the MPCV program, were to demonstrate the major capabilities that NASA required be preserved through the arc-jet consolidation project. These tests fully vetted the operation of the facility with the new arc heater, new set of conical nozzles, new gas delivery systems, and new control system. During this series the arc heater was operated over a wide range of input power settings and gas flow rates. Tests used four conical nozzle exit diameters: 12.7, 19, 50.8, and 102 cm (5, 7.5, 20, and 40 in). Data were acquired from the facility and from various instrumented calorimeter bodies, including stagnation calorimeters and two wedge bodies.

A summary of the experimental data acquired at ARC is shown in Figure 2 for the stagnation-point calorimeter bodies with 10.2 cm (4 in) diameter and a spherical nose radius equal to the body diameter (called “iso-q” geometry). A pitot tap was located close to the stagnation point in the same calorimeter body. The data in Figure 2

were measured on the nozzle centerline by one of two types of stagnation-point heat flux sensors: water-cooled Gardon-type constantan-foil, or uncooled copper slug-type (thermal capacitance). The data cover the range of arc heater power levels from 0.30 MW to 9.5 MW. A video-capture image of the flow field through a side-viewing window port in the test chamber is shown in Figure 3, showing one of the calorimeters in the flow stream. Heat flux data in all arc-heated flows, including this one, are generally considered to be measured to uncertainty of approximately $\pm 15\%$, and the pressure data to approximately $\pm 5\%$. Figure 2 does not represent the entire operating envelope of the arc heater, only that which has been measured to date.

