SUPERSONIC TURBINE NOZZLE FLOW MEASUREMENTS

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ABSTRACT

An accelerated test program to measure the flow field of a rocket engine supersonic turbine nozzle assembly was successfully executed using gaseous nitrogen (GN_2) as the fluid medium. Flow field measurements were made with a conical 5-hole pressure probe and attempted with a laser-2-focus (L2F) laser velocimeter. In addition, the first stage turbine rotor was instrumented for static pressure measurements and with strain gages to ascertain blade loads as well. Data were collected in an effort to anchor computational fluid dynamic (CFD) codes describing the flow interaction between the nozzles and the rotor. The test program was characterized by the interplay between economic forces, time constraints and the engineering pursuit of data.

KEYWORDS

Turbine nozzle; supersonic flow; computational fluid dynamics; turbomachinery; testing; laser velocimetry; particle seeding.

INTRODUCTION

The overall goal of the project was to characterize the exit flow from a supersonic turbine nozzle in an effort to anchor or verify the CFD nozzle design codes. A better understanding of the flow physics, combined with an anchored code, conveys the ability to cheaply and readily perform product improvements or future upgrades on existing designs. This can be accomplished with a greater degree of confidence through iterations of the design on a workstation rather than actually fabricating and testing iterative hardware.

As with all engineering endeavors, economic factors played a key role in the overall test process. The project benefited from the availability of several important pieces of test equipment but the design, purchase and fabrication of specialized test hardware and interconnects proved to be major schedule drivers. Since these were blowdown tests, a fundamental parameter requiring attention in the design and execution of the test plan was in regards to the quantity of data versus the cost of acquiring the data. This was particularly true for the laser velocimeter data acquisition process, as it involved real-time engineering intervention to acquire. The velocimeter data rates were also completely dependent on the availability of adequate particle seeding in the flow, which meant that the supplemental seeding system had to perform correctly. Low or inadequate seeding rates would lead to prodigious consumption of gas with very little data to show for the high cost. Consequently, the test program was structured so that other forms of data were acquired first and the hardware modified last for the riskier velocimeter data collection process.

Because no single test facility initially had all of the necessary infrastructure or instrumentation in place, it was necessary to perform a test site selection process. The process involved assessing what was needed to conduct the testing and determining which facility conferred the greatest chance of achieving the test goals within the allotted time and budget. The process was partially subjective as ultimately it was up to those responsible for the success of the testing to use their “gut feel” based on the available imperfect site data to make the decision, rather than performing an elaborate analysis of the siting data. The basic issue was the availability of the GN_2 blowdown gas: it had to be available in sufficient quantities and pressures to facilitate a flowrate that allowed the measurement data to be collected before the gas supply was exhausted. A tradeoff was conducted between the gas availability factor and various other factors such as the amount and type of installed instrumentation infrastructure, indoors versus outdoors test setups, the difficulty in relocating and installing the laser velocimeter system, what key personnel would be available, how much noise the tester would generate, health issues involved in seeding the gas flow for laser velocimeter application, etc. In the end, it was decided that the greatest chance for success would be to bring the gas to an established indoor water-based pump test facility. The facility already had the instrumentation, laser velocimeter system, a method to both muffle the tester and contain the seeding material, and key personnel readily available to accommodate the testing. The combination of these factors lead us to believe this was the best choice.

TEST HARDWARE AND INSTRUMENTATION

Since the test facility chosen did not have the necessary GN_2 required for the testing, a high pressure tube trailer mounted on a flatbed truck was brought to the facility and plumbed to the tester. The tube trailer held 4,163 scm (147,000 scf) of GN_2 at 17.93 MPa (2,600 psig). At the 13.2 kg/sec (6 lbm/sec) flowrate to the test article at an inlet pressure between 690 and 1,379 kPa (100 and 200 psia), the gas in the trailer yielded a test run-time of approximately 16 minutes. This was sufficient to achieve a particular set of test goals, such as performing a pressure probe sweep over several nozzles, before the gas pressure was too low to maintain the required tester inlet pressure. After the trailer was emptied, the time needed to perform data reduction and analysis was typically longer than the turn-around time for refilling the tubes with gas.

