

NASA Glenn Research Center 10- by 10-Foot Supersonic Wind Tunnel Air Heater Capability and Characterization Plans

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The NASA Glenn Research Center 10- by 10-Foot Supersonic Wind Tunnel, capable of generating Mach 2.0 to 3.5 flow through the test section, is the largest high-speed propulsion wind tunnel within NASA. This facility has historically had the ability to raise the total temperature of the test section to reach flight-match total temperatures between Mach 2.0 and 3.1 using a natural-gas-supplied tunnel air heater ahead of the test section. Test section characterization efforts began in 1964 with the original 'Hot' calibration and the most recent characterization test entry to use the tunnel air heater was in 1999. To enable this capability once again, a reactivation of the heater systems and a characterization of the test section flow field and gas composition are being planned and pursued.

Nomenclature

Variables

C_P = Specific heat at constant pressure

C_V = Specific heat at constant volume

P = pressure

R = gas constant

T = temperature

γ = ratio of specific heats

Subscripts

$_{BM}$ = refers to a parameter, measured or calculated, using the bellmouth rakes in the 10x10 SWT

$_S$ = static condition of a given parameter (i.e., P_S = static pressure)

$_T$ = stagnation condition of a given parameter (i.e., P_T = stagnation pressure)

$_{TS}$ = refers to a parameter, typically a calibrated or calculated value, in the test section

I. Introduction

GROUND testing facilities generally strive to reproduce environments which correspond to the mission of a flight vehicle. The 10- by 10-Foot Supersonic Wind Tunnel (10x10 SWT) seeks to achieve this goal between Mach 2.0 and 3.5 for a wide range of simulated altitude conditions. Additionally, the facility has the infrastructure to support testing at flight-matching total temperature from Mach 2.0 to 3.1 through the use of a direct-combustion tunnel air heater. The use of the air heater produces a vitiated flow in the test section which complicates the accurate estimation of test section variables of interest, such as Mach number, freestream total pressure, etc. Past test section characterization efforts have pursued measurements of the effects of the tunnel air heater upon the test section flow field, and there are plans to further improve upon the current understanding of the tunnel air heater and its impact on test section conditions. This report describes the 10x10 SWT facility capability, previous tunnel air heater characterization efforts, and the goals of the wind tunnel characterization team to increase the quality of data produced during tunnel air heater operation.

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II. Facility Overview*

The 10-by 10-Foot Supersonic Wind Tunnel at the NASA Glenn Research Center is a continuous flow, propulsion, variable density wind tunnel. It is NASA's only high-speed ($Mach > 2.0$) propulsion wind tunnel. The facility layout is shown in Figure 1. The facility can be operated in either an aerodynamic cycle (closed-loop) or propulsion cycle (open-loop) mode. In the aerodynamic cycle, the tunnel operates in a continuous flow mode and the tunnel pressure level can be varied to match 200 psf to slightly above atmospheric (this provides a Reynolds number range of approximately 0.5 million to 3.5 million per foot; the full operating envelopes of the facility are found in Reference [2]). The facility pressure level is controlled by a vacuum system that is used to lower the pressure within the tunnel shell. In propulsion cycle, the tunnel operates at atmospheric pressure and in a single pass mode where the air is brought in through the air dryer and exhausted out the muffler. Propulsion cycle is used for models that introduce contaminants into the airstream, such as the products of combustion from an engine test, or when the facility air heater is used. The operating mode is controlled by the position of a 24-ft valve.

