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Hypersonic Ground Test Capabilities for T & E Testing Above Mach 8 "A Case Where S & T Meets T & E"

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ABSTRACT

Simulation of hypersonic flight in ground test and evaluation (T&E) facilities is a challenging and formidable task, especially to fully duplicate the flight environment above approximately Mach 8 for most all hypersonic flight systems that have been developed, conceived, or envisioned. Basically, and for many years, the enabling technology to build such a ground test wind tunnel facility has been severely limited in the area of high-temperature, high-strength materials and thermal protection approaches. To circumvent the problems, various approaches have been used, including partial simulation and use of similarity laws and reduced test time. These approaches often are not satisfactory, i.e. operability and durability testing for air-breathing propulsion development and thermal protection development of many flight systems. Thus, there is a strong need for science and technology (S&T) community involvement in technology development to address these problems. This paper discusses a specific case where this need exists and where significant S&T involvement has made and continues to make significant contributions. The case discussed will be an Air Force research program currently underway to develop enabling technologies for a Mach 8-15 hypersonic true temperature wind tunnel with relatively long run time. The research is based on a concept proposed by Princeton University using radiant or beamed energy into the supersonic nozzle flow.

BACKGROUND AND INTRODUCTION

There is a need for the United States (U.S.) to develop military flight vehicles which fly at hypersonic speeds in the atmosphere to serve as transporters for space access and have capabilities of fast response, global reach (strike and reconnaissance), and missile defense. Currently, the development of these various flight vehicles is constrained by the lack of ground-based test facilities that are necessary to provide affordable development testing and to reduce technical risk to acceptable levels.

In 1992, the U.S. Air Force (USAF) and National Aeronautics and Space Administration (NASA) jointly conducted a study to assess the US test needs and capabilities for development of hypersonic flight systems (Richey and McKinney 1994). The results of this study were confirmed by the joint NASA/Department of Defense (DoD) National Facilities Study in 1994 (Laster and Bushnell 1994) and again in 1997 by the DoD Aeronautical Test Facilities Assessment study (Griffin, Berry and McErlean 1997). These studies revealed serious gaps in hypersonic test capabilities relative to test needs. An especially important issue is that the US does not have test facilities that can be employed for development testing of air breathing propulsion flight systems at the necessary flight simulation conditions above Mach 4. Technologies are available for building development test facilities that can test to Mach 7, but not beyond (note that development testing implies relatively long run duration, since there are short duration facilities).

There are several envisioned air-breathing systems which would fly to Mach 10-15 and some to perhaps as high as Mach 20. It is critical that the environment of hypersonic flight be simulated, and actually duplicated for most cases, in terms of velocity, temperature, pressure, air chemistry, and test time, so that operational and durability features can be assessed.

* The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were performed by personnel of Sverdrup Technology, Inc., AEDC Group, technical services contractor for AEDC, by personnel of Lawrence Livermore National Laboratory, by personnel of Princeton Unviersity, and by personnel of MSE-TA. Further reproduction is authorized to satisfy needs of the U. S. Government.

Technologies for duplicating hypersonic flight conditions in wind tunnels that will provide the required test environments above Mach 7 have not been satisfactorily developed. There have been three major technical obstacles to the development of these hypersonic wind tunnels: (1) providing sufficient energy into the air while (2) maintaining correct air chemistry, and (3) availability of materials that will contain the high-temperature, high-pressure test gas. Electric arcs and compression heating have been employed to heat the test gas in a stagnation chamber and expand the test gas through a nozzle throat to the desired velocity. These techniques have proven to provide insufficient run time, unacceptable gas chemistry, and/or unacceptably low gas density in the test gas. Materials capable of withstanding the requirements of high stagnation temperatures and the severe nozzle-throat heat-transfer requirements limit practical run times to a few milliseconds or less at enthalpies required for flight duplication above approximately Mach 10.

