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Heavy Gas Conversion of the NASA Langley Transonic Dynamics Tunnel

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HEAVY GAS CONVERSION OF THE NASA LANGLEY TRANSONIC DYNAMICS TUNNEL

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ABSTRACT

The heavy gas test medium has recently been changed in the Transonic Dynamics Tunnel (TDT) at the NASA Langley Research Center. A NASA Construction of Facilities project has converted the TDT heavy gas from dichlorodifluoromethane (R12) to 1,1,1,2 tetrafluoroethane (R134a). The facility's heavy gas processing system was extensively modified to implement the conversion to R134a. Additional system modifications have improved operator interfaces, hardware reliability, and quality of the research data. The facility modifications included improvements to the heavy gas compressor and piping, the cryogenic heavy gas reclamation system, and the heavy gas control room. A series of wind tunnel characterization and calibration tests are underway. Results of the flow characterization tests show the TDT operating envelope in R134a to be very similar to the previous operating envelope in R12.

INTRODUCTION

The Transonic Dynamics Tunnel (TDT) is a large-scale, sub-atmospheric wind tunnel originally constructed as the Langley 19 Foot Pressure Tunnel[1] in 1938. In the late 1950's the facility was converted to a transonic wind tunnel capable of using the heavy gas dichlorodifluoromethane (R12), as well as air, as the aerodynamic test medium.

The TDT is a national facility with transonic aeroelastic testing capabilities unmatched anywhere in the world. Aircraft designers depend heavily upon its unique testing capabilities to investigate the aeroelastic characteristics of many new aircraft. Aeronautical researchers utilize the facility to evaluate transonic aeroelastic phenomena for an extensive range of military and commercial aircraft applications[2,3]. A photograph of the TDT is shown in Fig. 1.

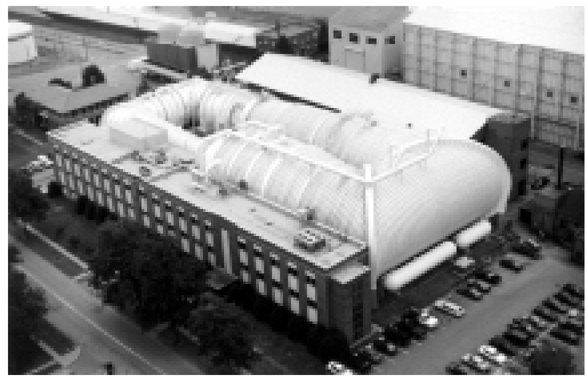

Figure 1: The Langley Transonic Dynamics Tunnel

The original TDT heavy gas test medium, R12, is a chemical classified as a chlorofluorocarbon (CFC). In 1987 the Montreal Protocol was established which mandated that its signatory nations cease production of CFC's by the year 2000. In 1992 the United States accelerated that schedule by requiring domestic production of CFC's to end by 1996. In accordance with the Montreal Protocol and the U. S. Clean Air Act, NASA has been converting its CFC-based systems to use alternative chemicals, such as hydrofluorocarbons (HFC's), which are recognized to be less harmful to the environment than CFC's.

In 1994, realizing that R12 supplies would quickly diminish, NASA initiated the TDT Heavy Gas Conversion Project. The project's objectives were to: 1) select a new heavy gas test medium for the TDT; 2) implement the facility modifications needed to process the new heavy gas; and 3) measure the facility's aerodynamic testing boundaries with the new heavy gas.

FACILITY DESCRIPTION

The TDT (Fig. 2) is a closed-circuit wind tunnel capable of testing with either air or heavy gas as the test medium. The higher density of heavy gas (compared to air) provides a great advantage in the scaling of aeroelastic models. The facility operates primarily at sub-atmospheric pressures with an available total pressure range from near vacuum to about one atmosphere. Test velocities up to Mach 1.2 in the 16 ft square test section are possible with the 30,000 horsepower fan system. The combination of large scale, high speed, high density, and variable pressure make the TDT ideally suited for testing aeroelastically scaled models.