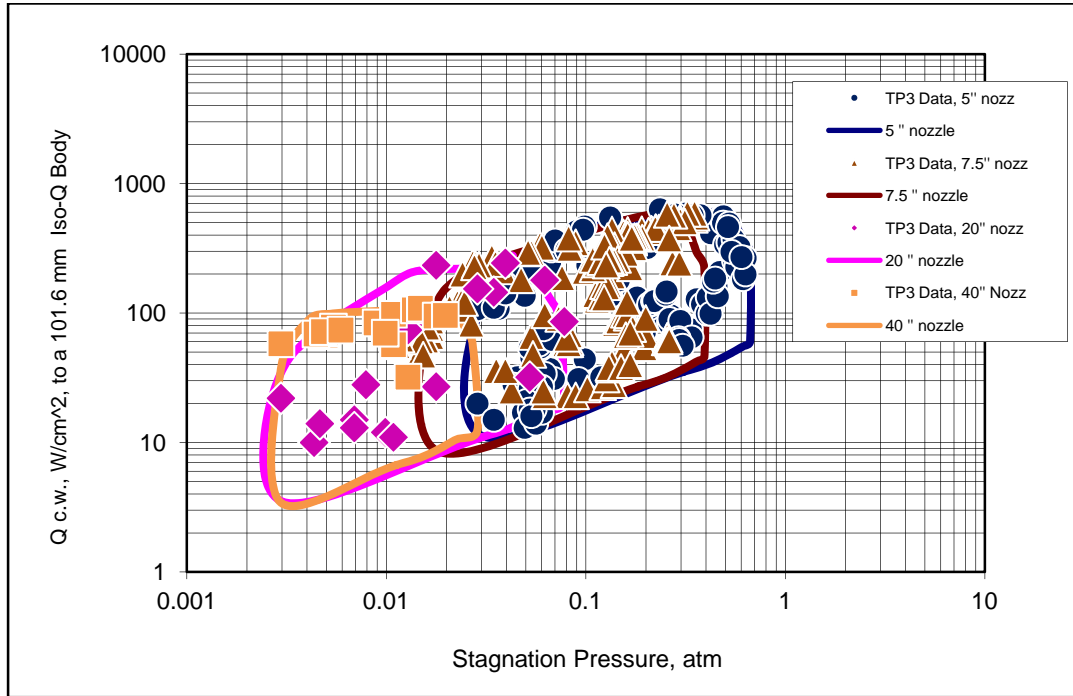


Figure 2. Stagnation point heat flux and pressure data summary

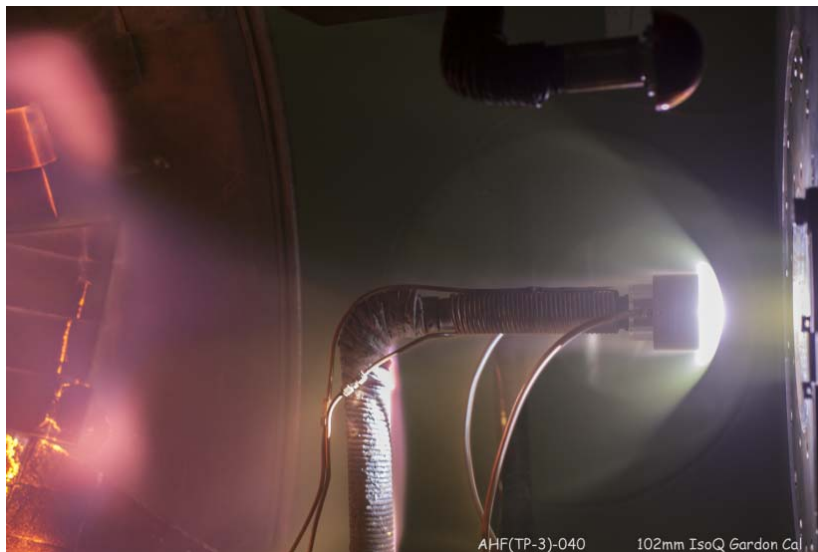
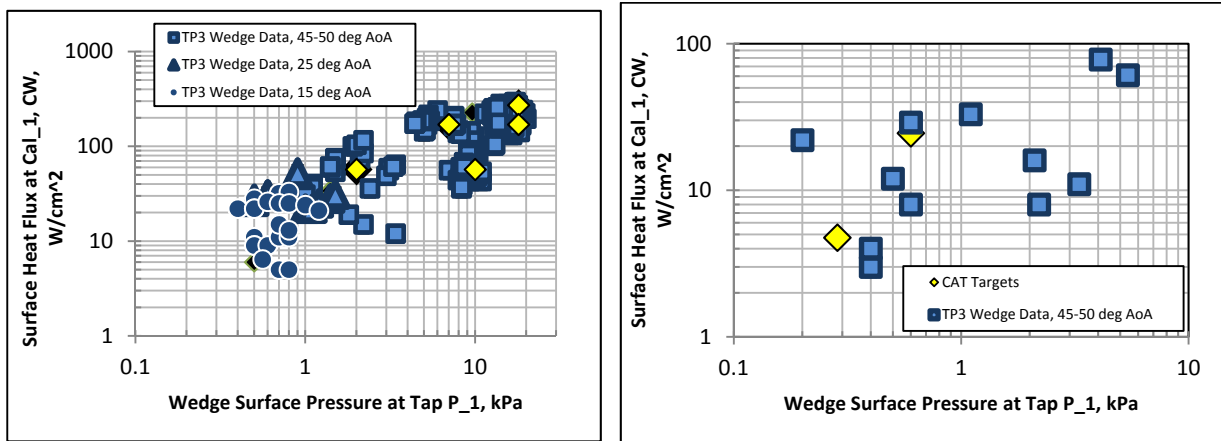


Figure 3. Side view of supersonic flow field and 102 mm diameter iso-q calorimeter body (flow is right to left) (photo no. AHF(TP3)-040 AJD13-aTP-3IST-248)