Adding energy to the test gas downstream of the nozzle throat has been considered a possible solution to the nozzle-throat heat-transfer and chemical-dissociation problems. Two ideas have emerged: (1) adding thermal energy to the supersonic test gas by radiant energy means and expanding to the desired velocity, pressure, density, and temperature (Brown et al 1996), and (2) magnetohydrodynamic (MHD) body force acceleration of the test gas followed by expansion of the test gas (Crawford, Chapman and Rhodes 1990). Both ideas, however, have their respective physical constraints. Radiant heating requires an ultra high-pressure (UHP) driver operating to 20,000 atm (near the practical limit of materials) just to achieve Mach 12 simulation at the correct gas entropy. Higher Mach number duplication would require even higher pressure, which raises additional questions relative to high-pressure generation, containment, and run time. The MHD approach requires that the test gas be electrically conductive. Seeding the test gas with an alkali metal such as potassium or cesium to achieve the needed conductivity has been demonstrated successfully at relatively low pressures, provided the air and seed static temperature is of the order or 2500 K or greater, but these static temperatures have been shown to be impractical for achieving the required flight duplication conditions (Crawford, Chapman and Rhodes 1990; Baughman et al 1997). In addition, such seeding materials have unknown effects on the test results, which is a highly undesirable situation. However, if a way can be found to maintain electrical conductivity at low temperature without undesirable chemistry effects on the test gas, MHD would be attractive. Seeding the gas with an electron beam (e-beam) or electric arc filaments has been proposed recently (Macheret, Miles and Nelson 1997; Macheret et al 1998).

A hybrid concept of coupling supersonic thermal energy addition by radiant means with MHD acceleration augmentation may be the optimum approach. This would reduce the pressure requirements on the UHP air supply and also provide a broader range of needed hypersonic test capabilities. Figure 1 shows a schematic layout of a hybrid concept where supersonic thermal energy is supplied by an electron beam augmented with an MHD accelerator. For comparison, a conventional wind tunnel concept is also shown. In this case the thermal energy is supplied ahead of the nozzle at near-stagnation conditions by some form of thermal energy addition to the test gas. Figure 2 is an artist's concept of a medium-scale hypersonic wind tunnel (MSHWT) facility employing the electron beam and MHD energy addition devices.

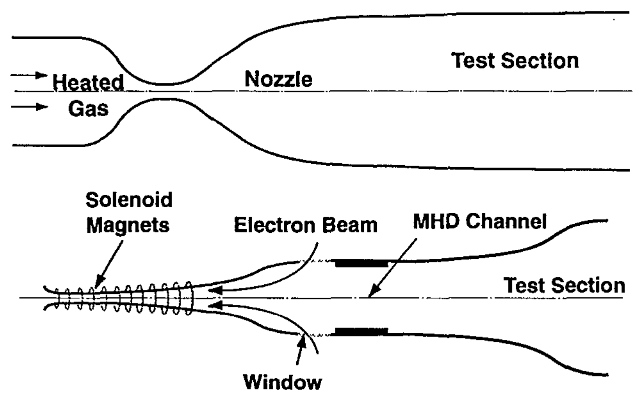

Fig. 1. Conventional and hybrid concepts.