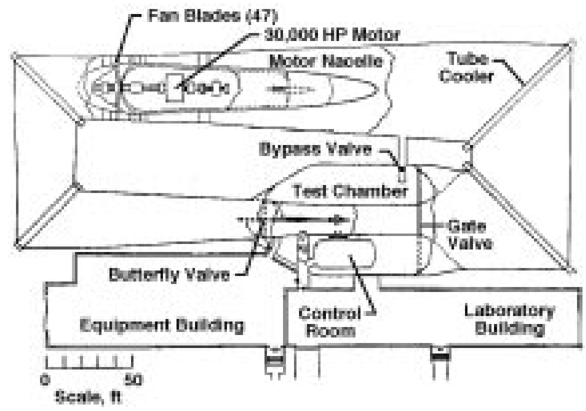

Figure 2: TDT General Arrangement

Plenum Isolation System

The TDT utilizes a test chamber plenum isolation system to provide rapid access to the test section area for model configuration changes. The plenum isolation system consists of a gate valve upstream and a butterfly valve downstream of the test section (see Fig. 2). With the valves closed the heavy gas reclamation system can quickly condition the plenum volume (250,000 cubic feet) for personnel entry, while the remainder of the tunnel circuit (750,000 cubic feet) remains in heavy gas at low pressure.

Bypass Valves

Aeroelastic tests can quickly damage models due to the rapidly diverging structural dynamics exhibited during flutter conditions. These dynamic conditions can result in the structural failure and complete loss of major model components such as wings or flaps. To reduce the probability of such failures, the TDT is outfitted with four large valves which bypass flow from the tunnel's back leg into the plenum (see Fig. 2). When dangerous model dynamic conditions are evident, hydraulic cylinders open the bypass valves and rapidly drop the test section Mach number and dynamic pressure. The reduced aerodynamic loads protect the model from catastrophic damage.

Model Support Systems

A variety of test section model support systems are available at the TDT. These include a conventional rear sting mount, a sidewall semi-span model mount, floor-mounted stands, a floor turntable, and a "free-flying" cable-mount capability. The cable-mount support, shown in Fig. 3, allows the interactions between fuselage flexibilities, flight stability modes, and aeroelastic modes to be simulated.

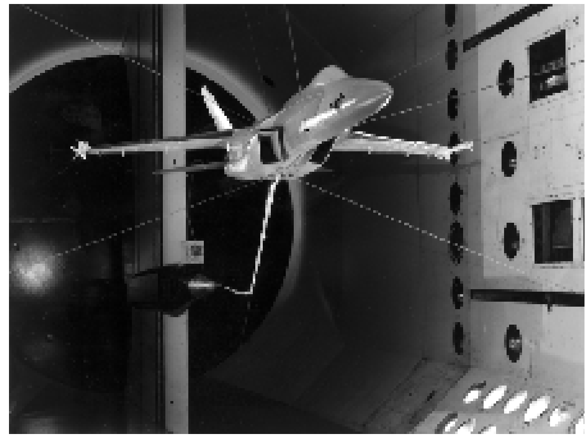

Figure 3: TDT Cable Mount Model Support

SELECTING A NEW HEAVY GAS

The first objective of the project, to select a new heavy gas, was started in 1994 and completed in 1995. Two candidate gases were considered, sulphurhexafluoride (SF6) and R134a. The two gases were evaluated considering alternative gas reclamation processes, aerodynamic characteristics, and the system modifications required to convert the facility to the new gas. R134a was found to be an environmentally safe alternative to R12, and would require fewer facility modifications than converting to SF6. A comparison of the environmental and physical characteristics of the original R12 and the new R134a is shown in Table 1.

Table 1: R12 and R134a Characteristics

	R12	R134a
Global Warming Potential	3.00	0.26
Ozone Depletion	1.00	0.00
Molecular Weight	120.9[4]	102.0[5]
Speed of Sound (ft/s)	505	540
Ratio of specific heats	1.14	1.13

Due to the higher speed of sound and lower molecular weight of R134a compared to R12, a small reduction was anticipated in the facility's maximum Mach number and maximum dynamic pressure. The predicted reduction in performance required a full mapping of operational boundary characteristics in conjunction with facility calibrations following the project construction effort.

THE TDT HEAVY GAS RECLAMATION SYSTEM

The TDT Heavy Gas Reclamation System (HGRS) performs two primary functions: to introduce heavy gas into the wind tunnel circuit prior to testing, and to recover the heavy gas at the completion of testing. In air-only operation the system performs the ancillary function of evacuating the wind tunnel circuit to the desired test pressure. The heavy gas system is comprised of the following major components shown schematically in Fig. 4.