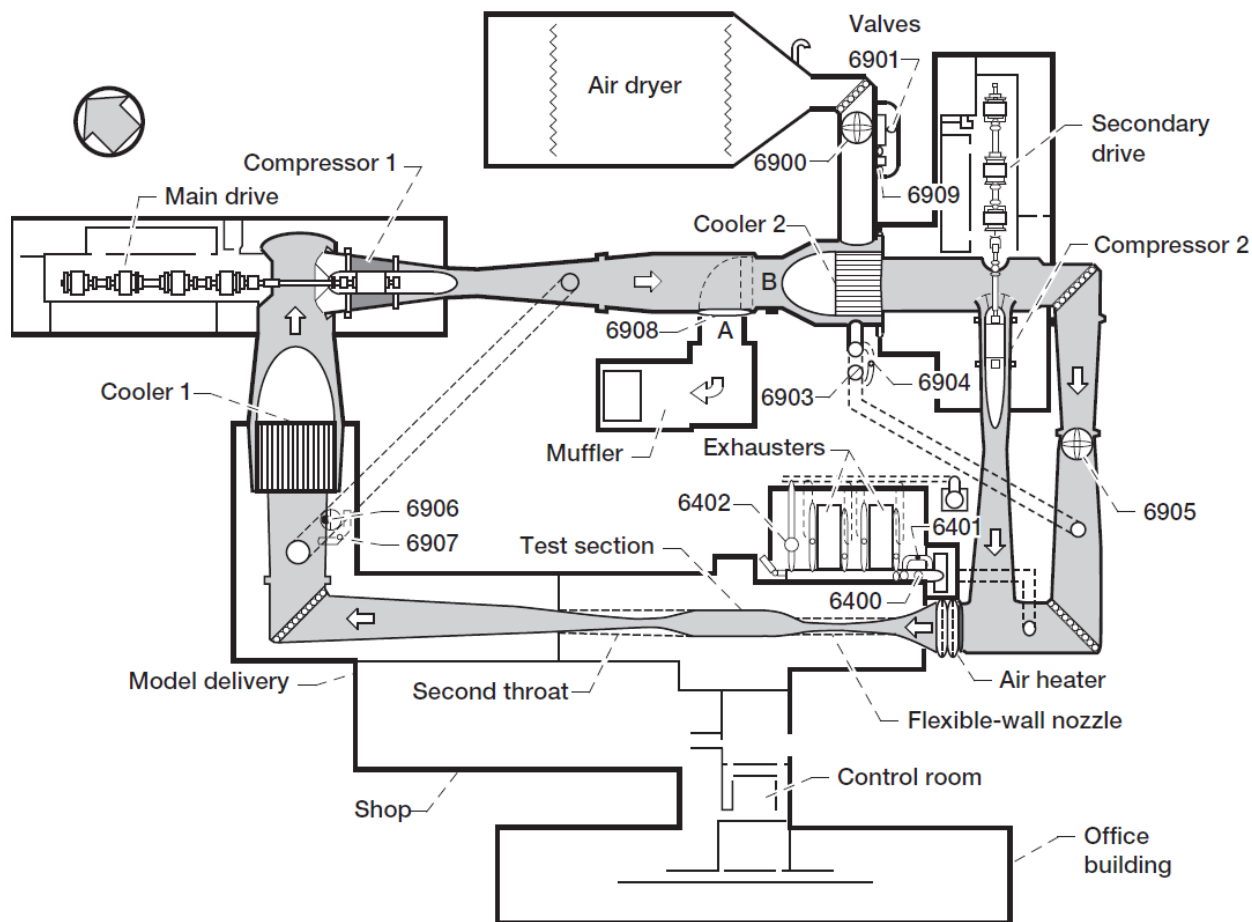


Fig. 1 NASA Glenn Research Center 10- by 10-Foot Supersonic Wind Tunnel Diagram.

The test section elevation view is shown in Figure 2. The upstream cross section of the test section is 10 ft wide by 10 ft high. The test section is 40 ft long and its walls diverge $0^\circ 22'$ to a width of 10.51 ft at the downstream end. The floor and ceiling of the test section are parallel. There are two areas where models are positioned, the upstream and downstream test sections, each of which have their own optical access for schlieren or laser imaging.