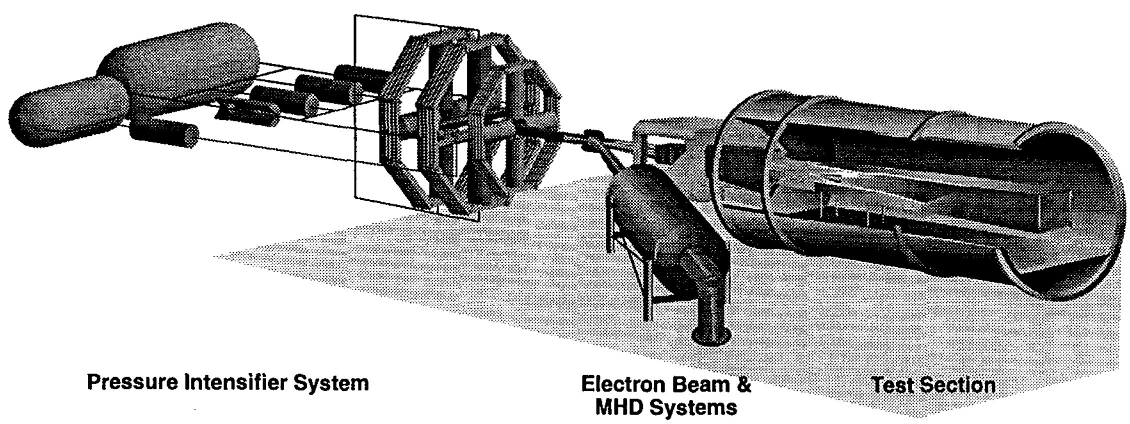

Fig. 2. Artist concept of MSHWT.

In Fig. 3 the performance of the proposed radiantly heated hypersonic wind tunnel is compared with continuous and blow-down wind tunnels with conventional stagnation heating approaches that can produce test flows for relatively long test times. With MHD augmentation, some additional test capability appears possible for flight simulation altitudes above about 110,000 ft. A maximum Mach number of 14.5 has been calculated by Macheret, et al. (1999), for a flight dynamic pressure of 2000 psf, considered to be the lower altitude limit of manned air-breathing propulsion applications. At higher altitudes the MHD augmentation is expected to provid somewhat higher Mach number capability.

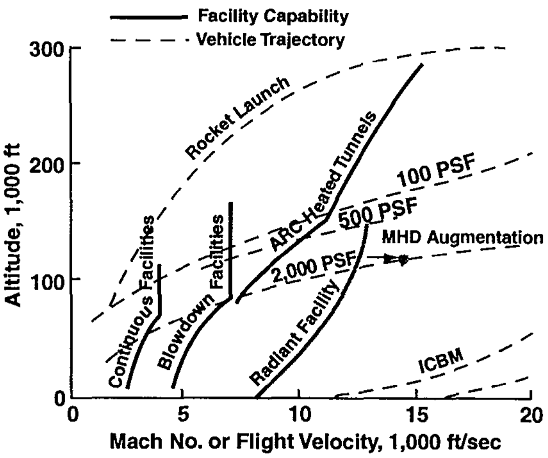

Fig. 3. Performance comparison of various facility concepts.

The following section of this paper discusses a number of science and technology issues that must be addressed relative to this hybrid radiantly heated, MHD-augmented hypersonic wind tunnel concept. With congressional funding, the Air Force is sponsoring research on the concept, which is named MARIAH II. The defined goal of this program is to develop sufficient technology to prepare design criteria for a medium-scale hypersonic wind tunnel that will provide true temperature test simulation at flight Mach 8-15 and a dynamic pressure up to 2000 psf with adequate flow quality and run time. These conditions will provide a development test capability in the disciplines of air-breathing propulsion as well as aerodynamic, aero-thermal, and aero-optical for the development of future hypersonic flight systems.

The Air Force Research Laboratory sponsored the initial supersonic radiant energy experiments. One set of experiments was conducted in 1997 using laser-beamed energy into a supersonic nozzle. A second set of demonstration experiments was conducted at the Sandia National Laboratory where energy was added to a supersonic flow by an electron beam. Both sets of experiments were very successful. This S&T-sponsored activity has given significant technical impetus to the current congressionally sponsor effort.

SCIENCE AND TECHNOLOGY ISSUES

NOZZLE SYSTEM

The operating characteristics of the T&E facility are critically dependent on the thermodynamic path followed by the air as it passes through the nozzle. In a conventional wind tunnel there is only one path and that path is an adiabatic constant entropy expansion where the total enthalpy in the plenum is converted to kinetic energy and residual static enthalpy in the test chamber. In the MARIAH II facility, since energy is added downstream of the throat, there are an infinite number of thermodynamic paths that can be taken before the air arrives in the test section. The S&T challenge has been to determine which of these thermodynamic paths optimize wind tunnel performance, and how closely these paths can be followed, given the practical considerations of the nozzle contour, boundary-layer growth rates, heat transfer to the walls, and thermal energy addition. Figure 4 shows a Mollier diagram with an example of such a thermodynamic path. Any thermal energy addition process increases the enthalpy, Δh, while simultaneously increasing the entropy, $\Delta s = \Delta h/T$. The final operating point in the test facility can be represented as a single point on this diagram. Since the entropy of the flow cannot be reduced (heat cannot be extracted from a hypersonic flow except by radiation), any energy addition requires that the initial flow have entropy lower than the final state. It is this low initial entropy requirement that moves us as far as possible to the left on this Mollier diagram, and necessitates an ultra high pressure driver.