- R134a liquid storage tank
- Heavy gas vaporizer
- Six vacuum blowers
- Five stage reciprocating recovery compressor
- Gas dryer
- Cryogenic condensation system (cold boxes)
- Atmospheric vent stack
- Air dryer
- Langley air distribution system

Figure 4: TDT Heavy Gas Reclamation System

Heavy gas is introduced into the wind tunnel circuit by performing an “air-to-heavy gas exchange.” The HGRS is configured to evacuate air from the top of the tunnel back leg and/or plenum, and to introduce heavy gas into the bottom of the same tunnel volumes. The vacuum blowers and compressor are brought on line and the tunnel evacuated to 300 psf at which pressure the air-to-heavy gas exchange is performed. Liquid is transferred from the R134a liquid storage tank through the steam-heated vaporizer prior to entering the tunnel volume. The heavy gas enters the tunnel volume as saturated vapor at the exchange pressure. The heavy gas gradually fills the tunnel volume from the bottom until it reaches the suction line of the vacuum blowers.

The air/heavy gas mixture is drawn into the suction line and compressed by the vacuum blowers to approximately 5-7 psia. The mixture then enters the compressor where it is compressed in five stages causing liquid R134a to condense out of the mixture at the 3rd, 4th, and 5th stages. The condensed liquid drops into pressure vessel collection pots and is returned to the R134a liquid storage tank.

The remaining air/heavy gas mixture exits the compressor 5th stage at 600 psia and enters the cryogenic condensation system at a maximum heavy gas concentration of approximately 25%. The cryogenic condensation system consists of two “cold boxes” connected in series which drop the mixture temperature and pressure in stages to -140 °F and 315 psia. The cold boxes are cooled by liquid nitrogen provided by two on-site storage tanks, one of which is shown in Fig. 5. Liquid R134a is again condensed out of the gas mixture, collected in phase separators, and returned to the R134a liquid storage tank. The final effluent discharge to atmosphere contains only 200-1000 parts-per-million (ppm) of heavy gas, depending on the compressor suction conditions.

Figure 5: Liquid Nitrogen Storage Tank

A "heavy gas-to-air exchange," where the heavy gas is removed from the tunnel, is performed by configuring the HGRS to remove the heavy gas from the bottom of the tunnel while introducing air into the top of the tunnel. The operation of the vacuum blowers, compressor, and cold boxes is similar to that for the air-to-heavy gas exchange.

The control system monitors the HGRS performance using pressure, temperature, flow, and heavy gas concentration measurements which provide the needed data for facility personnel to safely operate the system.

MODIFICATIONS TO THE HGRS

The second project objective, to modify the HGRS for processing the new heavy gas, was initiated in 1995. The initial design effort focused on the necessary modifications to ensure compatibility with handling and reclaiming R134a instead of R12. Laboratory tests were performed to assess materials compatibility with R134a, oil and moisture absorption levels in R134a, and combustibility of air/R134a mixtures. These test results were integrated with past system performance data and existing industry standards to design the required system modifications for R134a compatibility. The system modifications were driven by three top level requirements:

- To ensure safe processing of R134a
- To maintain, as a minimum, the existing tunnel productivity
- To limit the atmospheric effluent concentration of R134a to 1000 ppm or less

HGRS auxiliary subsystems were evaluated for potential improvements in reliability, performance, and design life. These included the cooling water system, high-pressure air system, instrument air system, steam system, and main drive lube oil systems.

The project construction effort began in October, 1995 at which time preliminary site measurements were completed by the prime contractor and subcontractors. The facility was shut down in May, 1996 for the actual start of site construction. In August, 1997 the facility was brought back on-line for the start of the tunnel calibration tests.

Liquid Storage Tank

The 5500 cubic foot liquid storage tank holds 350,000 pounds of R134a. The tank supplies the liquid R134a to the heavy gas system vaporizer for introduction into the wind tunnel circuit, and is also the receiver of condensed R134a liquid from the recovery compressor and cryogenic condensation system. Converting the storage tank from R12 to R134a was completed in accordance with U. S. Environmental Protection Agency regulations. The existing liquid R12, approximately 100 tons, was first pumped from the tank. The tank was then evacuated to approximately 100 microns to recover the remaining R12 vapor and prevent moisture contamination of the new R134a.