VII. Wedge Calibration Tests

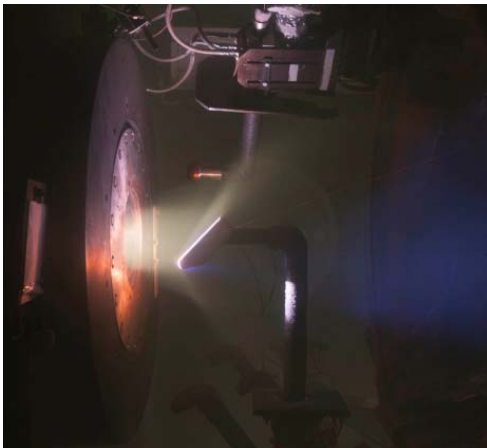
Wedge model holders may be installed in order to test flat samples of TPS materials in shear flow when immersed in the free jet plasma stream. The CAT series included calibration tests to measure the heating rate and pressure environment on an inclined flat wedge surface using two water-cooled copper wedge bodies, 18 cm (7 in) width (for 6x6 in. flat material samples) and 36.8 cm (14.5-in) width (for 12x12 in. material samples). Each wedge is capable of holding either a cooled copper calorimeter plate or a flat TPS sample flush with the wedge surface, and the inclination angle, or angle of attack (AoA), may be changed between runs. Both wedges used the same calorimeter plate installed with Gardon-type calorimeter gages. The objective was to demonstrate the capability of the 10 MW arc jet and nozzles to achieve a specified range of environments on the surface of the wedges. During this series the arc heater was operated over a wide range of input power settings gas flow rates, and conical nozzles. A summary of the data from ARC are shown in Figure 4 and photographs of each wedge are given in Figure 5. The location of calorimeter #1 (of 6) was at the most upstream location on the center of calorimeter plate (see the data circles in Figure 9b). The pressure tap #1 (of 3) is near the #1 calorimeter (see the colored data points in Figure 9a). Figure 4 does not represent the entire operating envelope of the arc heater, only that which has been measured to date.



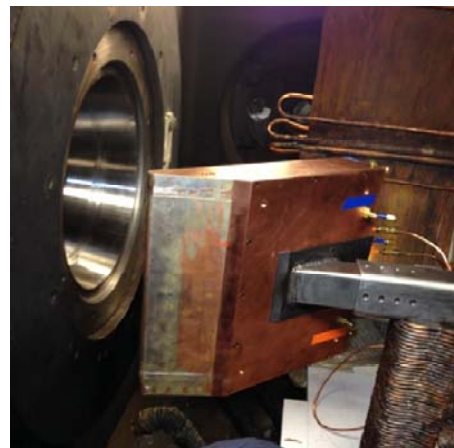
(a) 18 cm (7-in) wide wedge

(b) 36.8 cm (14.5-in) wide wedge

Figure 4. Surface heat flux and pressure data summary from two wedge bodies



(a). Free jet with the 18 cm (7 in) wide wedge calorimeter body



(b). The 36.8 cm (14.5 in) wide wedge calorimeter body between runs

Figure 5. Side views of two wedge test bodies (flow is left to right)

Yellow symbols in Figure 4 indicate target conditions while blue symbols are the experimental data. Wedge angle of attack in Fig. 4 was either 45° and 50° to the centerline, or 25°, or 15°, as indicated by the shape of the symbols.

VIII. Carbon Dioxide

Commissioning tests are planned for the fall of 2015 using varying nitrogen-carbon dioxide test gas mixtures intended to simulate the composition of the atmospheres of Mars or Venus. The objective is to test a new carbon dioxide liquid-gas vapor delivery system, obtain calibration heating data, and verify safe operations when running CO₂. During this series the arc heater will be operated over a wide range of input power settings, gas flow rates, and conical nozzles. Summary data will be published in a later technical paper. Performance of the 10 MW arc heater with carbon-dioxide test gas was previously demonstrated in TP2 at JSC's ARMSEF (Ref. 3).

IX. CFD Simulations

CFD simulations for the 10 MW arc heater tests were performed⁴ to provide accurate estimates of the test environment parameters, provided that the simulations also reproduce measured facility and calorimeter/calibration data. To characterize the flow during the CAT series, the centerline total enthalpy of the test flow is estimated using CFD simulations, and other test requirements such as wedge boundary layer thickness and wedge boundary layer edge Mach number are also verified through CFD simulations. Refer to reference 4 for a detailed description of these simulations.

Computational analyses of the arc-jet tests were performed through simulation of nonequilibrium expanding flow in the arc-jet nozzle and supersonic jet, and simulation of the flow in the test box and around the test articles. For all CFD calculations, the Data Parallel Line Relaxation (DPLR) code (Refs. 5-6), a NASA Ames in-house code, is used. DPLR has been used extensively at Ames for hypersonic flight, planetary entry and arc-jet simulations. DPLR provides various options for thermo-physical models and formulation. For CFD calculations presented in this paper, two-dimensional axisymmetric or three-dimensional Navier-Stokes equations, supplemented with the equations accounting for nonequilibrium kinetic processes, are used in the formulation. The thermo-chemical model employed for the arc-jet flow includes five species (N₂, O₂, NO, N, O) and the thermal state of the gas is described by two temperatures, translational-rotational and vibrational-electronic, within the framework of Park's two-temperature model (reference 7).