The nozzle design then follows a process which begins with the selection of an ideal thermodynamic path, which the design will target. That path begins with a first step which is

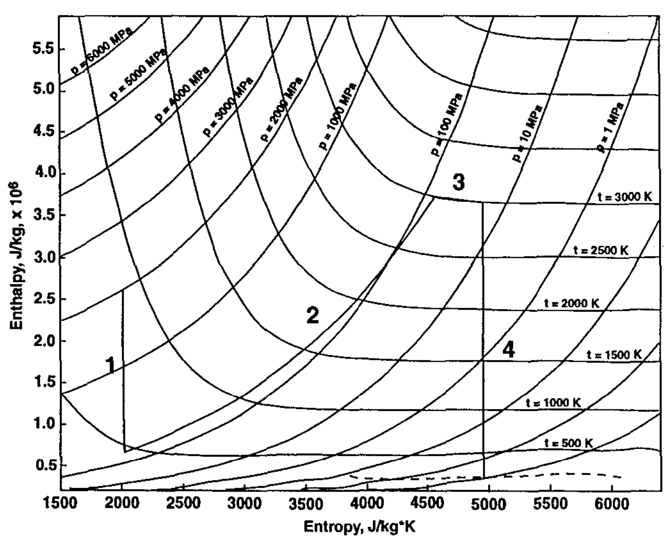

Fig. 4. Mollier diagram showing idealized thermodynamic path from 2000 MPa, 900 K.

an adiabatic constant entropy expansion (path 1 on the diagram) from the ultra high pressure plenum through the throat. This expansion continues to a Mach number somewhat greater than 1, usually chosen for the purpose of these calculations to be Mach 2. In order to deposit the maximum amount of enthalpy into the flow, the gas must be heated as rapidly as possible downstream of the throat to minimize the increase in entropy. The maximum heating rate is limited by choking, and, for the purposes of our calculation, the initial heating is assumed to occur at constant Mach number. The closer to Mach 1, the better, but Mach 2 is chosen to avoid coming too close to choking conditions. Heating at constant Mach number (path 2) continues until the maximum allowable temperature is achieved. That temperature is determined by constraints on the chemical composition of the flow and may, in some cases, exceed the temperature that would be associated with equilibrium concentrations because the residence time at this temperature is relatively short. For sample calculations, we assumed that the maximum temperature is 3000 K. Heating then proceeds at constant temperature until the entropy in the test section or the MHD entrance is reached (path 3). At that point the flow is expanded into the test chamber through an adiabatic, isentropic expansion (path 4). If MHD augmentation is added, then the flow is expanded at an earlier stage and passed into the MHD acceleration section before entering the test chamber.

This idealized path has been used to determine operational limits of the thermal energy addition section of the wind tunnel. Figure 5 shows the idealized operating conditions as a function of plenum pressure and temperature for atmospheric flight conditions at a dynamic pressure of 2000 lb/ft^2. The thermodynamic path assumed for this diagram is that shown in Fig. 4, i.e., expansion to Mach 2, constant Mach number energy addition to 3000 K, and constant temperature energy addition followed by a final isentropic

