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Arc Heater Nozzle Heating Test with Hydrogen Combustion Products

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A single-edge expansion test nozzle was tested in the Large Core Arc Tunnel of the McDonnell Douglas Corporation Aeromechanics Laboratory to obtain hypersonic vehicle flight-level nozzle heating data by using water to simulate hydrogen combustion products. The test objectives were to expand the data base for nozzle thermal design and computer code validation. A total of 34 runs were made for 15- and 25-deg nozzle ramp angles and water content of zero and 15 mol%. Six gauges each of heat flux and pressure were installed along the centerline of the nozzle ramp surface and one each at an off-centerline location. The fixed lower cowl was instrumented with two pressure gauges. Higher water injection rates produced higher heating rates, as did a higher enthalpy and lower ramp angle. Test data compared favorably with BARTZ and BLIMPK88 code predictions with equilibrium chemistry.

Introduction

THE peak heating rates on the engine exhaust nozzle surface of hypersonic vehicles are expected to range from 500 to 750 Btu/ft^2-s at the combustor exit. The remainder of the nozzle airframe surface will experience heating rates less than 250 Btu/ft^2-s. These surfaces will require active cooling by the cryogenic hydrogen fuel. Actively cooled hydrogen heat exchanger design and optimum fuel flow management require accurate nozzle heating environment.

Most powered model tests use ambient air or other simulant gases to obtain nozzle pressure distributions. Heating data from these tests are seldom available due to the difficulty in designing a suitable test article and the absence of a design requirement to precisely map nozzle heating. A typical hypersonic vehicle nozzle is a single-edge expansion ramp nozzle with a shorter opposing cowl.

Most of the earlier nozzle heating tests could neither match the flight nozzle heating levels nor simulate the hydrogen combustion products. Because of the safety issues, high-temperature flow tests, where combustion of hydrogen takes place, are not routinely run. It is predicted that up to 20% of the exhaust gases from the hypersonic engines when operating on hydrogen fuel/oxygen will be water vapor. Because of its high enthalpy and surface recombination, water vapor can dominate the heat transfer processes.

The Large Core Arc Tunnel (LCAT) of the McDonnell Douglas Corporation (MDC) Aeromechanics Laboratory is unique in that it is capable of not only providing gas temperatures up to 12,000 R and heating rates up to 500 Btu/ft^2-s, but it is also capable of injecting water into the arc heater chamber upstream of the test nozzle to produce a well-mixed water and air flow that simulates hydrogen combustion products.

Test results were compared with two computer code predictions. Boundary Layer Integral Matrix Procedure with Kinetics, 1988 (BLIMPK88)[1] is a widely used state-of-the-art two-dimensional code for nonsimilar laminar and turbulent boundary-layer flows of chemically reacting systems. BARTZ is an engineering code developed from the Bartz[2] method for nozzle flow heating.

Testing

Test Facility

The test was performed in the LCAT facility of the MDC Aeromechanics Laboratory in St. Louis. The LCAT is a continuous-flow, arc-heater-driven, free-jet aerothermal test facility. For this test the MDC-200 arc heater supplied the test gas mixture for expansion through a rectangular nozzle extension and the test nozzle.[3]

In the MDC-200 arc heater a high voltage arc is maintained between tandem electrodes, and the test gas is tangentially injected between the electrodes to create a stable test condition. The injection point of the water–air mixture is at the left end of the arc heater, as shown in Fig. 1. The mixture is spun and heated along the full length of the heater, with a well-mixed flow exiting the heater through the nozzle at the right. The mass flow through the nozzle throat for these tests was verified by stream sampling and stream tracing. The LCAT nozzle chosen for this test was contoured to provide Mach 2.2 flow into the test nozzle.

To quantitatively check the level of mixing of the water vapor and air, surveys of the test stream exiting the arc heater nozzle were performed. These surveys are conducted with a null point calorimeter and a recovery pressure probe, both swept through the centerline of the nozzle. The profiles of pressure and heat flux measured were then compared with the profiles measured for dry air. The profiles were checked for uniformity and plateau levels and compared with the dry air arc heater operating conditions.

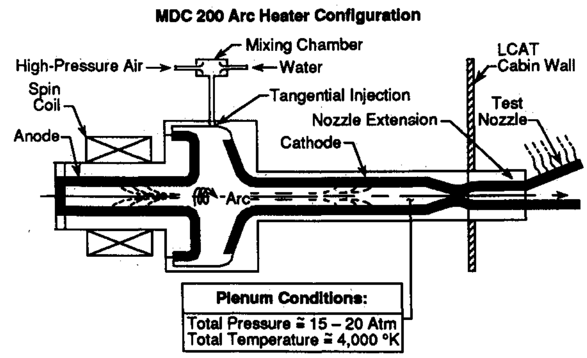

Fig. 1 Water injection used to simulate hydrogen combustion products effects on nozzle heating.