Oil Coalescing Filters

Past experience at the TDT had shown that lubricating oil from the recovery compressor cylinders was dissolving in the R12 and being introduced into the wind tunnel. This was evidenced by an oil film on the wind tunnel walls, tunnel internal components, and models. The capacity of R134a to absorb oil is much less than that of R12, and two new coalescing filters designed for this application were installed downstream of the vaporizer. The filters trap and collect oil droplets before they are introduced into the wind tunnel circuit. Subsequent tunnel operations have indicated a dramatic reduction in the quantity of oil inside the wind tunnel.

Vacuum Blowers

The TDT is a sub-atmospheric facility which tests at total pressures down to 50 psf. Six 8500 CFM, screw-type vacuum blowers (Fig. 6) are arranged in three pairs to boost the tunnel pressure to the 5 psia minimum suction pressure required by the recovery compressor. The first pair can be configured in parallel or series with the remaining two parallel pairs depending on the tunnel pressure conditions. The original vacuum blowers were over 40 years old, had become unreliable, and were losing their design compression ratio. To improve the system's performance and facility productivity, all six vacuum blowers were replaced with new Dresser-Rand blowers and new lube oil systems.

Figure 6: TDT Vacuum Blowers

Recovery Compressor

The Clark recovery compressor (Fig. 7) is a 5-stage, 6-cylinder, 8500 CFM reciprocating machine that is also about 40 years old. The compressor was experiencing multiple reliability problems including lubricator failures and cracks in the cast-iron pistons. Compressor repairs were time-consuming due to the single-piece heads and single-piece pistons which limited access to the compressor internals.

Figure 7: Refurbished TDT Recovery Compressor

The entire compressor was over-hauled with new three-piece aluminum pistons, new two-piece cylinder heads, new valves, and new lubricators. The two-piece cylinder heads have removable plugs which allow the piston rings to be replaced in 4 hours compared to the 5 days originally needed.

Compressor Piping

The compressor piping historically exhibited very high vibration levels which caused numerous fatigue cracks in the piping system. Failures of the heavy gas piping are a serious safety issue considering the 600 psia operating pressures and the asphyxiation potential of R134a. The piping vibrations are initiated by mechanical vibration of the compressor and acoustic pulsations from the double-acting compressor pistons. Thorough finite element and acoustic analyses were performed of the piping system. As a result of these analyses, new pipe supports, pulsation bottles, and orifices were installed throughout the piping system, an example of which is shown in Fig. 8.

The system modifications resulted in significant improvements, in some cases an order of magnitude, to the piping vibration levels for both air and heavy gas operation. Fig. 9 shows the reduction in vibration levels at twelve pipe locations for the 10 Hz fundamental acoustic frequency of the system. The improved vibration levels and lower alternating stresses ensure infinite life of the system per ASME Boiler and Pressure Vessel Code criteria.

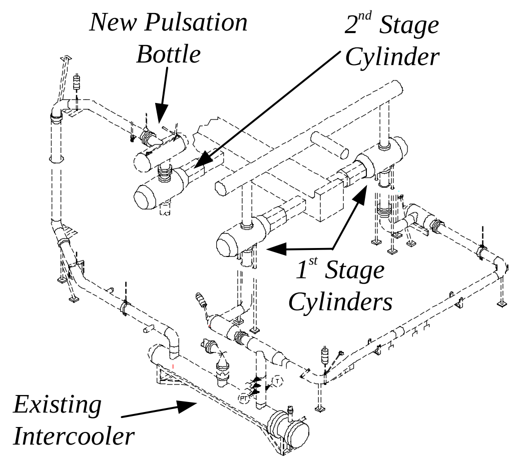

Figure 8: Improvements to Piping Between First and Second Compressor Stages

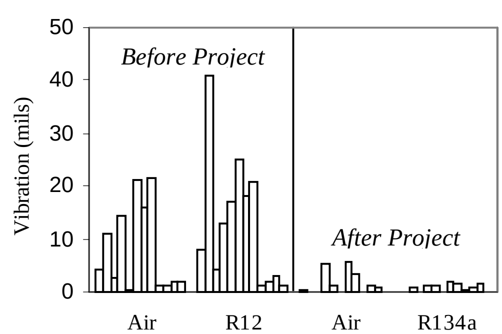

Figure 9: Reduction in 10 Hz Piping Vibrations

Cryogenic Condensation System (Cold Boxes)

The cold boxes are a liquid nitrogen-cooled pair of condensers which remove remnant heavy gas from the process stream before discharging to atmosphere. The cold boxes were installed in 1990 when atmospheric discharge of R12 was becoming increasingly regulated. The system originally operated at temperatures down to -220°F when processing R12. However, R134a has a freezing point of -154°F compared to the -252°F freezing point of R12. The operating temperatures and pressures of the cold boxes were adjusted to accommodate the higher freezing point and other differing thermodynamic properties of R134a. Additional instrumentation was also added which better monitors the cold box status to prevent freezing of the process stream. In this new configuration the cold boxes are successfully reducing the concentration of the final atmospheric effluent to 200-1000 ppm of R134a.