The tube trailer was plumbed to the tester using 5.08 cm (2.00 in) diameter stainless steel tubing. Calculations proved this diameter piping was sufficient to deliver the required 2.72 kg/sec (6.0 lbm/sec) flowrate to the tester. The tubing was bent to the required shape, flanges welded on and pressure-tested on-site. Since this was to be a temporary test setup, the tubing was attached to unistrut steel fixtures anchored to the concrete floor. A dome pressure regulator was installed in the line immediately downstream of the interconnect to the tube trailer. The regulator was controlled by a hand loader in the control room and set to 4.48 MPa (650 psig). Further downstream an orifice plate mass flow meter was installed to quantify the mass flow through the tester. Figure 1 shows a schematic of the flow loop used in the test setup.

The test article was composed of a rocket engine fuel turbopump turbine nozzle manifold with an integral set of 19 supersonic nozzles. The tester was mounted to a steel plate held vertical by a network of steel I-beams bolted to the facility floor. GN_2 was supplied to the manifold through the 5.08 cm (2.00 in) tubing which connected to a 10.16 cm (4.00 in) diameter pipe at the manifold inlet. Attached to the turbine manifold was a large dome-shaped discharge housing which contained an 20.32 cm (8.00 in) diameter flange for the discharge pipe. In order to both mitigate the noise generated by the gas flow and to contain the particle laden gas stream needed for the laser velocimeter portion of the testing, the discharge flow was ducted to the 28,766 L

(7,600 gallon) water tank at the test facility. The gas was bubbled up through the half-full water tank which was vented to atmosphere through two 15.24 cm (6.00 in) diameter open flanges. To conserve gas, only 5 of the 19 nozzles were flowing and the rest plugged. Data would be collected over the center three nozzles with full-flowing neighbors.

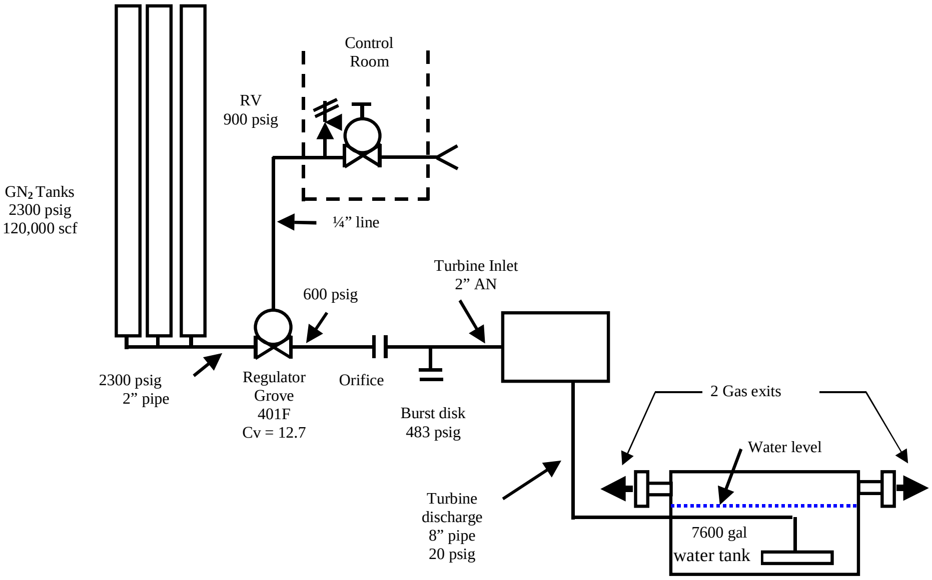

Figure 1 A schematic of the flow loop in the test facility

Figure 2 A view of the assembled tester

Figure 3 A view showing 3 of the supersonic nozzles

A conical supersonic 5-hole pressure probe was one tool selected to characterize the flow downstream of the nozzles. The 3.18 mm (0.125 in) diameter probe was mounted onto a specially designed carrier which rotated the probe in an arc at two separate radial locations relative to the nozzle. The carrier was made especially massive to keep it stationary in the supersonic flow emanating from the nozzles. The probe was positioned at the angle which oriented it parallel to the design exit angle of the nozzle. The carrier shaft passed through the tester and was attached to a motor driven rotary stage, which precisely rotated the probe across the nozzles in small repeatable angles. The probe was designed and calibrated for use in supersonic flows. The center tap measured the total pressure while the four circumferential taps measured the static pressure. The pressures were conveyed outside the test article with nylon tubing mounted to a hollow shaft which ran from the probe carrier out through the dome housing.

