The Marshall Space Flight Center Turbine Test Equipment; Description and Performance

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ABSTRACT

Performance evaluations of rocket engine turbopump drive turbines are difficult to obtain from turbopump or engine firings due to measurement limitations and operating point restrictions. The Marshall Space Flight Center (MSFC) Turbine Test Equipment (TTE) was developed to provide an accurate, economical method of measuring the performance of full-scale turbopump gas turbines. By expanding air at pressures as high as 435 psia (3.0 MPa) to atmospheric conditions, the TTE provides metered air at nominal conditions of 100 psia (0.69 MPa), 550 °R (350 °K), and 15 lbm/sec (6.8 kg/sec) with run times of 100 seconds or greater. A 600 hp (448 kW) direct current dynamometer and gearbox provide turbine power absorption for speeds up to 14,000 rpm. This paper describes the MSFC TTE and its performance including the performance envelope, turbine inlet flow quality, and measurement uncertainty.

INTRODUCTION

Pump-fed liquid propellant rocket engines use high-speed turbopumps to pump the propellants into the combustion chamber. These turbopumps are powered by high temperature gas turbines. The performance and environment of turbopump drive turbines are difficult to obtain from turbopump or engine level testing. First, the harsh environment found in hot-fire turbopump and engine tests limits the number of measurements and the accuracy of the measurements. Often a half dozen measurements or less must be used to evaluate the performance of individual turbopump components such as the turbine. Second, safety considerations and test-stand operating limitations often restrict the range and number of independent test parameters. With these restrictions, engine components cannot be tested to their operating limits. Finally, hot-fire turbopump and engine tests are costly and time consuming. The potential hazards of testing highly combustible cryogenic fluids and hardware at high energy levels require specialized test hardware, facilities, and personnel driving up both the cost and time. Proposed design changes require an extensive review process and long lead times to be added to the engine test program.

In view of the inherent difficulties of prototype testing, the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) developed a cold air flow blowdown Turbine Test Equipment (TTE) to test full-scale turbine models. The TTE is located in building 4777 on the MSFC and is maintained and operated by the MSFC Structures and Dynamics Laboratory's Aerophysics Division (ED31). The TTE was designed, fabricated, and installed from 1986 to 1989 and became operational in January of 1990.

Tests at the TTE rely on the principle of fluid dynamic similitude. Turbines are tested in air at reduced Reynolds numbers with matched corrected speeds and pressure ratios allowing moderate temperatures, pressures, flows, and shaft rotational speeds to be used. For example, the Space Shuttle Main Engine (SSME) High Pressure Fuel Turbopump (HPFTP) is powered by a two stage axial flow turbine. The turbine operates with an inlet pressure of 5187 psia (35.8 MPa), inlet temperature of 1832 °R (1018 °K), and shaft speed of 35,131 rpm. Operating at these conditions in a superheated mixture of gaseous hydrogen and water, the turbine average Reynolds number (average of the first stator and second rotor blade actual chord Reynolds numbers) is 1.12x10^7. A full-scale air flow model with an inlet pressure of 100 psia (0.69 MPa), inlet temperature of 550 °R (350 °K), and shaft speed of 6982 rpm can accurately simulate the HPFTP turbine. The resulting

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cincinnati, Ohio — May 24–27, 1993
model average Reynolds number is $1.47 \times 10^6$. At these conditions the model produces 240 hp (180 kW) as compared to the prototype's 65,415 hp (48,880 kW). Unlike the prototype, the model can contain detailed measurements, and model changes can be made quickly and inexpensively. Measurements of the turbine overall performance and internal environment (pressures, temperatures, and velocities) are then scaled to predict the prototype's performance and environment.

This paper describes the hardware and performance of the MSFC Turbine Test Equipment. A detailed description of the TTE plumbing, controls, and instrumentation is given. The TTE operating capability and performance are discussed including the operating envelope, set point accuracy, flow quality, and measurement uncertainty.

**EQUIPMENT DESCRIPTION**

The MSFC Turbine Test Equipment is a blowdown facility that operates by expanding high pressure air from storage tanks to atmospheric conditions. The overall arrangement of the TTE including the building enclosure, control room, gas path, and drivetrain is shown in figure 1.

The air flows from compressed air reservoirs (1) through a filter (3), heater (6), and quiet-trim pressure control valve (15). The air then passes through a mass flow measurement venturi (18), a plenum section (20, 21, and 22), turbine test article (23), and exhausts through a back-pressure control valve (28) into a vent silencer (30). A direct current dynamometer (27) coupled to the test article output shaft by way of a gearbox (26) and torquemeter (25) provides power absorption.