The facility Mach number range is 2.0 to 3.5; the full Mach number range can be achieved in either aerodynamic or propulsion cycle. The air flow is moved through the facility by two drive systems, each consisting of a large axial flow compressor powered by electric motors. The primary drive is used for Mach number conditions from 2.0 to 2.6. The primary drive is an eight-stage, axial-flow compressor powered by four 41,500 hp electric motors. For Mach numbers of

*Adapted from [1]; NASA-TM-2000-209799

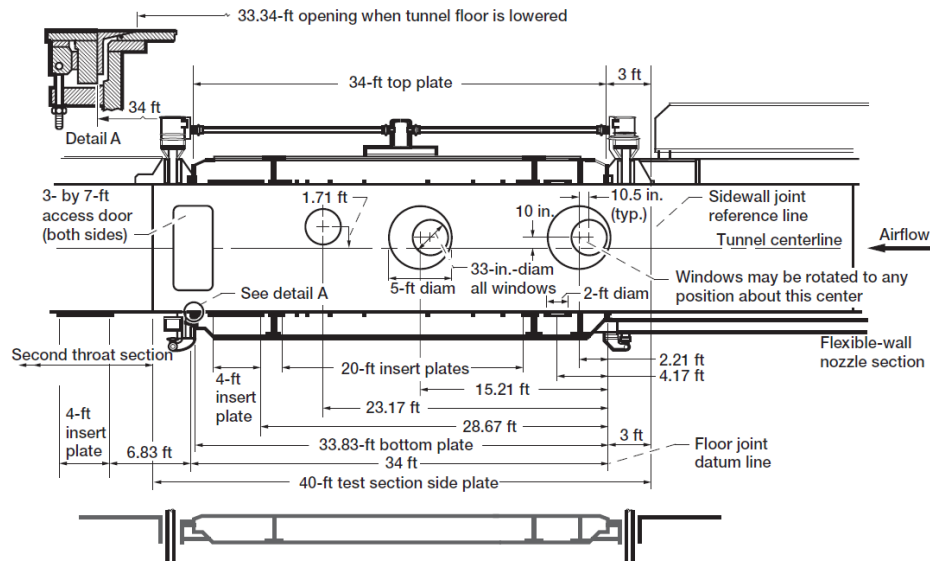


Fig. 2 10- by 10-Foot Supersonic Wind Tunnel test section elevation view.

2.6 and above, both the primary and secondary drive systems are used. The secondary drive is a ten-stage, axial-flow compressor driven by three 41,500 hp electric motors.

The test section Mach number is controlled by the mass flow generated by the drive systems and the position of the flexible-wall nozzle (flexwall). The flexwall consists of two 10-ft-high, 76-ft-long and 1.375-in-thick stainless steel plates that are positioned by hydraulically operated screwjacks. The positioning system incorporates cams on a common shaft; the cams have flats that correspond to 0.1 Mach number increments. The control system for the flexwall position was improved prior to the 1995 calibration to allow for repeatable setting of the flexwall at off-design conditions (that is other than the 0.1 Mach number increments or off the cam flats). This improved position control allows for a nearly continuous Mach number range between 2.0 and 3.5. Reference [2] provides a detailed description of the facility and its operation.

A. Tunnel Air Heater

Starting outside the facility, there are three natural gas pipes split off from a main supply line to the lab. Each of these natural gas supply lines is instrumented with orifice plates to provide feedback to tunnel operators on natural gas mass flow rates. The three supply lines are routed to three circular zones of the tunnel air heater which can be seen in Figure 4(a). There are a total of 64 burners in the air heater, each of which contains three J47 combustor cans (Figure 4(b)). The tunnel air flow is metered through the combustor cans via butterfly valves between and around rows of combustor cans as can be seen in Figure 5(a). Thermocouple and visual feedback (Figure 5(b)) is used to ensure flame ignition during tunnel air heater operation. For reference, the total temperature operating envelope (Ref. [2]) is included in Figure 3. The design and operational information for the tunnel air heater were drafted by Corsetti in 1957 which indicates flight match total temperatures of 246°F for Mach 2.0 and a maximum facility temperature of 680°F for Mach 3.5 requiring approximately 205,000 and 490,000 SCFH total of natural gas flow, respectively. As noted in Reference [2], the conditions at high Mach number and high temperatures are limited to 5-10 minute increments with non-heater operation required between 'Hot' conditions to allow for the flexwall to cool. The flexwall thermal growth is monitored and the heater will be shutdown if proximity switches are triggered between the flexwall and floor and ceiling of the tunnel.