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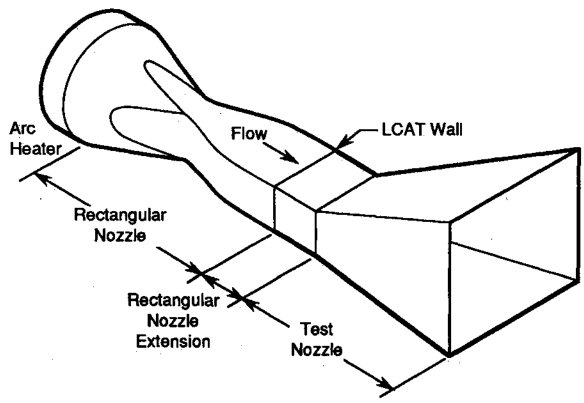

Fig. 2 Test nozzle arrangement.

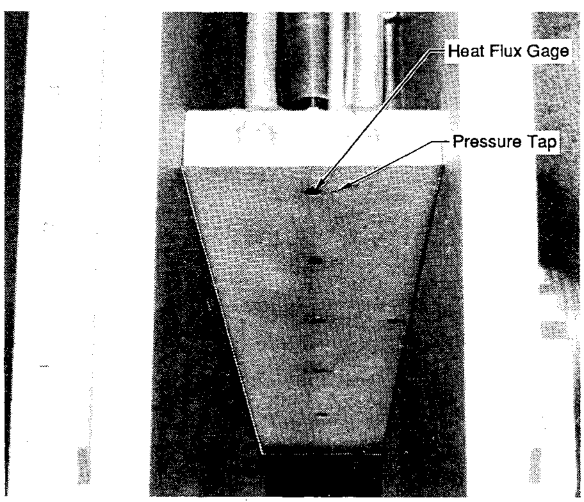

Fig. 3 Test nozzle (looking into throat).

Test Model

A two-dimensional single-edge expansion nozzle test unit was designed to simulate the flow predicted for the nozzle surface of the hypersonic vehicle. The test nozzle was connected to the arc heater as shown in Fig. 2. The transition from the axisymmetric arc heater flow to two-dimensional flow was achieved by using a 1-in.-long rectangular extension nozzle.

The test nozzle is made up of four water cooled copper plates: a movable expansion ramp upper plate, the primary test surface; a flat cowl lower plate, which extends the bottom surface of the rectangular extension nozzle; and two flat side plates, which were angled away from the flow to accommodate boundary-layer growth. The test nozzle can be set at expansion ramp angles of 15 and 25 deg (Fig. 3).

Instrumentation

A detailed layout of the test nozzle is shown in Fig. 4, with the location of each heat flux and pressure gauge defined. The upper ramp surface was instrumented with seven pairs of heat flux and pressure gauges, six at the centerline and one off centerline. Two pressure ports were installed on the cowl plate opposite locations three and six on the ramp surface.

Gardon heat flux gauges from the Medtherm Corporation were used in the test. These circular, thin-foil gauges are watercooled and capable of continuous measurement of up to 2000 Btu/ft^2-s. CEC and Statham pressure transducers were used in the test. The CEC transducers have slightly higher accuracy than the Statham transducers.

Arc Heater Performance

Standard data acquisition systems recorded arc heater operating conditions and on-line facility status. Arc voltage and current, chamber pressure, air and water mass flow rates, cooling water flow rate and temperature rise, and test cabin pressure were recorded. Performance parameters derived from basic measurements are heat balance (bulk enthalpy) and efficiency. The nozzle plume was recorded on video during each run and selected runs were recorded on 16-mm motion picture film to provide higher resolution data.

Mass flow rate and arc heater pressure were held essentially constant throughout the test: mass flow rate from 0.701 to 0.771 lb/s and arc heater pressure from 21.7 to 24.2 atm. Thus the total run-to-run variation of air mass flow rate was approximately 10% and the arc chamber pressure was approximately 12%.

The arc heater was operated at three arc current levels: 730, 1100, and 1400 amps. Most of the runs were made at 1100 amp, because this level offered the best compromise between enthalpy performance, steady operation, and electrode erosion. Arc voltage and enthalpy are generally less reproducible than other parameters, because they are influenced by the arc length, which varies within the arc heater.