Field Air Source

Prior to the Heavy Gas Conversion Project, atmospheric air was used in the TDT tunnel circuit. The air was passed through a desiccant dryer to reduce the dew point prior to being introduced into the tunnel. As part of the project, the ability to use dry, compressed air from the high-pressure air storage fields at NASA Langley was added to the TDT. This has provided a dry air source with higher flow capacity and lower dew points than previously available. The higher flow capacity has reduced the time required to perform certain tunnel operations, and the lower dew point has reduced the possibility of freezing R134a hydrates and blocking flow in the cold boxes.

Heavy Gas Reclamation System Controls

The original HGRS controls consisted of a graphic operator's panel located in the heavy gas control room. The system was limited in its ability to control and monitor system variables such as valve positions, and required operators to make multiple, simultaneous decisions depending on the system conditions. The entire control system was overhauled and the control room refurbished. New Programmable-Logic-Controllers (PLC's) were installed with new graphical operator interfaces. All operator controls were moved from the graphics panel to a dedicated console (Fig. 10). A new graphics panel was installed showing all critical process variables. A new 240-channel Process Data Acquisition System (PDAS) was installed which continuously records process variables to assess system performance and perform diagnostics.

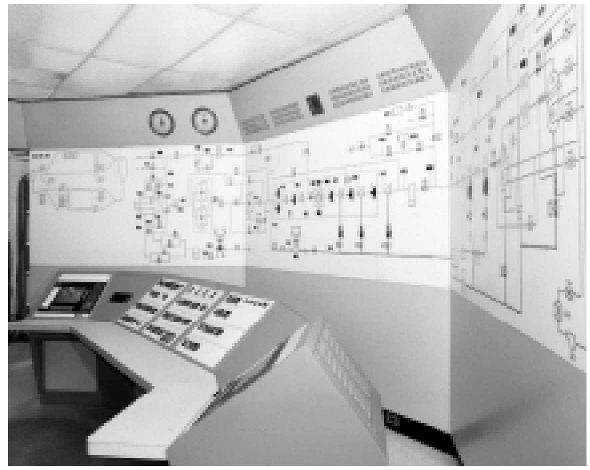

Figure 10: Modified Heavy Gas Control Room

Heavy Gas Reclamation System Performance

The modified HGRS has been thoroughly checked out in both R134a and air operation. Table 2 shows the times required for heavy gas processing in the plenum and the remainder of the circuit (back leg). R134a processing times are similar to those previously needed with R12. To minimize the impact of the heavy gas processing time on tunnel productivity, extended operational hours are used at the TDT. The extended hours maximize research testing time during the normal two-shift operations.

Table 2: Timing of Key HGRS Operations

Plenum air removal	15 min
Plenum air-to-R134a transfer	30 min
Plenum R134a-to-air transfer	40 min
Plenum air pressure 300psf to 1 atm	10 min
Tunnel back leg air removal	60 min
Tunnel back leg air-to-R134a transfer	55 min
Tunnel back leg R134a-to-air transfer	55 min
Tunnel back leg 300 psf to 1 atm (air)	30 min

If tunnel entries are not necessary to access the test article, then R134a test time can approach that of the more efficient air test medium. Unfortunately, the nature of aeroelastic testing leads to frequent model changes and tunnel entries. For a flutter clearance model where a few passes across the tunnel envelope are made, followed by sequential configuration changes, about three model configuration changes can be made in a typical two-shift day of R134a operations.

Heavy Gas Purity

The HGRS repeatedly provides R134a concentrations of 95-98% in the tunnel circuit for research. As the tunnel pressure is lowered, air in-leakage causes the R134a concentration to decrease, so periodic purification operations are required to maintain the R134a concentration to desired research levels. As part of the project, the original R12 gas analyzers which measure gas purity were replaced with eight new infrared R134a analyzers. The new R134a analyzers have increased measuring accuracy compared to the original R12 analyzers, and have improved the quality of the TDT's research data.