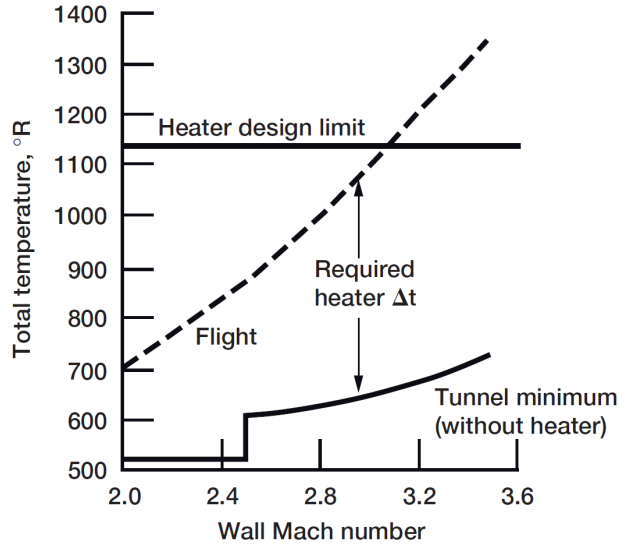
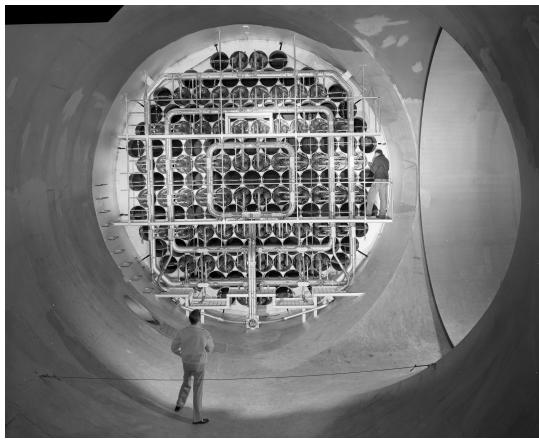
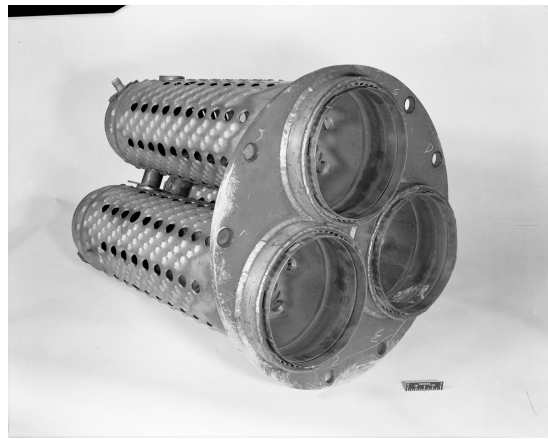


Fig. 3 Total temperature operating envelope for propulsion cycle in the test section of the 10x10 SWT during supersonic operation [2]. NASA/TM-2004-212697.



(a) View looking downstream. GRC-1958-C-47713.



(b) J47 combustor cans in 10x10 SWT tunnel air heater. GRC-1958-C-47793.

Fig. 4 10- by 10-Foot Supersonic Wind Tunnel direct-combustion tunnel air heater in 1958.