The flow field in an arc-jet facility, from the arc heater to the test section, is a very complex, three-dimensional flow with various nonequilibrium processes occurring. In order to simulate the flow field, several simplifying assumptions are made, and corresponding numerical boundary conditions are prescribed for CFD simulations. Simulations of the arc-jet flow are started from the nozzle inlet. The total enthalpy at the inlet is prescribed either as uniform or parabolic based on the facility and calibration data, and the flow properties at the inlet are assumed to be those at thermo-chemical equilibrium. The measured facility data, total pressure (arc-heater pressure), mass flow rate, and test box pressure are used as boundary conditions. The calibration data obtained include stagnation calorimeter heat flux and pressure, as well as water-cooled calibration-plate measurements of cold-wall heat flux and surface pressure at multiple locations on the wedge test bodies. Water-cooled copper nozzle walls and copper calibration plate surface are assumed to be fully catalytic to atomic recombination reactions of N and O at a constant temperature of 500 K. The present computational approach follows some of our earlier work in Refs. 8-10, and details are presented in Ref. 4.

As an illustration of a typical axisymmetric simulation, Figure 6 shows computed Mach number contours of the flow field produced by the 7.5-in exit diameter conical nozzle over an Iso-q stagnation model through a cutting plane at the center of the nozzle extending from the subsonic nozzle inlet into the free jet of the test chamber and past the cylindrical test body that is coaxial with the nozzle on the centerline. The iso-q shape of the 10.2-cm diameter body is defined as a cylinder whose nose radius is equal to its body diameter. The mass flow rate and enthalpy of the test gas in Fig. 6 are listed in the caption for Figure 8.

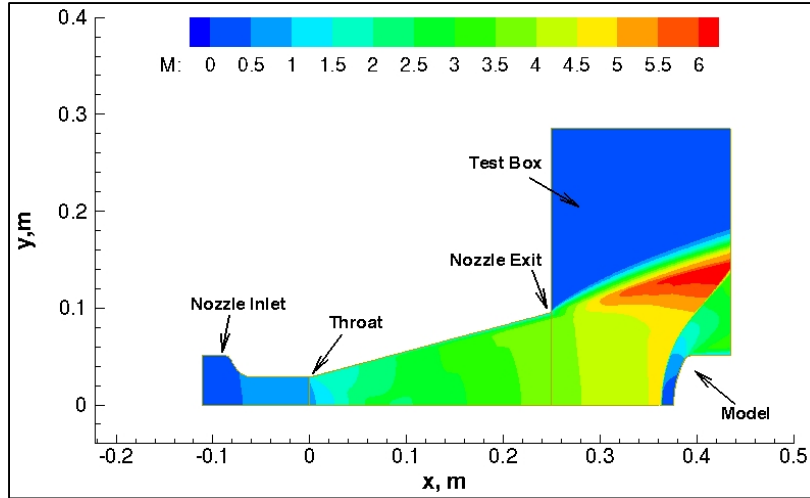
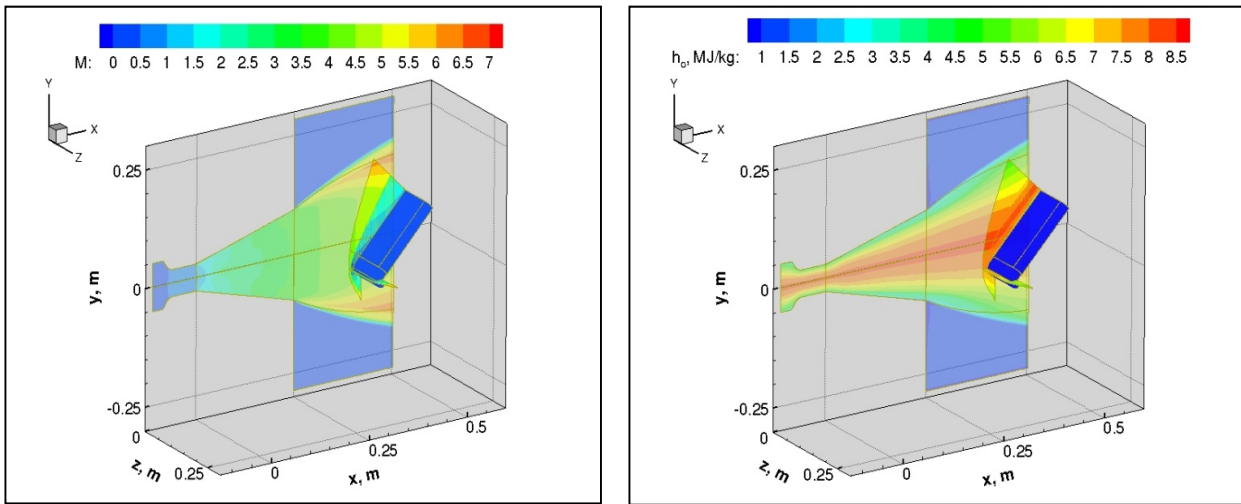