Water Injection

Figure 5 illustrates how several arc heater parameters vary during a typical run (run 614) with water injection. The air mass flow rate (Fig. 5a) decreases when water enters the arc heater, which keeps the total flow rate constant during the run.

Chamber pressure and arc current (Figs. 5b and 5c) are controlled during the run; however, both are slightly perturbed by water injection. Chamber pressure drops slightly during the water injection. Arc current was decreased slightly throughout the run, but the increase in the amplitude of the current fluctuation during water injection is still evident (Fig. 5c). The current fluctuation is an indication of increased amplitude of the arc motion during water injection.

Arc voltage (Fig. 5d) jumps noticeably during water injection. The resulting increase in arc power input more than offsets both the energy required to complete the vaporization of the injected water and the increased heat loss. Consequently the bulk enthalpy increases during water injection, as seen in Fig. 5e. The reason for the apparent decrease in the bulk enthalpy level is the unsteady heat loss measurement. In contrast, the sonic flow enthalpy level is flat up to the point of water injection (excluding the starting transient), because no heat loss measurement is involved.

Test Stream Diagnostics

Pitot pressure and stagnation point heat flux profiles were measured using the standard facility diagnostic probes, as shown in Fig. 6. Figure 7 shows the pitot pressure profiles taken at three locations. Four measurements were made at

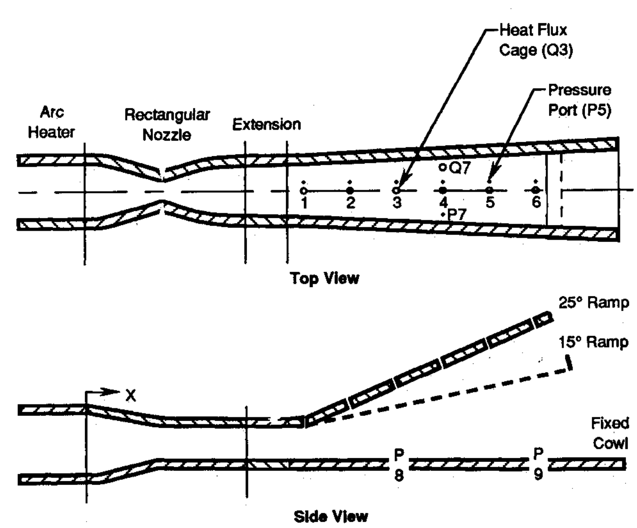

Fig. 4 Nozzle contour and gauge locations.

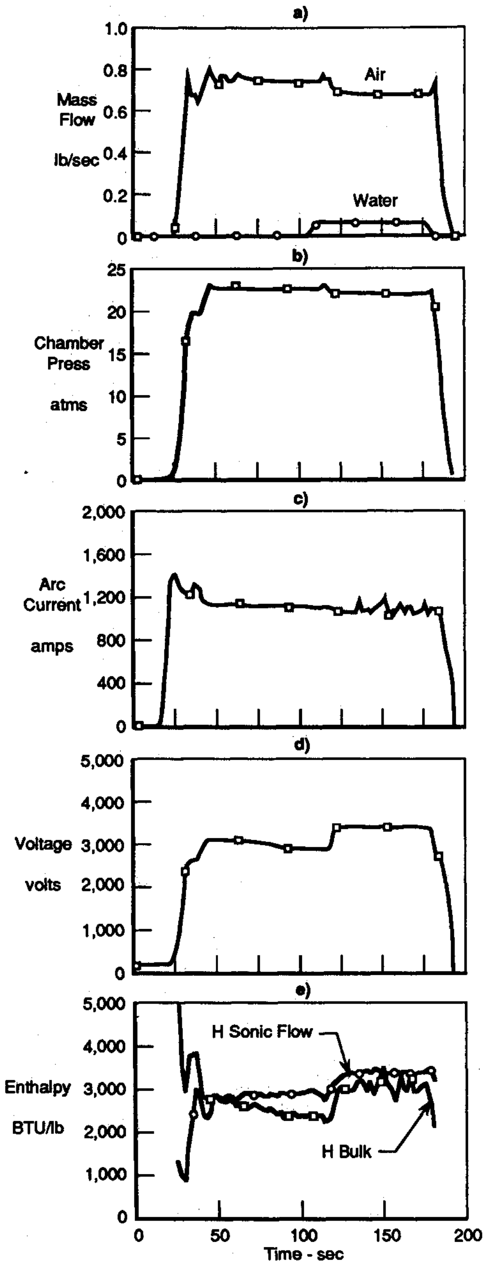

Fig. 5 Typical arc heater parameter profiles (run 614).