III. Characterization Hardware

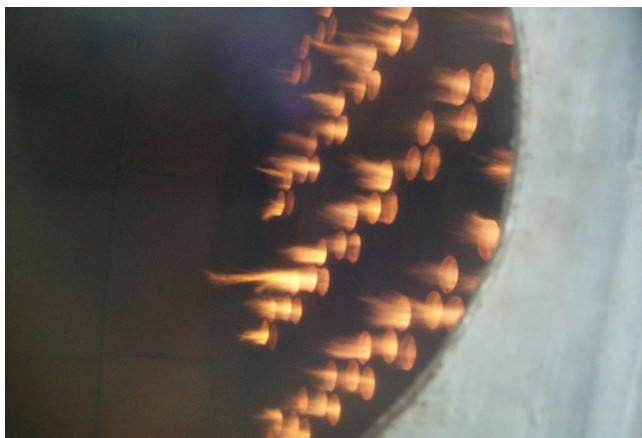
A. 17-Wedge Array

The 17-wedge array has been used to collect calibration and flow field data in the 10x10 SWT test section during each of the following calibration test entries: 1964, 1991, 1993, 1995, and 1999. The test hardware is a 4-ft by 4-ft array to which all of the flow sensing probes are mounted. The array is mounted to the end of a remotely-controlled rack and pinion mechanism mounted on two fixed struts. The rack and pinion provides eight feet of axial translation of the array. The whole apparatus can be mounted at either the upstream or downstream test section schlieren window stations. Figure 6 shows the 17-wedge array installed in the 10x10 SWT during the 1991 characterization alongside boundary layer survey rakes.

As the name implies, the primary instrumentation on this piece of hardware are seventeen 20-degree-half-angle



(a) View looking upstream.
GRC-1958-C-47803.



(b) Visual ignition indication of combustor cans.

Fig. 5 Additional perspectives of the 10- by 10-Foot Supersonic Wind Tunnel tunnel air heater.



Fig. 6 17-Wedge Array installed in the 10x10 SWT test section during the 1991 test section characterization test entry. GRC-1991-C-09146.

supersonic wedge probes[†]. Sixteen of the wedges are in an evenly spaced square pattern with the seventeenth wedge located at the center of the square on the test section centerline. The wedges provide a measure of the total pressure, Mach number and flow angle (one component depending of the orientation of the wedge). The array also has 18 thermocouples (one near each wedge except for the center wedge which has two). For more detailed information on the 17-wedge array, see Reference [1].

B. Characterization Array

The 10x10 SWT Characterization Array was designed and built between 2020 and 2023 in preparation for an upcoming tunnel characterization following significant facility data system, instrumentation, and control system upgrades. The new array is a 5- by 5-ft square with a variety of flow sensing probes to calibrate the test section Mach number, total pressure, and total temperature and survey the test section flow quality, such as flow angularity, unsteady pressure characteristics, uniformity, etc. The array contains a single variable-angle-wedge probe at centerline, twelve 20-degree-half-angle cone probes, twelve pitot static probes, two dynamic wedge probes containing Kulite pressure

[†]As the wedges had not been used since the 1964 calibration, all were refurbished prior to the 1991 calibration test.

transducers for unsteady pressure characterization, and thirty total temperature probes. There are also locations on the array which are designed to allow for up to five gas sensing probes to be installed for gas composition characterization during tunnel air heater operation. The new array is intended to be mounted to a 96-inch Translation System on the lower strut of the facility for surveying closed-loop and open-loop, non-heater conditions. During tunnel air heater operation, the array will utilize a fixed-sting on the lower strut[‡]. For further information regarding the details of the array and probe arrangements, see Reference [3].

IV. Previous Characterization Tests

There have been several major test section characterization entries in the history of the 10x10 SWT. A few of these entries will be described in the following sections as they're related to previous efforts to characterize the tunnel air heater performance and its impact upon test section conditions.

A. Original 1964 'Hot' Calibration

Reference [4] details the effects of the the 10x10 SWT tunnel air heater on test section freestream flow parameters during the 1964 test entry. The results of the 1964 test were used to develop the original 'Hot' calibration of the facility (the term 'Hot' was used to differentiate the calibration models from those used during typical non-heater or 'Cold' operations of the facility). During this test entry, an array of 17 supersonic wedge probes (see section III.A) was used to survey the flow field at conditions across the entire operating envelope of the facility, including propulsion-cycle (or open-loop) operation with the tunnel air heater enabled. Following a recording at a 'Cold' condition at a given Mach number, the tunnel air heater was ignited and natural gas flow rates metered to achieve several temperature settings. Temperature settings approaching, approximately matching, and exceeding (when possible) the flight-match total temperature for a given Mach number were surveyed.