Figure 6. Computed Mach number contours of the 7.5-in nozzle flow with a 4-in diameter iso-q model.

Examples of simulation results for the 7.5-in nozzle with the 45-deg wedge model are shown in Figs. 7-10. Figure 7 shows the computed Mach number and total enthalpy contours of the 7.5-in nozzle flow from the subsonic nozzle inlet to the exit, including the wedge body (in blue) immersed in the free jet inside the test chamber. The contours are shown on the x-y planes of the nozzle flow field (symmetry planes) and on similar planes of interest for the flow field of the test box and over the wedge model. The expansion waves emanating from the nozzle exit into the test box ordinarily affect the shape and strength of the shock formed over the wedge model, hence affecting the pressure distribution on the model. For this CFD case, as in the experiment, the wedge model was tested at an off-centerline location (the stagnation line is ~ 5.7 cm below centerline) in order to reduce the effects of the expansion wave on the uniformity of the model surface pressure.



(a) Mach number

(b) total enthalpy

Figure 7. Computed flow field contours of the 7.5-in nozzle flow with the 45-deg wedge model.

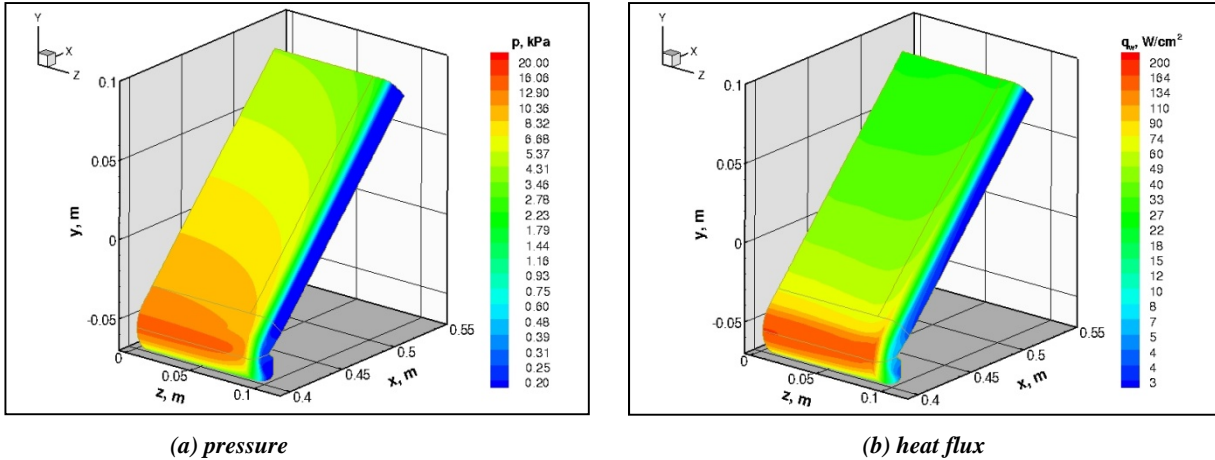
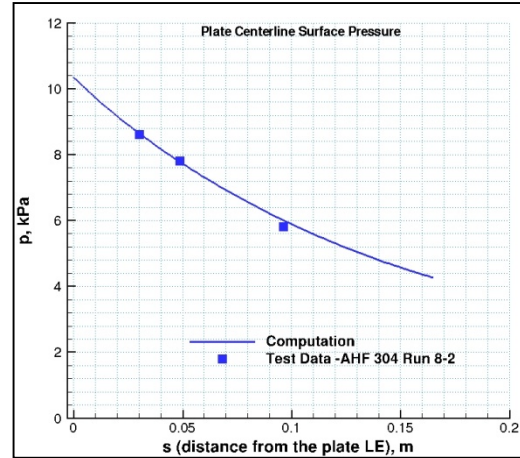
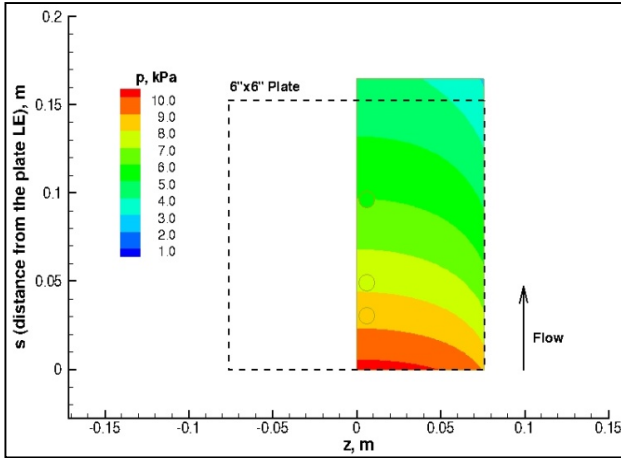