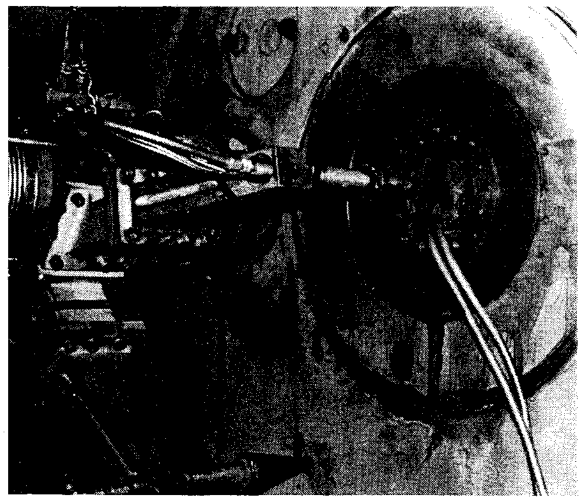

Fig. 6 Heat flux probe.

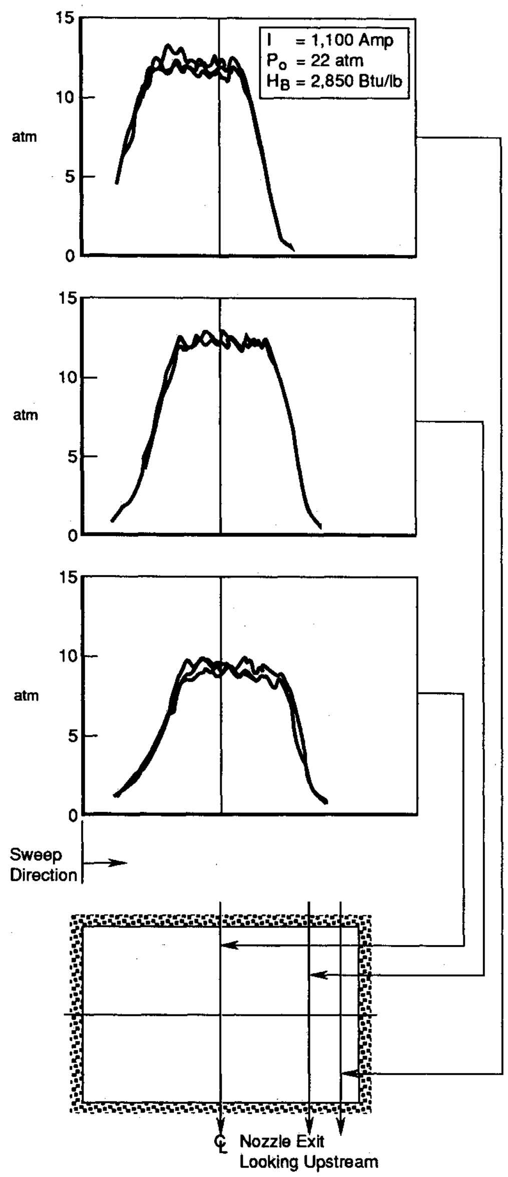

Fig. 7 Pitot pressure profiles across the exit of the rectangular nozzle.

the center and three each at two off-center plane locations. The pitot pressure probe face was positioned approximately 0.375 in. downstream of the nozzle exit. Excellent repeatability of the flow is evident from the profiles.

Stagnation point heat flux profiles (Fig. 8) were taken in the same manner as the pitot pressure profiles with a null-point calorimeter. The null-point calorimeter probe is of a sphere-cone configuration. Although some variations in the profiles are obvious, the general profile trends show run-to-run consistency. Figure 9 shows the effects of water injection on the heat flux profiles. The center plane heat flux is largely unaffected, but the plateau of peak heating is less than half as wide with a more gradual increase leading up to the peak. The pitot pressures are less affected by water injection. Profiles in Figs. 6 through 8 were taken from one of the pretest runs.

Test Data and Discussions

Test Data

A summary of all 34 runs made is shown in Table 1. Nozzle ramp angle, mole percent water, arc operating conditions, and bulk enthalpy are listed for each run. Typical heat flux and pressure time histories for run 619 are shown in Fig. 10: centerline heat flux data in Fig. 10a and all nine pressure profiles in Figs. 10b and 10c.

Discussion of Data

Three aspects of the data are discussed. The first is the flow uniformity data obtained from probe surveys. Second is surface data quality in reference to the arc heater operation. Third is the data comparison with the two analytical methods: BARTZ and BLIMPK88.