The results of the 1964 'Hot' calibration yielded models which allowed for the decrement in test section Mach number and total pressure recovery from the bellmouth[§] to be estimated. During this test entry, no experimental data were acquired to adjust the ratio of specific heats, γ . Instead, the effect on γ was predicted assuming complete combustion of the natural gas to achieve the desired rise in temperature. The analyses showed that the products of combustion were at most 7.5% of the total airflow, and the model predicted a reduction of 0.023 in γ when producing the maximum temperature rise in the facility (see Figure 5 in Reference [4]).

B. Characterization Tests in the 1990's

A very similar characterization test entry was conducted in 1991 in which the 17-wedge array was used to perform test section flow surveys across the operating envelope of the facility, including tunnel air heater surveys. In this entry, air samples were collected using a probe mounted near test section centerline on the leading edge of the forward support strut for the array. The samples were stored in canisters below the test section and taken to a chemistry lab post-test for analysis. The results of the gas sample analyses were determined by a NASA chemist to be in error due to problems with the sampling technique and/or in the sample analysis. In 1999, another survey with the 17-wedge array was conducted which included conditions using the tunnel air heater but without any objective towards sampling the gas composition. Recommendations from both the 1991 and 1999 post-test summary reports include mention of gas sampling to better understand the products of combustion in the test section during tunnel air heater operation.

C. Activities Related to the Tunnel Air Heater Since the 1990's

Following the 1999 test section characterization entry, there was also a particle-induced velocimetry (PIV) test in 2007 which used the tunnel air heater ducting to supply seed material to the flow [5]. In the time between 2007 and the present, the tunnel air heater was unused until customer interest arose in the 2017 time-frame. During efforts to reactivate the tunnel air heater, electrical engineers determined a significant investment would need to be made into bringing the electrical systems supporting the heater operation up to code. Preparations and plans had been made but not yet executed due to cancellation of the test program interested in the use of the tunnel air heater. The facility

[‡]The 96-inch Translation System uses a hydraulic cylinder atop the assembly to drive the sting forward and aft in the test section. The hydraulic system is the primary limiting factor which prevents use of this translation system for test section characterization with the tunnel air heater in use.

[§]Total pressure recovery is defined as the ratio of measured/calculated test section freestream total pressure to bellmouth total pressure as measured by the 16 pitot pressures across the 4 bellmouth rakes.

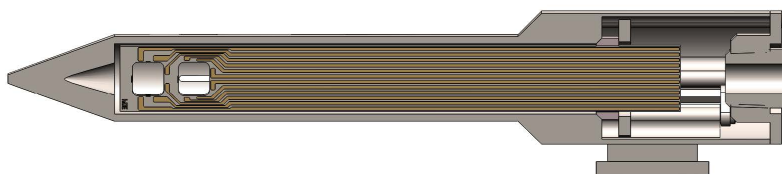
engineering team will retain the project proposal until a time when facility maintenance funding becomes available and/or investment in the system becomes critical to the success of a test campaign.

V. Recent Tunnel Air Heater Characterization Efforts

Starting in 2017, an effort was initiated within the wind tunnel characterization team at NASA Glenn to create a gas analysis system capable of surveying the products of combustion from the 10x10 SWT tunnel air heater in near real-time. The effort began due to customer interest for a future test program in which the tunnel air heater and an oxygen replenishment system would be involved. The oxygen replenishment capability does not exist at the facility, but there were design studies conducted. Initial gas sampling designs involved several racks of gas analyzers, heated conduit to transfer flow from the test section to the analyzers while preventing water vapor condensation in the sample, vacuum pumps, etc. In late 2017, a researcher from the Smart Sensors and Electronics Systems Branch at NASA Glenn who was working with emissions sensors was introduced to the wind tunnel characterization team. Makel Engineering, Inc., the company who produced the aforementioned emissions sensors, was contacted, an iterative design process began with the company, and eventually a gas sensing probe, an electronics package for signal processing, and custom software were procured in 2018. Figure 7(a) shows a probe fabricated and delivered to the 10x10 SWT, Figure 7(b) illustrates the sensor location within the probe housing, and Table 1 shows the range of gas species' concentrations for which the probe was originally calibrated by the company.