Figure 8. Computed surface quantities, 45-deg wedge model; 7.5-in nozzle: $\dot{m} = 296 \text{ g/s}$, $h_{ob} = 6.0 \text{ MJ/kg}$, $h_{ocl} = 8.1 \text{ MJ/kg}$.

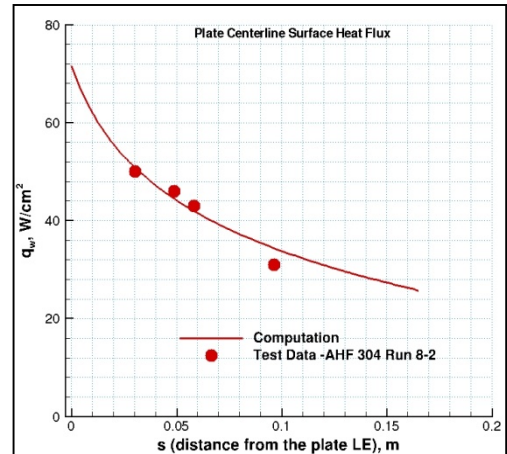
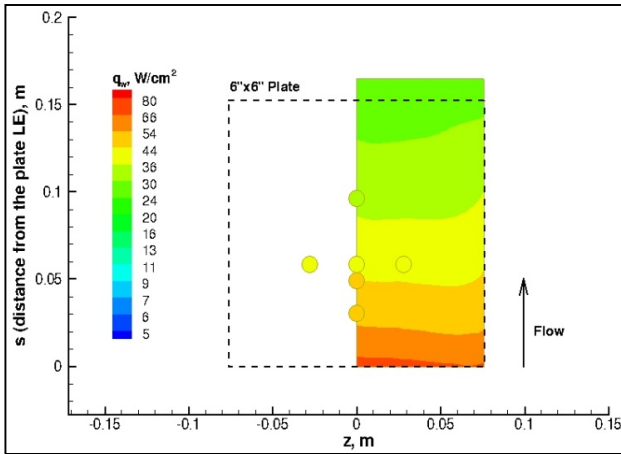
Figure 8 shows contours of the computed surface pressure and heat flux on the wedge model in the 7.5 inch diameter exit nozzle. The wedge model is divided through the centerline at $z=0$. A test model can be installed flush with this surface.

Figure 9 shows comparisons of computed calibration-plate surface quantities (surface contours and their centerline profiles) compared with the test data (circle symbols) from a calibration plate installed on this surface. Note that both computed and measured surface pressure and heat flux drop significantly along the wedge plate centerline. This is primarily a result of the continuing conical expansion of the supersonic free jet inside the test chamber.