Flow Uniformity

Flow uniformity can be evaluated using the pitot pressure and stagnation heat flux profiles obtained at the test nozzle entrance. In addition, examination of streamline tracing on the wall of the test nozzle provided information on the magnitude of the flow swirl component. Both of these evaluation parameters showed acceptable levels of uniformity and repeatability in the flow entering the test nozzle.

The pitot pressure profiles for dry air in Fig. 7 show a relatively uniform profile over 67% of the nozzle width. This, combined with a 10.7 and 8% variation in the pressure levels over the width of the plateau (for the three sweeps each at the two center positions), indicates that the flow velocities are uniform.

Examination of the plateau regions in the stagnation heat flux profiles in Fig. 8 for the same sweep leads to the conclusion that the temperature distribution is not as uniform as the velocity and resulting pressures. The variation averages 28.6% of the plateau magnitude, and a temperature distribution asymmetry is indicated. Fortunately, the nonuniformity is indicated to be in the half of the flow plane farthest from the test nozzle surface.

Surface Data Repeatability

Repeatability of pressure and heat flux measurements on the ramp is demonstrated in Figs. 11a and 11b for the 15-deg

Table 1 Test run summary

Run Number	Nozzle Ramp Angle (deg)	Mole % Water	Arc Chamber Pressure (atm)	Arc Current (amp)	Arc Voltage (volt)	Bulk Enthalpy (Btu/lb)
575	15	0	23.8	1,080	3,080	2,420
576		0	24.2	1,100	3,150	2,740
577		0	23.4	1,100	2,890	2,310
578		0	23.1	1,080	3,130	2,640
580		0	23.0	1,080	3,050	2,430
580		10	22.8	1,100	3,420	2,850
580		10	22.6	1,100	3,080	2,340
580		15	22.6	1,080	3,340	2,450
581		0	22.2	1,130	2,910	2,470
581		10	22.0	1,110	3,200	2,580
581		15	22.0	1,110	3,430	2,740
583		0	23.5	1,400	2,970	2,880
583		10	23.1	1,420	3,180	3,110
583		10	23.1	1,420	3,120	2,860
584		0	23.7	1,430	2,890	2,940
584		10	23.2	1,420	3,220	3,250
584		15	23.2	1,410	3,110	2,810
586		0	22.4	738	3,780	2,140
586		10	21.3	730	3,660	1,810
586	15	15	21.3	721	4,190	2,170
607	25	0	22.4	1,130	2,830	2,180
609		0	22.4	1,110	2,810	2,210
610		0	22.2	1,130	2,840	2,330
611		0	21.8	1,150	2,890	2,370
612		0	23.2	1,430	2,480	2,260
613		0	22.7	1,440	2,760	2,800
614		0	22.4	1,120	2,930	2,340
614		15	21.9	1,090	3,430	2,840
615		0	22.7	1,110	2,880	2,210
615	25	15	22.1	1,110	3,580	3,230
616	15	0	22.1	1,130	2,820	2,310
617		0	22.3	1,130	2,820	2,280
618		0	22.3	1,110	2,930	2,280
619	15	15	21.7	1,120	3,180	2,840