The following subsections contain a description of the flow conditioning subsystems, power absorption drivetrain, test section, and controls and instrumentation. Further details on the design and construction of the TTE can be found in Carter (1991).

**FLOW CONDITIONING SUBSYSTEMS**

Two 6000 cubic foot (170 cubic meter) cylindrical, carbon steel tanks (1) with a maximum operating pressure of 435 psia (3.0 MPa) store compressed air before a blowdown. The compressed air is supplied to each tank by a center-wide air source or an on-site, three-stage reciprocating compressor. The supply tank discharge flow is filtered to 10 micron particle size to prevent rust particles from entering the downstream equipment. The air filter (3) and hardware downstream of the filter are stainless steel.

The TTE air heater (figure 2) is a passive thermal storage system in which a large mass of stainless is heated in batch mode before a blowdown. The matrix storage heater, as it is called, consists of five cylindrical modules (tube bundles) that direct the air through the inside diameter of 4650 thick-walled...
The test article back-pressure is controlled with an eight inch (20.32 cm) hydraulically operated valve (28) after which the air is exhausted to the atmosphere through a vent silencer (30). A pyrotechnic burst disk (29) was included in the exhaust ducting system. In the event of a test article overspeed or high differential pressure condition, the disk is ignited equalizing the pressure across the turbine in less than 65 ms. For testing with turbine inlet air above ambient temperatures, equipment is available to preheat the piping, plenum, and test article by flowing air through an additional electric heater (32) and then through the above mentioned items.

**POWER ABSORPTION DRIVETRAIN**

The power absorption drivetrain consists of a 600 horsepower (448 kW), variable speed, direct current dynamometer (27), gearbox (26), and torquemeter (25). The dynamometer is capable of motoring the turbine before initiation of a blowdown as well as the normal absorption mode. The dynamometer controls automatically switch the unit from motoring to absorption mode as required to maintain the set point speed. A gearbox is used to maintain the speed and torque within a desired operating envelope by way of three gear ratios (1:2, 1:1, and 2:1). Test article output torque is measured by an in-line, pedestal-mounted torquemeter. Currently, the torquemeter can be fitted with torque cartridges of 30, 500, and 1000 ft-lb (40.7, 678, and 1356 N-m).

**TEST SECTION**

The test section (23 and 24) is directly downstream of the plenum assembly and can be modified to suit test requirements. The distance from the plenum exit to the torquemeter connection can be varied from 0.5 to 6.0 feet (0.2 to 1.8 m) by moving the entire plenum assembly which is mounted on rollers for this purpose. The exit diameter of the plenum assembly can be adjusted by replacing the contraction extension at a flange provided within the contraction section.
The typical test section dimensions are:

- Plenum assembly exit diameter: 10.9 inches (28 cm)
- Axial distance from plenum exit to torquemeter: 63.0 inches (160 cm)
- Exhaust pipe diameter: 10.0 inches (25.4 cm)
- Distance from shaft centerline to floor: 60.3 inches (153 cm)

**CONTROLS AND INSTRUMENTATION**

All controls and instrumentation required to operate the TTE are located in the control room (33). The controls and instrumentation have been divided into three groups, "control", "performance", and "health monitoring" measurements.

The TTE controls five items: test article shaft rotational speed, inlet total pressure and temperature, test article pressure ratio (or pressure differential), and model lubrication.

The test article speed is manually preset before a run (blowdown). To satisfy test operating requirements, a separate controller from that of the dynamometer's is used to motor the turbine to the preset speed and maintain the speed during a run. This controller also allows the model to be "ramped" at constant ramp rates before, during, and after a run.

Inlet total pressure, total temperature, and test article pressure ratio (or pressure differential) are controlled by individual controllers. These controllers use an automatic analog feedback with manual set points. The set points are preset before a run, but can be changed during a run.

The model's bearing oil flow, pressure, and temperature are also controlled. The bearing oil temperature is controlled using an electric heater element in the supply tank and in-line potable water heat exchanger.

Three types of TTE performance measurements are made: (1) mass flow; (2) torque or horsepower; and (3) test article pressures, temperatures, and special measurements.