(a) Photograph of fabricated gas sensing probe.



(b) Cross section of gas sensing probe.

Fig. 7 Makel Engineering, Inc. gas sensing probe (18SSP307-5109) designed for the 10x10 SWT.

Sensor	Calibrated Range
O ₂	10-21%
CO ₂	0-1.5%
CO	0-400 ppm
HC	0-200 ppm (based on CH ₄)
NO _x	0-400 ppm

Table 1 Range of gas species concentrations over which the Makel Engineering, Inc. gas sensing probe (18SSP307-5109) was originally calibrated.

In the event of customer interest in 10x10 SWT heater operation, the wind tunnel characterization team has continued working with Makel Engineering, Inc. on proper probe calibration techniques to meet the facility's needs. To validate the operation of the probe and the health of its calibration, resources have been borrowed from the combustion test cells within the NASA Glenn Engine Research Building. Custom test fixtures have been created to allow for a controlled gas sample to be pushed across the gas sensing probe's sensors while also being measured by a set of gas analyzers. The rack-mounted gas analyzers belong to the combustion test cell and chemical engineering team within the testing division. This process is planned to be used to validate the operation of the gas sensing probe capability and health of the calibration developed by Makel Engineering, Inc.

Additionally, the NASA Glenn Data Systems Branch has been contacted to ensure communication between the gas sensing probe and facility data acquisition systems can be established and computing requirements achieved for real-time or near-real-time determination of test section gas properties. The standard facility reference instrumentation (i.e., bellmouth pressures and temperatures, flexwall setting, dewpoint temperature), the gas sensing probe readings, and

tunnel air heater natural gas flow rates are required inputs to compute the test section gas properties. The calculation routine is an iterative process using a Netwon-Raphson method to compute the ratio of specific heats and gas constant which includes balancing of the combustion reactants and products, verification of mass-flow continuity, and use of NIST REFPROP[¶] to estimate the specific heats, C_P and C_V , of each constituent gas in the products of combustion. With real-time adjusted values of γ and gas constant, R , free-stream conditions can be computed through the various data reduction routines for the Characterization Array's probes (i.e., isentropic relations, oblique and normal shock relations). A more detailed description of the anticipated calculation routine is included in Appendix VI.

Test plans have been drafted for a potential tunnel air heater characterization campaign. Lessons learned from previous test entries have been borrowed to assist in the test matrix design; with knowledge of the expected Mach number and total pressure decrements during tunnel air heater operation, the shape and order of the expected regression models can be anticipated thus guiding the test team to efficiently acquire data points. The total temperature gradients observed by the 17-wedge array during tunnel air heater operation also led to the incorporation of multiple gas sensing probe mounting locations on the Characterization Array in anticipation of potential spatial differences in gas composition. Pending performance of the current gas sensing probe from Makel Engineering, Inc., up to 4 additional probes may be purchased.

VI. Concluding Remarks

Building upon lessons learned from previous research groups, wind tunnel characterization engineers, and facility engineering testing experiences, there are plans in place to reactivate the 10- by 10-Foot Supersonic Wind Tunnel tunnel air heater and properly characterize freestream flow parameters, including gas composition. Approval must be granted for funding the heater reactivation and associated electrical work prior to executing the aforementioned facility characterization efforts. At present, a single gas-sensing probe has been procured and is being evaluated as an option for providing real-time or near-real-time estimates of the concentrations of several gases expected to be observed in the 10x10 SWT test section during operation of the direct-combustion tunnel air heater. With the information provided by the tunnel characterization hardware and gas-sensing instrument(s), the facility will be able to produce higher-fidelity estimates of freestream flow conditions during future ground test campaigns which utilize the tunnel air heater.