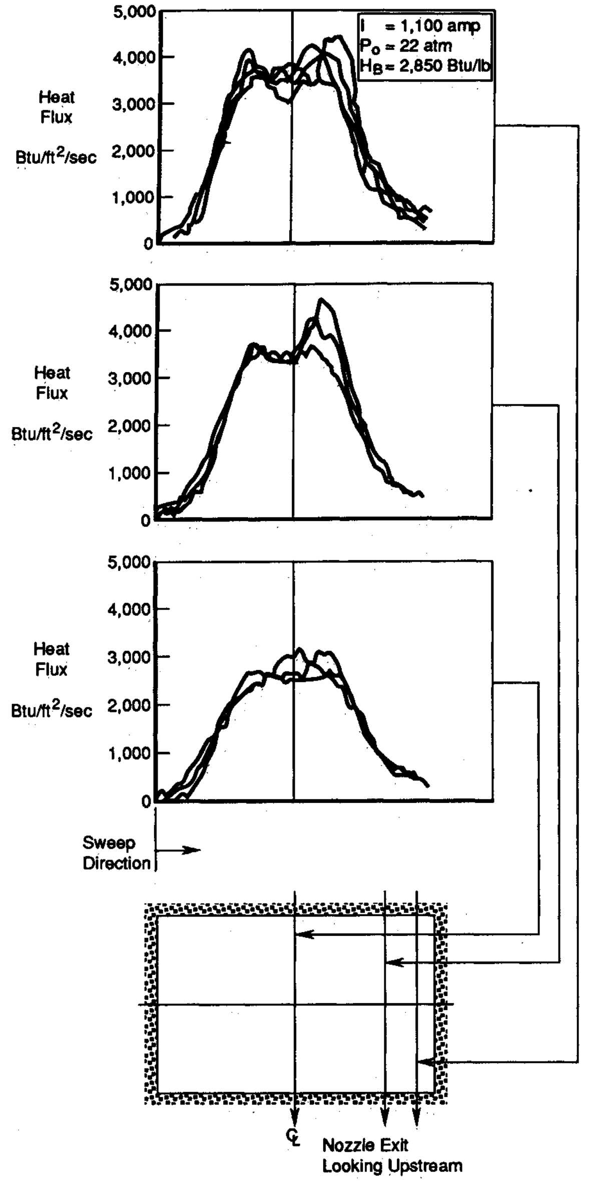

Fig. 8 Stagnation point heat flux profiles across the exit of the rectangular nozzle.

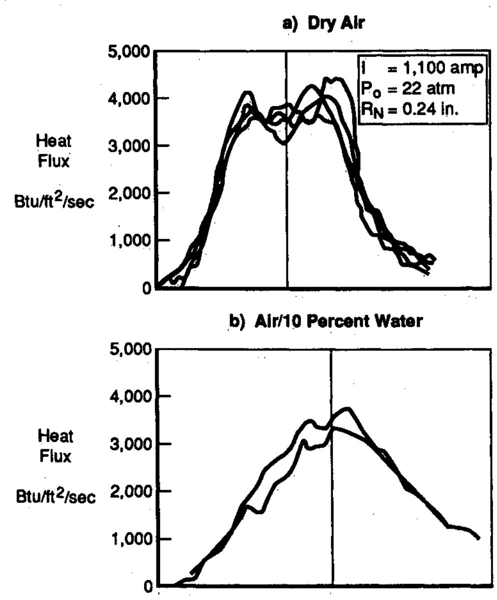

Fig. 9 Effect of water injection on the stagnation point heat flux profiles.

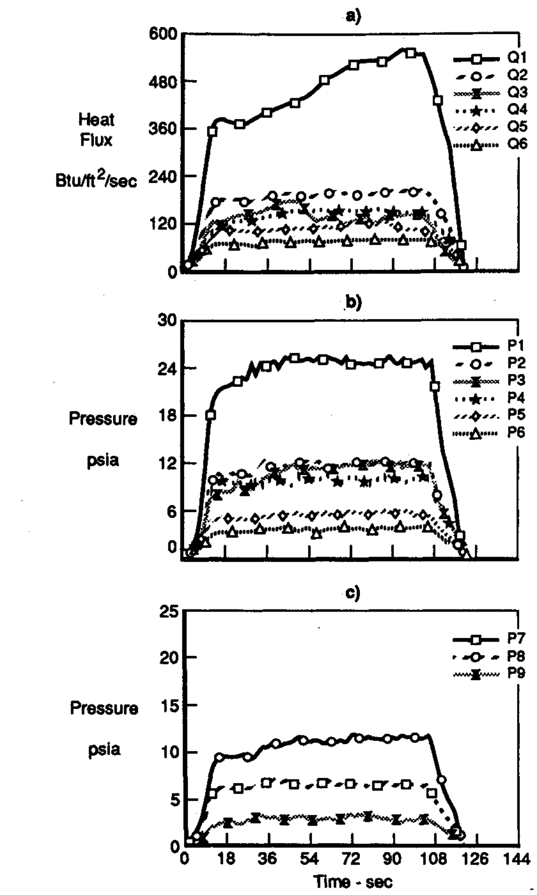

Fig. 10 Heat flux and pressure measurements (run 619).

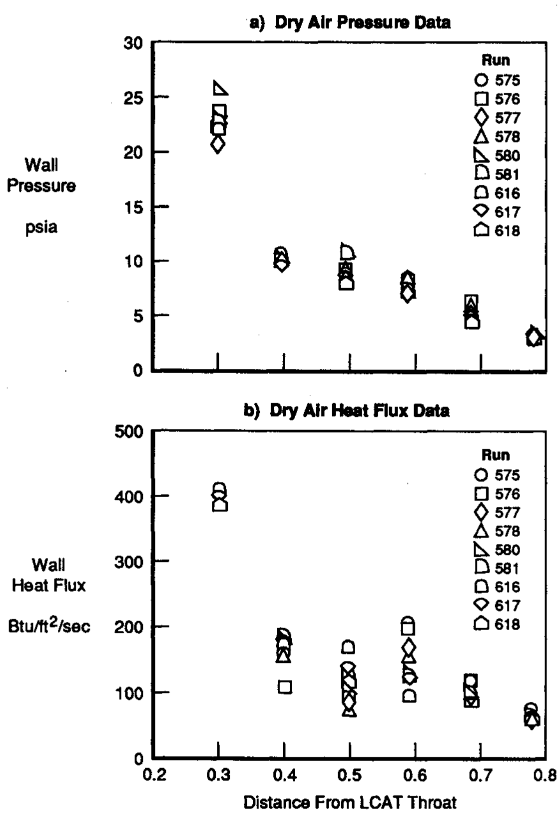

Fig. 11 Fifteen-degree dry air pressure data and heat flux data.