Interchangeable subsonic Herschel venturi tubes are used for precision TTE mass flow metering. The mass flow is calculated using the venturi inlet static pressure, inlet-to-throat static pressure drop, and inlet gas temperature. The venturi tubes were calibrated over a range of Reynolds numbers. Finally, to reduce flow-induced noise and maintain subsonic flow, the Mach number at the venturi throat is not allowed to exceed 0.95.

Model torque is measured by an in-line, pedestal-mounted torquemeter. The torquemeter can be fitted with different size torque shafts. During operation, the torque shaft angular strain is determined by measuring the relative angular displacement of toothed flanges at either end of the shaft. The torque is then computed using the measured displacement, a calibration constant, and a shaft stiffness temperature correction.

Test article pressures are measured by an electronic pressure scanning system. It is a 382 channel unit equipped with various ranges of differential and absolute modules each containing 16 channels. The system can measure up to 20,000 pressures per second. Model pressures are measured 10 times for each run and then numerically averaged. Pressure data for an entire run is stored in the electronic scanner system and up-loaded to the data acquisition computer after each run. The system can be calibrated by an internal calibration system before each run or series of runs.

Test article temperatures are measured by a digital system configured for 200 thermocouple channels and 40 strain gauge or other low-level voltage inputs. The thermocouple channels will accommodate any conventional type thermocouple; however, the wiring to the thermocouple modules is currently divided into 120 channels of type E and 40 channels of type K. The remaining channels are available as required.

The equipment to make special measurements is available at the TTE to support test needs as required. Special measurements include blade tip clearance, flow angle, turbulence intensity, boundary layer thickness, and dynamic pressure measurements. A remote control probe positioning system allows pressure and temperature probes to be traversed circumferentially and radially at the turbine inlet and exit during a run. Radial actuators also provide the capability of rotating probes about their axes to provide auto-nulling flow angle measurements. Probe circumferential and radial locations are preset and loaded into the system and can be advanced automatically during a run. Probe auto-nulling positions are measured and up-loaded to the data acquisition computer.

The entire data acquisition system operates through the IEEE-488 bus controlled by the master data acquisition computer. After each run data is reduced on-site, printed, written to a disc file, and wire transferred to a central computer for storage and further analysis.

To ensure proper operation and health of the TTE, parameters are monitored by the test operator or test engineer by means of digital, rack-mounted displays or video monitor. Monitored parameters include mixer temperature, heater tubing temperatures, heater and heater by-pass leg valve positions, inlet pressure valve position, exhaust pressure valve position, model vibrations, model bearing temperatures, model bearing lubrication system parameters, and model seal air pressure differential.

**EQUIPMENT PERFORMANCE**

The equipment performance results included in this paper were obtained during several tests. For more information on these tests, the following references may be consulted: test TTE0003 -- Hudson et al. (1991) and Tran et al. (1991), test TTE0006 -- Gaddis, Hudson, and Johnson (1992), and test TTE007 -- Boynton, Tabibzadeh, and Hudson (1992). The tests completed to date have included tests with and without a turbine test article. Tests conducted without a turbine used an instrumented spool followed by a standard elbow in place of the test article. These tests were used to evaluate the performance of the flow-conditioning elbow and to determine the TTE performance envelope and inlet flow quality. The complete operating characteristics of the TTE were evaluated with an active turbine in place.
PERFORMANCE ENVELOPES

The operating capability of the TTE is represented by two performance envelopes: (1) Speed--Torque envelope and (2) Mach Number--Reynolds Number envelope shown in figures 4 and 5. These envelopes define the capability of the TTE drivetrain and air flow system, respectively.

The TTE is equipped with a manually adjustable gearbox with gear ratios of 1:2, 1:1, and 2:1. With these gear ratios and the dynamometer's 600 hp (448 kW) power and 1000 ft-lb (1356 N-m) torque limits, the range of torque and speed the TTE can provide to the test article is illustrated by figure 4. The TTE can be operated anywhere within the crosshatched boundaries for a given gear ratio. With the current torquemeter cartridges, however, the maximum obtainable test article speed is limited to 14,000 rpm. Figure 4 shows that for speeds less than 5000 rpm, the 1:2 gear ratio allows testing to 14,000 rpm. For speeds up to 10000 rpm, the 1:1 gear ratio is required allowing test article speeds up to 7000 rpm.