MEASURING THE FACILITY PERFORMANCE

The third project objective was to measure the new facility testing boundaries with R134a. As an extension of this objective, a series of calibration tests are being conducted to quantify test section flow properties and flow quality. The majority of these calibration tests have been completed, with only the turbulence measurements still underway. The tests included measurements of: 1) the primary tunnel parameters; 2) the test section Mach number distribution; 3) the test section boundary layer thickness; 4) the test section flow angularity; and 5) the test section turbulence.

Primary Tunnel Parameters

The most important aspect of the calibration efforts was to determine proper instrumentation locations to ensure accurate flow property measurements, particularly with R134a. Determining the primary flow parameters fundamentally requires the measurement of four properties: stagnation pressure, static pressure, stagnation temperature, and R134a purity.

Stagnation Pressure- Historically at the TDT, stagnation pressure has been measured upstream of the test section by a total pressure probe mounted two feet from a settling chamber side wall and slightly below the chamber's vertical centerline. For the calibration tests, total pressure probes were mounted at nine locations several feet downstream of the tunnel turning vanes immediately upstream of the settling chamber. The purpose was to determine if the original probe provided a representative measurement of stagnation pressure, or if a new location or technique, such as averaging several probes, may be needed in future testing.

Static Pressure- The primary static pressure measurement has historically been made between a side wall of the plenum chamber and the wind tunnel control room near the vertical centerline of the tunnel circuit. This is a reasonable location if the test medium in the vicinity is relatively still and at nominally uniform pressure. To check the accuracy of the existing static pressure measurement, static pressure tubes were located at various positions in the plenum during the calibration tests to assess static pressure measurement as a function of location in the plenum.

Stagnation Temperature- In the past, stagnation temperature has been measured with a thermocouple in the TDT. The primary measurement was made just a few feet downstream of the tube cooler (see Fig. 2). A number of temperature measuring devices and tunnel locations were tested during the calibration effort to determine the most appropriate location and device for measuring the facility stagnation temperature.

R134a Purity- Heavy gas flow properties in the TDT are calculated based on purity measurements made with gas analyzers. However, it is possible to eliminate the need to directly measure R134a purity if the gas mixture's speed of sound can be accurately measured. The measured speed of sound can then be used to calculate the R134a concentration of the gas mixture. To demonstrate this possibility, a system of acoustic transmitters and receivers was developed to measure the speed of sound of the test medium. This capability may lead to improved flow property measurements compared to the gas analyzers, or at the very least, may be used to supplement the gas analyzer data.

Mach Number Distributions

Local Mach numbers in the test section are calculated from the local test section static pressure, settling chamber stagnation pressure, stagnation temperature, and R134a purity. An important aspect of calibrating the TDT was to measure static pressure variations, and subsequent local Mach number variations, as a function of position in the test section. The Mach number distribution was determined using sidewall pressure measurements, centerline tube measurements, and survey rake measurements.

Sidewall Pressure Measurements- The term sidewall pressure measurements as used here describes any measurement of local static pressure at the wall, ceiling, or floor surfaces of the TDT test section. Four streamwise rows of 28 static pressure ports were installed in the test section for these calibration efforts, one row on each of the test section surfaces. Fig. 11 shows a line on one sidewall of the test section to highlight one of the four rows along which pressure measurements were made.

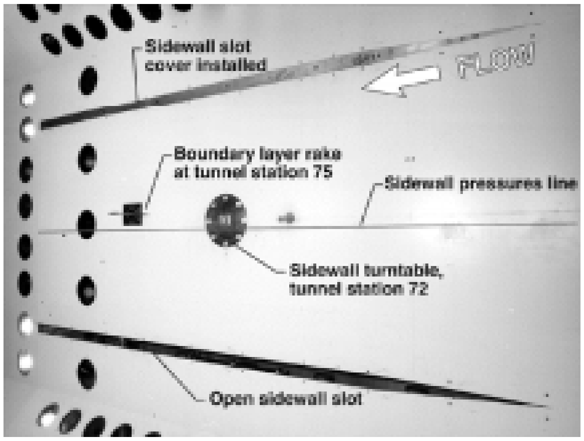

Figure 11: One Location of Static Pressure Measurements

<u>Centerline Tube Measurements</u>- A tube apparatus, shown in Fig. 12, was used to measure static pressures along the centerline of the TDT test section. The tube was attached to the TDT sting support and extended forward through the test section into the downstream region of the settling chamber. Positioning the nose of the centerline tube in the lower-velocity flow of the settling chamber minimized wake disturbances that could have caused erroneous static pressure measurements downstream along the tube. Static pressure ports were spaced at 127 streamwise positions, including the nose of the tube in the settling chamber.