ramp dry air runs. Pressure data show better repeatability than heat flux data at all six gauge locations, mostly due to the insensitivity of surface pressure to the state of flow, and also due to the time averaging of the fluctuating heat flux data. Overexpansion of the flow at gauge locations three and four is quite evident from both sets of data. The worst data scatter is seen at locations three and four.

Comparisons with Code Predictions

Data comparison with analytical predictions are discussed to bring out and understand the flow structure and overexpansion. Results from this discussion will address the data quality issues also.

A heat flux analysis, using the correlation of BARTZ, proved useful in evaluating nozzle heat flux data. Figure 12a compares the BARTZ method for the 25-deg dry air data, showing 25–40% overprediction. The difference between BARTZ and test data is even larger for the air/water data (Fig. 12b). The BARTZ predictions assumed frozen flow at the throat and used measured ramp surface pressures.

Gas chemistry plays an important role in the accuracy of the BARTZ analysis because of the sensitivity of the mixture transport properties to the constituent mole fractions. For the dry air run 607, a BARTZ analysis, using equilibrium composition based on the measured pressures, is compared with

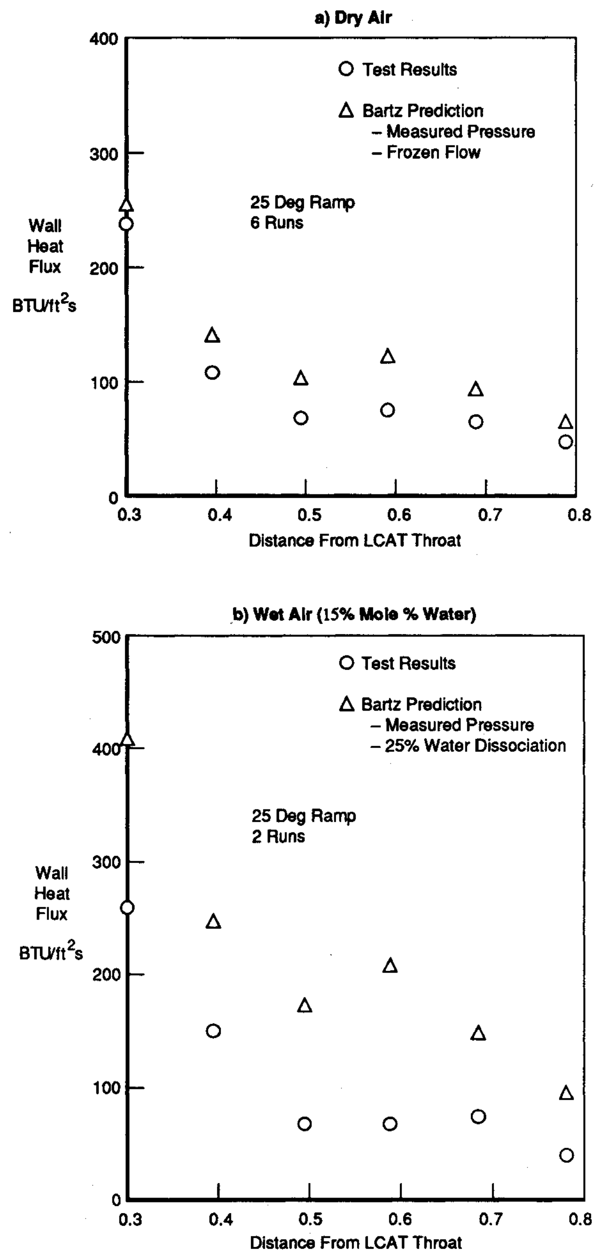

Fig. 12 Comparison between Bartz heat flux predictions and experimental results.