Appendix A: Calculation Routine Description

A routine to provide a real-time or near-real-time estimate of gas properties in the test section have been drafted for the 10x10 SWT. The following are the inputs considered for estimating the ratio of specific heats, γ , and gas constant, R :

- 1 Facility bellmouth conditions (i.e., $P_{T,BM}$, $T_{T,BM}$)
- 2 Flexwall setting or flexwall throat area
- 3 Dewpoint temperature and pressure at which it is measured upstream of the air heater
- 4 Test section gas concentrations: O_2 , CO_2 , CO , HC , NO_x
- 5 Total mass flow of natural gas through orifice plates^{||}

At a high level, the calculations required to determine the gas composition in the test section include the following:

- 1 Assumptions about the incoming air gas composition (i.e., atmospheric levels of Ar, etc.).
- 2 An outer-loop which iterates upon the initial estimate of γ and the gas constant, R , until convergence is reached using a Newton-Raphson method.
 - 2.1 Computing total mass flow rate of products of combustion using choked nozzle mass flow equation for ideal compressible gas.
 - 2.2 Separating the dry air and moisture content mass flows.
 - 2.3 An inner-loop which iterates upon the estimate of total mol flow rate in the products of combustion until mass flow convergence is reached using a Netwon-Raphson method.
 - 2.3.1 Use gas sensing probe measured concentrations to achieve mass flow rates of CO , CO_2 , O_2 ,

[¶]<https://www.nist.gov/srd/refprop>

^{||} The composition of the natural gas being supplied to the facility could help improve the estimates of carbon and hydrogen ratio to be used in the reactants' side of the mol balancing equations. Pre-test samples are recommended to be taken and analyzed, otherwise, methane is assumed to be the dominant hydrocarbon present.

- NO_x, and HC in test section.
- 2.3.2 Balance Nitrogen and Hydrogen mols to solve for H₂O and N₂ concentrations and mass flows in test section.
- 2.3.3 Verification of mass flow continuity between the choked-nozzle-flow and the estimated summation of mass flows of products of combustion.
- 2.4 Use of NIST REFPROP** for C_P and C_V for each constituent gas estimated to be in the test section at the given test section temperature and pressure, $T_{S,TS}$ and $P_{S,TS}$, respectively^{††}.
- 2.5 Mass-weighted averaging of the constituent gas C_P and C_V values to predict the γ and gas constant, R , of the test section flow.
- 2.6 Adjust initial estimate of γ and gas constant, R , until converged within acceptable tolerance of the calculated values of each.
- 3 With real-time adjusted values of γ and gas constant, R , free-stream conditions can be computed.

Acknowledgments

The authors would like to acknowledge the facility management team for their continued support of developing the characterization capability for this unique feature of the 10x10 SWT. Additionally, the NASA Aerosciences Evaluation and Test Capabilities (AETC) portfolio office has supported development of 10x10 SWT characterization hardware through funding, especially for the Characterization Array and its instrumentation. Additionally, throughout the past several years of pursuing the gas sensing capability for the 10x10 SWT, chemical engineers in the NASA Glenn Engine Research Building have been helpful in supplying bench-testing capabilities to the wind tunnel characterization team to validate probe performance. As always, the TFOME II engineering management has been supportive of facility characterization and ensuring the highest level of data quality produced by the NASA Glenn ground testing facilities.

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**<https://www.nist.gov/srd/refprop>

^{††}The test section temperature and pressure can be approximated by calibrated conditions for real-time computing in the facility data system, however, more accurate estimates can be made in post-processing by including measurements and calculations from the Characterization Array probes into the iterative routine. Additionally, both the static and total temperature conditions will likely be used to estimate the impacts to the air chemistry in the freestream and fully stagnated.