Figure 4 Conical supersonic 5-hole probe mounted in the probe carrier

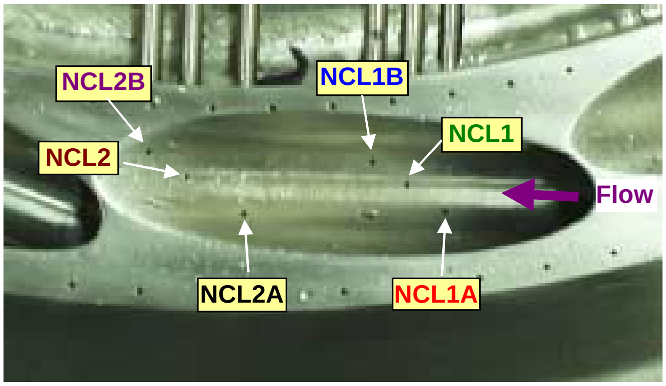

Figure 5 Nozzle wall static pressure ports and laser alignment holes

Static pressure taps were machined into the wall of one of the nozzles at six different locations. This data, coupled with the conical probe data, would aid in understanding the flow from the nozzle. The pressures were transmitted via small diameter tubes epoxied into the machined holes and through the wall of the tester where they were connected to the pressure transducers via nylon tubing. The 1.02 mm (0.040 in) tap holes were located along the centerline of the nozzle as well as at 45 degrees to the centerline taps as seen in figure 5.

Three of the first stage turbine rotor blades were instrumented with strain gages in an effort to measure the steady state loading on the blades. Although the blowdown tests would not mimic the centrifugal forces on the blades since the rotor would be held stationary (except when it was externally rotated to survey the pressure field), the steady state loads would prove useful in conjunction with on-going whirligig testing where dynamic loads were being measured. A total of six strain gages were installed near the hub of the rotor at the leading and trailing edges of three adjacent blades. A thermocouple was attached to the trailing edge of an adjacent blade to measure the local blade temperature. This data proved beneficial in the calibration and determination of thermal strain of the strain gages since the blade temperatures decreased during the test run from ambient to about - 40 F (- 40 C).

Static wall pressure taps were also instrumented on six adjacent rotor blades. Three of the taps were located on the suction side of a blade and three were on the pressure side. The taps were located nearer to the leading edge of the blade rather than further along the chord. These locations were selected so as to not coincide with the shock set up along the blade as this would only tend to yield confusing data. Due to budget and time constraints, it was decided to use small diameter tubing along the exterior of an adjacent blade to convey the wall static pressure measurements out the tester, as seen in figure 6. The alternate but cleaner approach would have been to drill intersecting holes through the rotor blade up from the hub and bring the pressure tubing out the hub.

Figure 6 Instrumented rotor blades for wall static pressure and strain gage measurements

Figure 7 A view of the rotor blades through the laser velocimeter optical window

The conical supersonic pressure probe was an invasive measurement technique and there were issues involved in the probe calibration that made interpreting the data difficult. Consequently, a two-component laser-two-focus (L2F) laser velocimeter was also used in an attempt to measure the flow velocities and flow angles. The non-invasive L2F velocimeter was ideally suited for this task since the high flow velocities were well within its range of performance; it required only a small optical access window and suitable flow seeding and would yield accurate gas velocities as well as flow angles (Ferguson and McGlynn 1999).