The capability of the air flow system, as determined by testing, is shown in figure 5 in terms of the venturi meter throat Mach number and Reynolds number. The venturi throat diameter is 3.396 inches (8.626 cm). Knowing this reference dimension as well as the test article geometry and set point requirements, one can calculate the venturi meter throat Mach number and Reynolds number and plot the desired test point on figure 5. The three TTE operating constraints that define the TTE's operating range are shown on this figure by crosshatched lines. The constraints are: (1) maximum venturi Mach number of 0.95; (2) maximum turbine pressure ratio lines; and (3) maximum turbine inlet total pressure. The TTE can be operated anywhere within these constraints.

These operating constraints arise because of three TTE physical constraints. First, the maximum venturi Mach number is kept below 0.95 to keep the venturi in a subsonic operating regime. Since the ratio of the Mach number at the turbine inlet and the Mach number at the throat of the venturi is fixed by the corresponding area ratio, this constraint also fixes the maximum obtainable test article inlet Mach number. Second, the TTE flow is exhausted to atmospheric conditions; therefore, the turbine exit absolute pressure must be equal to or greater than the TTE exhaust system pressure drop plus barometric pressure. As shown in figure 5 by the maximum pressure ratio curves, this constraint limits the minimum obtainable Reynolds number given the required turbine inlet Mach number and test article total-to-static pressure ratio. Finally, due to current pressure transducer ranges, the TTE is limited to a maximum pressure of 250 psia (1.72 MPa). This maximum pressure limits the maximum Reynolds number obtainable for a given turbine inlet Mach number. The TTE piping is designed for 400 psia (2.76 MPa); therefore, the 250 psia pressure constraint could be moved with higher range pressure transducers.

Not shown on figure 5, but of great importance when considering the TTE's performance capability is the run time capacity. Run times are not plotted because the TTE has demonstrated by test to have at least 100 seconds of run time for the entire operating area shown in figure 5.

SET POINT ACCURACY, REPEatability, AND STABILITY

The TTE provides automatic analog feedback control of the test article rotational speed, turbine inlet total pressure and temperature, and turbine total-to-static pressure ratio. These four control parameters define a unique TTE set point. Each control parameter is input into the TTE control system before
each run; and once activated, the TTE control system automatically "ramps" to and holds the preset set point. In this subsection the set point accuracy, repeatability, and stability are discussed. In this paper, "accuracy" refers to the difference between the values of each parameter input by the TTE operator and the actual values obtained. "Repeatability" refers to the scatter in the set point obtained from one run (blowdown) to the next with the same set point. Finally, the set point "stability" refers to the fluctuation of the set point during a test run (data acquisition period). In the results given below (except for test article speed), the actual set point was measured by a different set of instrumentation (test article performance instrumentation) than that used by the TTE control system. This second set of instrumentation is considered more accurate and is used to determine the performance of test turbines. Table 1 summarizes the results of a study of the set point accuracy, repeatability, and stability using runs from test TTE0007.

**TABLE 1. TTE CONTROL SYSTEM ACCURACIES, REPEATABILITIES, AND STABILITIES**

<table>
<thead>
<tr>
<th></th>
<th>Shaft Speed (rpm)</th>
<th>Inlet Total Temp. (°R)</th>
<th>Inlet Total Press. (psia)</th>
<th>Press. Ratio (T-T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Design Pt.</td>
<td>6982</td>
<td>550.0</td>
<td>100.0</td>
<td>1.470</td>
</tr>
<tr>
<td>Test Range 2000-10,000</td>
<td>550.0 only</td>
<td>27.0-200.0</td>
<td>1.2-2.0</td>
<td></td>
</tr>
<tr>
<td>Avg. Accuracy at Design Point</td>
<td>± 0.2 %</td>
<td>+/ - 0.4 %</td>
<td>- 0.6 %</td>
<td>not applicable</td>
</tr>
<tr>
<td>Avg. Accuracy at Design Point (%)</td>
<td>± 0.4 %</td>
<td>+/ - 0.5 %</td>
<td>- 0.6 %</td>
<td>not applicable</td>
</tr>
<tr>
<td>Avg. Accuracy Over Test Range</td>
<td>± 0.5 %</td>
<td>+/ - 0.6 %</td>
<td>- 0.7 %</td>
<td>not applicable</td>
</tr>
<tr>
<td>Run Repeatability at Design Pt.</td>
<td>±/ - 0.5</td>
<td>+/ - 0.2</td>
<td>+/ - 0.004</td>
<td></td>
</tr>
<tr>
<td>Stability at Design Point</td>
<td>+/ - 0.28</td>
<td>+/ - 0.5</td>
<td>+/ - 0.1</td>
<td>+/ - 0.002</td>
</tr>
</tbody>
</table>