Figure 12: Centerline Tube Installation

<u>Survey Rake Measurements</u>- The final apparatus that measured local Mach number in the test section was the sting-mounted flow survey rake shown in Fig. 13. The rake is a single horizontal blade with eleven probe positions on the leading edge. By mounting probes at the various positions across the rake, the Mach number distribution of the central span of the test section was determined. The probes on the rake spanned approximately five feet on either side of the test section centerline. In addition to this spanwise measurement of local Mach number, the rake was traversed to determine the vertical distribution of Mach number in the test section.

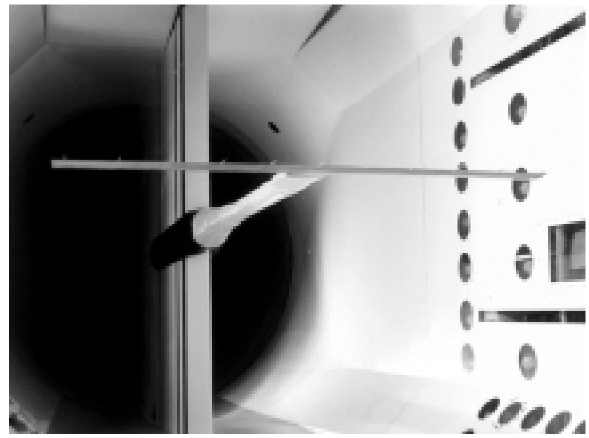

Figure 13: Flow Survey Rake

<u>Boundary Layer Measurements</u>

To assess the possible influence of model proximity to a test section sidewall, measurements were made simultaneously with a set of boundary layer rakes mounted at six positions around the test section perimeter as shown in Fig. 14. The rakes extended from the sidewall surface approximately one foot into the flow.

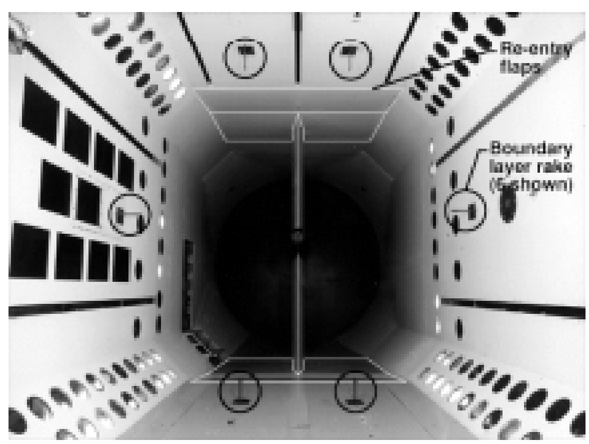

Figure 14: Boundary Layer Rake Locations

The boundary layer rakes (Fig. 15) had numerous stagnation pressure tubes along their span to measure the variation in stagnation pressure from the wind-tunnel wall out into the freestream flow. The rakes were moved to several streamwise positions in the test section to measure the streamwise variation in boundary layer characteristics.

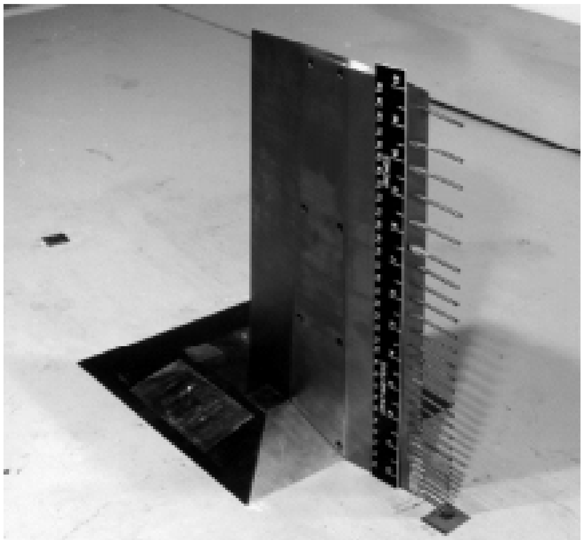

Figure 15: Boundary Layer Rake

Flow Angularity Measurements

Flow angularity was determined with a set of five-hole probes on the survey rake which measured flow angles with respect to both the horizontal and vertical planes of the test section. A thorough set of flow angularity data was obtained for many combinations of Mach number and dynamic pressure in the R134a test medium.