The tester hardware had to be modified to provide optical access for the laser beams into and the scattered light signals out of the tester. A small commercially available fused silica window was modified in size to accommodate these requirements. The window was epoxied to a specially designed frame and fit into a cut-out on the metal ring which simulated the blade tip seal, as seen in figure 4. The ring could be rotated from outside the turbine nozzle exhaust housing. This feature allowed the velocimeter access to different lines-of-sight across the nozzle at various circumferential angles. The completed window assembly is shown in figure 7.

The chief technical challenge in implementing the velocimeter, however, was the fact that it required the presence of sub-micron sized scattering particles in the gas upon which to make the velocity measurements. Since the GN_2 is nearly devoid of all particles the challenge was in designing, fabricating and implementing a high pressure seeder system. The supersonic nozzle flow velocities coupled with the presence of shocks in the flow meant that the seeder system had to supply only sub-micron sized particles. The aerodynamicist further requested that the seeder not introduce any other gases or contaminants into the GN_2 flow as that would complicate the analysis.

The method chosen was to utilize a commercially available high pressure atomizer to generate droplets of liquid nitrogen (LN_2) laden with titanium dioxide. The theory was that the LN_2 droplets would quickly evaporate, thereby liberating the sub-micron metal oxide particles which would act as scattering centers for the laser velocimeter. The atomizer was composed of a laser-drilled ruby with a 0.152 mm (0.006 in) orifice. It was installed into the 5.08 cm (2.00 in) diameter flow tubing (seen in figure 8) and supplied 5.9 MPa (850 psi) pressure liquid nitrogen from a pressure vessel (seen in figure 9). A small quantity of 0.17 micron titanium dioxide (TiO_2) powder was mixed into the LN_2 and kept in suspension by bubbling GN_2 through a rake (seen in figure 10) in the LN_2 vessel. Limited development tests with this setup proved it would atomize the LN_2, but actual implementation and operation proved difficult. In addition, the output of the system was not characterized to ensure that it was consistently generating only sub-micron sized particles. Calculations showed that if the scattering particle size doubled from 0.2 micron to 0.4 micron, the error in velocities measured in the turbine rotor blades would reach 6% and get progressively worse as the particle size increased (Dring 1982).

Figure 8 Atomizer in the flow pipe

Figure 9 Pressurized LN_2 seeder system

Figure 10 Bubbler rake used to keep TiO_2 in suspension

TEST METHODOLOGY

The first series of tests were performed without the first stage turbine blade rotor installed in the flow. In place of the rotor, the conical pressure probe holder was installed and used to sweep the 5-hole probe across the nozzles. Calculations showed that without the rotor, the nozzles would achieve full supersonic flow with an inlet pressure of 690 kPa (100 psia). Several tests were conducted in which the probe was swept across multiple nozzles at about 1 degree increments. The probe was positioned at two radial positions corresponding to 10% and 50% of the width of the nozzle. The probe was also positioned at two different axial positions above the nozzle: 6.10 mm +/- 0.26 mm (0.240 in +/- 0.010 in) and 8.64 mm +/- 0.26 mm (0.340 in +/- 0.010 in). Along with the 5-hole probe data, the nozzle wall static pressures were recorded as were facility parameters to ensure the correct flow conditions were maintained. A video camera was setup near the top of the discharge dome to aid in the alignment of the 5-hole probe with respect to the nozzles as well as to monitor the inside of the tester during blowdown for flow-induced vibration of the probe carrier or broken or loose pressure tubing. The camera peered through a window which also served as a test bed for the window design needed for the velocimeter optical access. The second test series was the rotor-in configuration using the strain gaged rotor blades along with the static pressure taps on the rotor blades. In addition, the laser velocimeter testing was attempted with this setup in which the nozzle exit flow as well as flow between the stationary rotor blades would be measured. The rotor was remotely moved via a double-connected mechanical and motor driven rotary stage. The mechanical stage withstood the torque imposed on the rotor blades by action of the gas flow while a second motor driven stage turned the handle of the mechanical stage. This setup not only permitted remote operation of the mechanical stage, but also conveyed precise repeatable control of the rotation using the electronic rotary controller with digital readouts. The turbine nozzle inlet pressure for the rotor-in configuration tests was 1.38 MPa (200 psia).