Table 1 shows that overall the control system accuracy or the difference between controller setting and actual reading is about 1/2% for the four control parameters. The run repeatabilities are all quite good and have proven to be acceptable. The stabilities at the design point are all less than or equal to 0.1% except for the speed stability which is 0.4%. The accuracy obtained for the pressure ratio was considered "not applicable" because the pressure ratio controller setting had to be obtained by trial-and-error before the desired pressure ratio could be achieved. Figure 6 shows two design point runs from test TTE0007. This figure shows a "ramp" to set point and the stability of each parameter once at the set point. Notice that the inlet air temperature takes the longest to stabilize. For this reason, data acquisition is usually started after the inlet air temperature has been allowed to stabilize. The control system repeatability is illustrated by the repeat run.

**FIGURE 6. TYPICAL CONTROL PARAMETER PROFILES**

**TEST ARTICLE INLET FLOW QUALITY**

The TTE's plenum and heater mixer were designed to provide "flat" velocity and temperature profiles as well as zero flow swirl at the test article inlet. The "flow quality" was
determined by measuring: (1) the pressure and temperature profiles; (2) the boundary layer thickness and turbulence intensity; and (3) the flow angularity across the test article inlet duct at the plenum exit. Figure 7 shows typical total pressure and gas temperature profiles for a 100 psia (0.69 MPa) and 100 °F (311 °K) run verifying that the velocity and temperature profiles are uniform. The small drop in temperature at the inlet duct wall is indicative of heat transfer at the wall. The inlet duct boundary layer thickness and turbulence intensity were measured with a hot-film probe. The velocity profile near the duct wall is shown in figure 8 and indicates a boundary layer thickness of approximately 0.3 inches at the plenum exit. Using the same hot-film probe, the turbulence intensity was measured for a range of flows and shown to range from 6 to 12 %. Finally, a five-hole probe was used to measure the flow angularity. The velocity profile was measured to be less than 0.5 degrees, which is on the same order of magnitude as the uncertainty of the probe.

MEASUREMENT UNCERTAINTIES

Tests conducted in the TTE are used to measure the test turbine’s performance and measure the pressure, velocity, and temperature environment within the turbine. The uncertainties of measurements and calculated turbine performance variables such as efficiency depend on the uncertainties of the TTE instruments and data acquisition system. In the ANSI/ASME Performance Test Code PTC 19.1 (1985), ”uncertainty” is defined as “the estimated error limit of a measurement or result for a given coverage.” As outlined by PTC 19.1, measurement and result uncertainties may be estimated as the root sum square of the precision (random error component) and bias (fixed or systematic error component). Using this method and a 95% coverage, estimates of the TTE's measurement uncertainties are given in table 2.

The bias limit estimates are based on instrument information and propagation of fundamental bias errors. The precision limit estimates are based on actual measurements during turbine testing. For tests of the SSME HPFTP turbine, these measurement uncertainties resulted in a turbine efficiency uncertainty estimate of +/- 1.0 to +/- 1.5 points (of efficiency) at the turbine design point. However, for comparative testing, the efficiency precision limit estimate at the design point is 0.3 points (of efficiency).

SUMMARY

The Marshall Space Flight Center's Turbine Test Equipment (TTE) is a unique blowdown turbine test facility providing cost-effective, quick-turnaround turbine performance and environment data. Through tests conducted to date, the TTE has proven to be easy to operate and has provided accurate, repeatable, and stable flow and drivetrain control. Tests of the Space Shuttle Main Engine High Pressure Fuel Pump drive turbine have demonstrated that cold flow turbine tests can provide an effective means of "screening" design concepts,
evaluating empirical and computational design codes, and verifying the performance and environment of final designs. The future looks bright for continued use of cold flow turbine testing in the development of liquid rocket engine drive turbines, and the MSFC's TTE will continue to provide the means toward this end.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of other key individuals involved in the design and development of the TTE. Sverdrupt Technology of Tullahoma, TN was the prime contractor responsible for the design, fabrication, and installation of the TTE. R. R. Williams served as Sverdrupt's project engineer and had overall responsibility for providing the equipment to NASA. Within NASA, C. D. Andrews served as administrative supervisor and J. A. Carter served as TTE project engineer during the design, fabrication, and initial checkout of the TTE. Without the many hours of work and long-term commitment of these individuals, the MSFC Turbine Test Equipment would not be the unique national resource it is today.

REFERENCES