Turbulence Measurements

Turbulence information is considered very important because it may greatly influence the dynamic response of aeroelastic wind tunnel models. The turbulence level measurements have not yet been completed. The turbulence measurements will be made using a number of hot-wire probes, unsteady pressure transducers, and microphones on the sting-mounted survey rake and at other locations in the test section, plenum, and settling chamber.

Tunnel Configurations

Another important aspect of calibrating the facility was to investigate other facility configuration variables. Aside from drive motor speed, the primary TDT facility variable is the position of the re-entry flaps located on the ceiling and the floor at the downstream end of the test section (see Fig. 14). The re-entry flaps capture flow that has escaped, or expanded, through the test section sidewall slots. A part of the calibration effort was dedicated to assessing the optimum re-entry flap settings to be used at different Mach number and dynamic pressure combinations to provide the best Mach number distribution through the test section.

The configuration of the sidewall slots on the test section wall where semispan models are mounted for testing (see Fig. 11) was also evaluated for its effect on flow properties. For most tests conducted in the TDT, the effect of the proximity of the test article to the test section sidewall slots has been considered minimal because most aeroelastic models are tested at nearly zero-lift conditions. Also, most often the important lift loads for aeroelastic testing are dynamic in nature and therefore the proximity of the sidewall slots may not be as important as they would be for large, steady aerodynamic loads. However, the possible influence of the sidewall slots led to a decision to conduct facility calibrations, particularly for the new heavy gas R134a, with these sidewall slots opened and closed.

Results of the Calibration Tests

The calibration tests of the primary tunnel parameters have been completed. For stagnation pressure, static pressure, and stagnation temperature, the data from the calibration tests verified that the historical measurement techniques are suitable for R134a testing. The prototype speed of sound measurement device showed great promise as an alternative method of measuring the test medium purity level. Additional evaluation of this system during subsequent operations will be performed to assess its future role in measuring the flow parameters.

As part of the primary tunnel parameter measurements, the new R134a operating envelope for the TDT was established. The resulting Mach number and dynamic pressure limits of the TDT for both air and R134a testing are shown in Fig. 16. The operating envelope in R134a was found to be virtually identical to the previous boundary with R12.

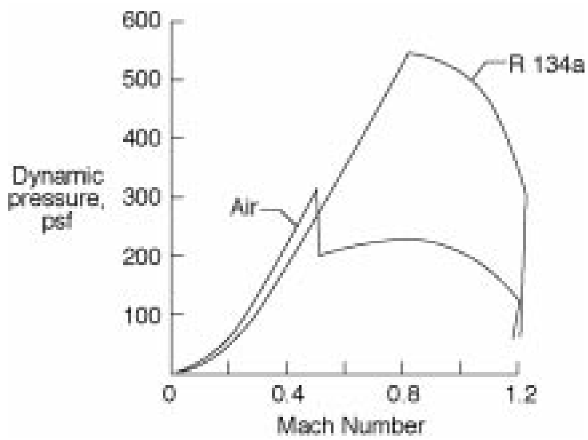

Figure 16: TDT Air and R134a Operating Boundaries

At the time this paper was written, the turbulence level measurements were still underway. The Mach number distribution, boundary layer, and flow angularity tests had been completed, but the final data and test results were not yet ready for inclusion in this paper.

CONCLUDING REMARKS

The purpose of the TDT Heavy Gas Conversion Project was to ensure long-term availability of the TDT's unique aeroelastic testing capabilities. The project has successfully converted the TDT from R12 to R134a testing. Improvements have been made to the operator interfaces, facility reliability and maintenance, and research data quality. The resulting facility performance with R134a is equivalent to the previous performance in R12. The successful completion of this project, and the demonstration of the facility's performance, have ensured that the TDT will remain a valuable national facility resource well into the 21st century.

ACKNOWLEDGEMENTS

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