TEST RESULTS: ROTOR-OUT CONFIGURATION

Some of the results for tests performed with the conical supersonic probe are presented in figures 11 and 12. The probe survey was conducted across the central three flowing nozzles and cover approximately 50 degrees of arc. The data were non-dimensionalized relative to the local maximum total pressure. The first figure shows the total pressure measured by the conical 5-hole probe at the 50% radial location and 6.10 mm (0.240 in) axial spacing. The prominent feature in the data was the presence of the pressure deficit near the middle of the nozzle passage. The magnitude of the total delta pressure was almost 50%. Figure 12 shows the total pressure measured by the conical 5-hole probe at the 10% radial location and the same 6.10 mm (0.240 in) axial spacing as before. The pressure deficit seen at the 50% location was absent and replaced with a smooth sinusoidal pressure variation. The magnitude of the total delta pressure was almost 100%.

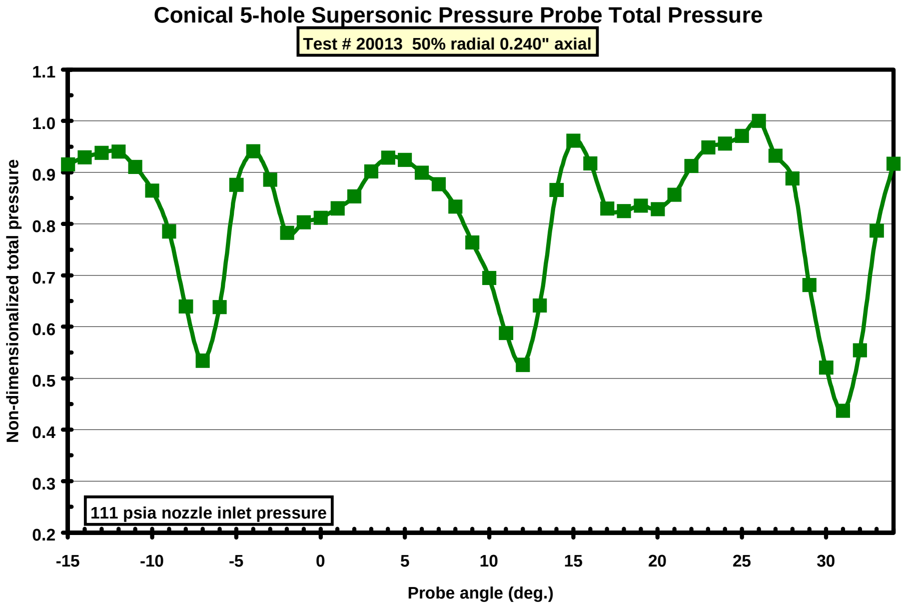

Figure 11 Probe total pressure as a function of angle at 50% radial location and 6.10 mm (0.240 in) axial spacing

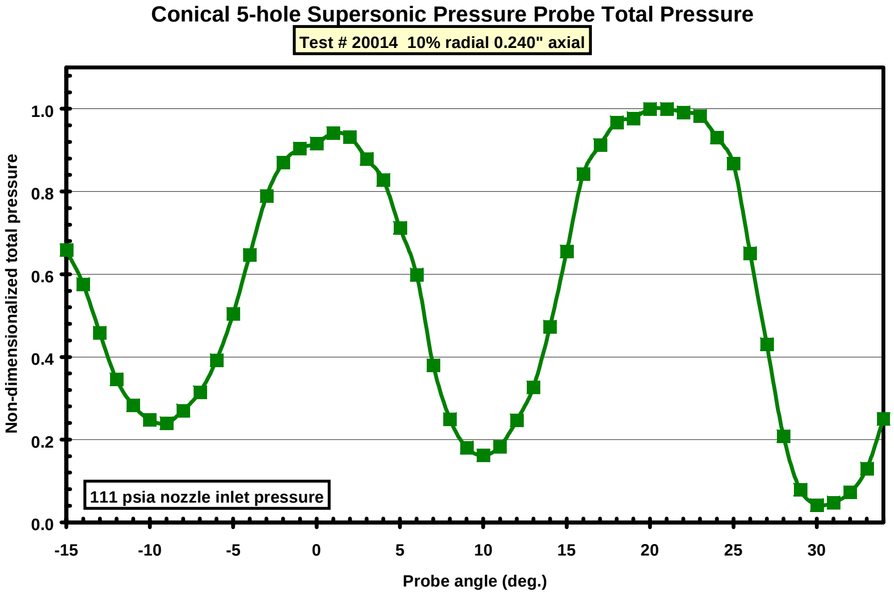

Figure 12 Probe total pressure as a function of angle at 10% radial location and 6.10 mm (0.240 in) axial spacing