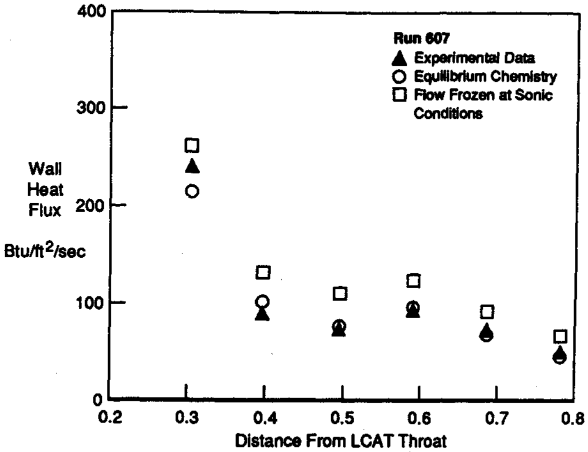

Fig. 13 Effect of gas chemistry on Bartz predictions of the heat flux to the wall.

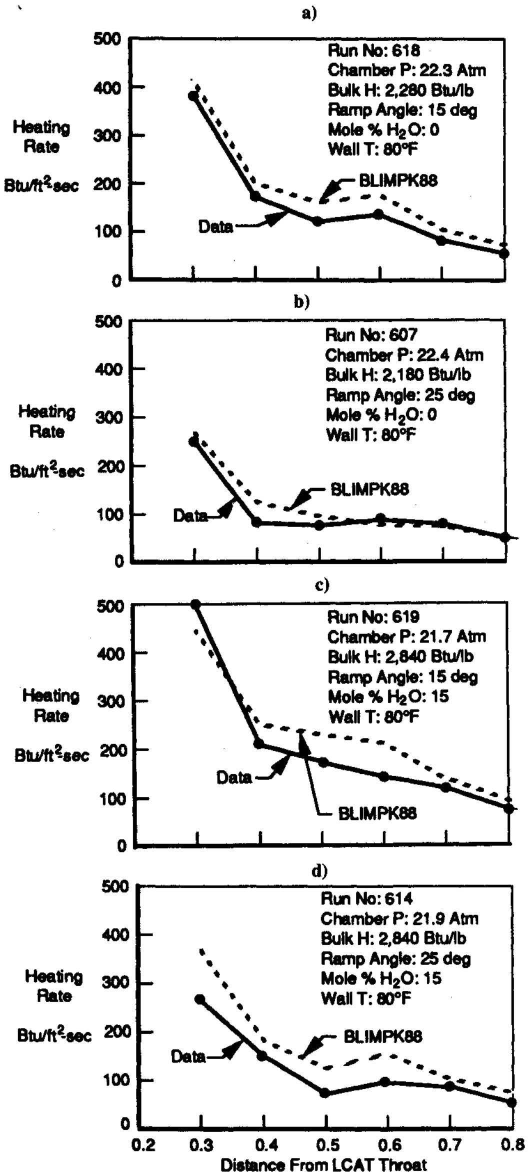

Fig. 14 BLIMPK88 comparisons with data.

the frozen-flow BARTZ and the test data in Fig. 13. In the equilibrium composition analysis, local gas compositions are computed using the tables and charts from Refs. 4 and 5.

Since the BARTZ method ignores the boundary-layer development, the above method for evaluating local flow properties within the nozzle is acceptable. For the high stagnation pressures and moderate flow expansion of this test, equilibrium flow throughout the nozzle was anticipated. Accounting for the changing gas composition down the length of the nozzle, which results in less dissociated species and lower energy flow, reduced the heat transfer rates and provided a better match with the test data.

BLIMPK88 predictions for equilibrium chemistry are compared with the test data in Fig. 14. Measured pressures are used in the BLIMPK88 analysis. Figures 14a and 14b are for dry air. The wet air comparisons are shown in Figs. 14c and 14d. As with Bartz, better comparisons are seen for the dry air runs. The level of agreement with the test data from BLIMPK88 with equilibrium chemistry is comparable to that of BARTZ with equilibrium chemistry. This indicates that the frozen-flow assumption may not be a valid approach for the nozzle heating analysis when the flow is rapidly expanding.

From Fig. 4 one can see that approximately 20–40% higher heating rates were measured on the 15-deg ramp compared to the 25-deg ramp. Water/air heating rates were approximately 20–30% higher than the air data. Other data showed the same trends.

Conclusions

1) Measurements of heat flux and pressure distributions along the ramp and fixed cowl surfaces were successful with water injection in an arc heater to simulate hydrogen combustion products thermochemistry.

2) The higher heating rates were obtained on the 15-deg ramp compared to the 25-deg ramp. Higher water content runs produced higher heating rates as did a higher enthalpy.

3) BLIMPK88 and BARTZ predictions, using equilibrium chemistry, compared with frozen flow gave better agreement with the test data.

Acknowledgments

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