Figure 10 shows the distributions of the predicted boundary-layer thickness and edge-Mach number along the model centerline. The boundary-layer thickness and edge-Mach number are often important to evaluate the performance of TPS materials test results and to map the test results to a particular flight environment. The Orion/MPCV program had specific test requirements for the boundary-layer thickness and edge-Mach number for the wedge tests. These requirements can only be verified through CFD simulations. These program requirements drove the choice for high angle of attack (45 + degrees) of the wedge surface, based on these CFD results.



(a) pressure



(b) heat flux

Figure 9. Comparisons of computed contours of surface pressure and heat flux on the calibration plate with the test data (circle symbols) for the 45-deg wedge model; 7.5-in nozzle flow: $\dot{m} = 296$ g/s, $h_{ob} = 6.0$ MJ/kg, $h_{ocl} = 8.1$ MJ/kg.

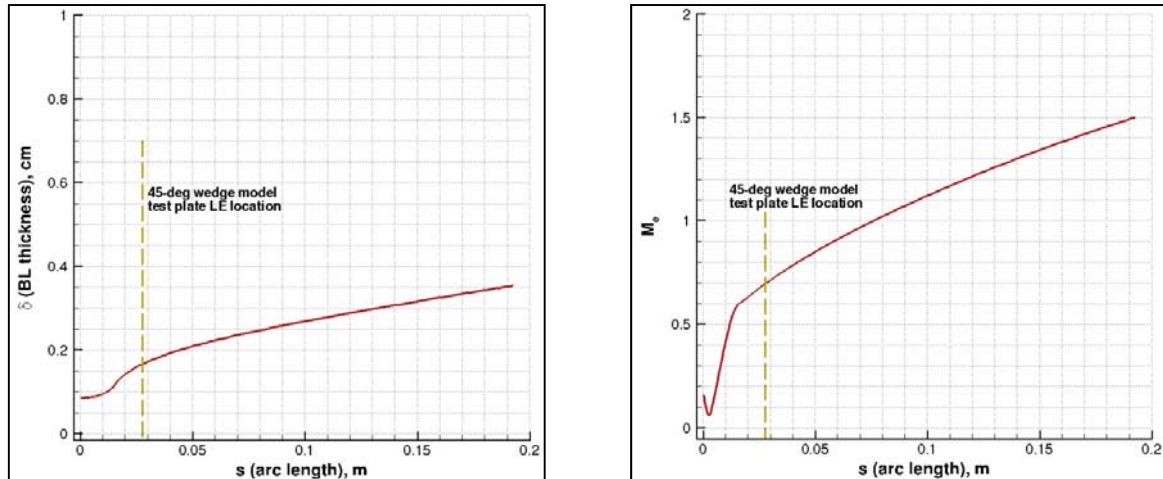


Figure 10. Computed boundary layer thickness and edge Mach number along the centerline of the 45-deg wedge model; 7.5-in nozzle flow: $\dot{m} = 296$ g/s, $h_{ob} = 6.0$ MJ/kg, $h_{ocl} = 8.1$ MJ/kg.

X. Summary

Consolidation of NASA’s high powered arc-heated test facilities at a single location has been completed. The capabilities of the 10 MW arc heaters, TP1 and TP2, at Johnson Space Center, and the hardware, were transferred to Ames Research Center to preserve unique testing capabilities for development and operation of thermal protection materials and systems for NASA’s future space missions, while shutting down the JSC arc-jet test facility. In order to integrate the TP3 arc heater into the Ames arc-jet complex, a new control system with new gas delivery systems was custom developed and installed. This paper reports on the capabilities of the consolidated arc heater equipment showing both experimental and computational results. A comprehensive test series acquired data measuring the surface heat flux and pressure on stagnation calibration bodies and on flat calibration plates mounted onto two wedge holder bodies in the free stream of the plasma flow. The data cover nearly the entire operating range of the newly installed 10 MW arc heater (TP3) using four conical nozzles. Test gases were mixtures of N_2 and O_2 . In the near future will come an option for N_2 - CO_2 test gases. CFD simulations of the high-enthalpy flow field were used to characterize, and guide the planning of, the experiments in the new arc heater. Computational results are compared with experimental data, and are used to interpret the experimental data. The CFD results also provide valuable insight into flow-field parameters that cannot be measured by experiment. The new AHF configuration with the 10 MW arc heater is operational using a family of nine conical nozzles with exit diameters from 12.7 cm (5 in) to 102 cm (40 in).

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