TEST RESULTS: ROTOR-IN CONFIGURATION

Pressure data were also collected using the static wall pressure taps located on the pressure and suction side of the rotor blades. Each rotor blade was swept across three flowing nozzles encompassing about 60 degrees of arc. The pressure side data mimicked the pressure deficit near the middle of the nozzle which was sensed with the conical 5-hole probe. The delta pressure was also about 50%. The similarity in the results between the conical probe data and the rotor blade wall static taps provided assurance as to the validiity of the data from the probe. Prior to this data set, it was thought that the probe might have been affected by the shocks in the flow in an unknown way, casting uncertainty on its results. The suction side data also revealed the pressure dip but the pattern near nozzle three was slightly different. The reason for this is unclear but may be a manifestation of the presence of the optical window for the velocimeter.

Unfortunately, no laser velocimeter data was collected. This was attributed to the lack of performance on the part of the cryogenic seeder. From the outset of the test program, the seeder was identified as a high risk item which would make or break the velocimeter measurement process. The seeder may not have worked for a variety of reasons, including: the atomizer might have clogged from foreign debris or with excess TiO_2; the TiO_2 may not have remained in suspension and therefore was not delivered to the atomizer; the TiO_2 particles might have dropped out of the flow or attached to the pipe walls before entering the turbine nozzles, etc. In hindsight, it would have been better to pursue the design, development and proof-testing of the seeder as a task separate from, and preferably prior to, the nozzle measurements. It was hoped that the velocimeter data would aid with the interpretation of the 5-hole probe data as there were issues involving the probe calibration which cast uncertainties on its data.

DISCUSSION

The conical 5-hole supersonic probe data suggested the presence of a pressure deficit near the middle of the nozzle. This was supported by evidence from other measurements including the rotor wall static pressure taps as well as the strain gage data. The data at the 50% radial location showed the pressure variations dissipate with axial distance from the nozzle, as expected. As the flow from the nozzle expands, the apparent location of the pressure deficit changes with axial distance as well. Similar trends were reflected in the data collected at the 10% radial location but the pressure deficit measured near the nozzle centerline was not present. The data is still be analyzed and will prove fundamentally important in anchoring the CFD codes used to predict nozzle performance.

The disappointing performance of the cryogenic seeder has lead us to think about alternate methods to seed the supersonic flow. A backup scheme involves the use of a commercially available fluidized bed seeder (Marple et al 1978). This device would be installed in a pressure chamber so that its aerosol output could be a delivered at the required high nozzle inlet pressure. The supersonic application requires the aerosol to be processed to remove any agglomerated particles larger than about 0.2 micron. This action might sharply decrease the particle number density below a threshold such that the velocimeter data rate would not be high enough to acquire data in a reasonable period of time, meaning the cost of the blowdown gas would become prohibitive. However, issues of this sort could be investigated in a bench-test environment. Additionally, the critical particle size distribution parameter could be ascertained with suitable instruments as well.

CONCLUSIONS

This test program presented an opportunity to expand the scope of testing performed in the nominally water-based pump test facility. Data collected with the supersonic 5-hole conical probe, the rotor blade wall static pressure taps, the strain gages and the nozzle wall static taps are being used to further our understanding of the complex flow emanating from the supersonic nozzle. The turbine manifold and nozzle test article can be used again in the future to acquire additional measurements on the existing nozzle as well as on other nozzle designs which can be fitted into the manifold. In that case, the lessons learned and the tester hardware designed and fabricated in the present testing can be leveraged to help ensure the economic as well as engineering success of these future test programs.

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