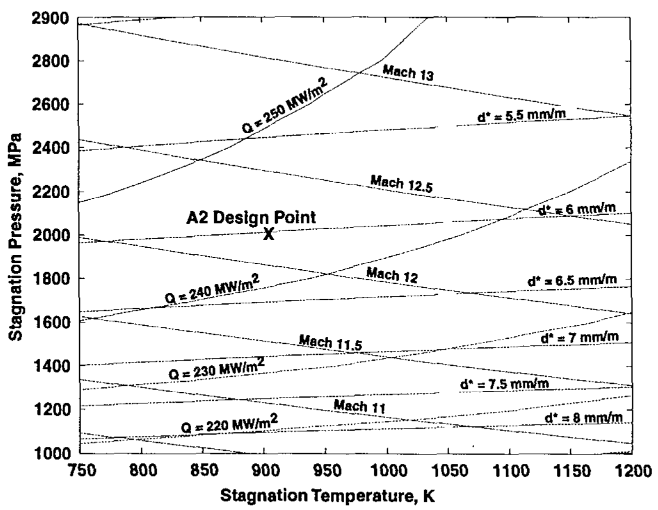

Fig. 5. Idealized operating conditions as a function of plenum pressure and temperature for atmospheric flight conditions at a dynamic pressure of 2000 lb/ft^3.

expansion to the operating point. The altitudes corresponding to these operating points are shown in Fig. 3. Also shown are the throat diameters in millimeters per meter test section diameter and the thermal energy addition requirements in megawatts per square meter of test section area.

These curves represent the predicted ideal performance of a wind tunnel, assuming the thermodynamic path shown in Fig. 4 can actually be followed. In practice, that path can only be approximated based on the physics of the energy deposition mechanism. A better estimate of the true path that can be achieved is found using a one-dimensional iterative design code. This code incorporates the real gas equation-of-state for air and computes the nozzle contour that is required in order to come as close as possible to the ideal performance target. Energy is deposited through either high-power laser radiation or electron beams which are focused into the nozzle section from downstream. The very high power required (hundreds of megawatts) and the high pressures in the energy deposition region (hundreds of atmospheres) preclude passing the energy through the wind tunnel walls. In practice, laser beams can be steered into the nozzle through naturally occurring index-of-refraction gradients, and electron beams can be focused in along magnetic field lines. Laser energy addition is assumed to be accomplished using a high-power hydrogen-fluoride laser which overlaps carbon dioxide molecular absorptions in the vicinity of 2.7 microns. The model uses measured and projected absorption constants based on experiments conducted in collaboration with the National Institute of Standards and Technology (Meinrenken et al 1997; Gillespie et al 1997). Electron beam absorption is computed using the Department of Energy Cyltran Monte-Carlo code at Sandia National Laboratories. These codes are iterated until a steady-state solution is found, giving the energy deposition as a function of axial position along the nozzle, and the nozzle contour that is required to achieve that solution. For example, a 0.5-m-diam test section, Mach 12, q = 2000 test facility will require the deposition of 52 MW of power from a 3-MeV electron beam generator. The predicted thermodynamic path for such a case is compared to the ideal thermodynamic path in Fig. 6.

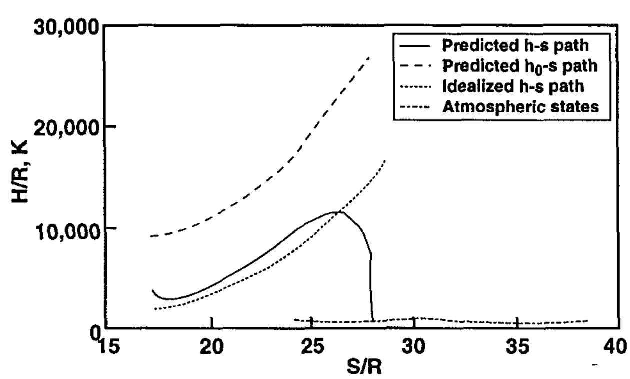

Fig. 6. Predicted thermodynamic path vs. ideal thermodynamic path.

Figure 7 shows the nozzle contour that is required to accomplish this heating profile, and the power deposition as a function of axial position. In this example, the throat diameter is only 3 mm, and the ultra high-pressure driver forces the air through that throat at 9.8 kg/sec. The energy deposition region is only a half a centimeter to a few centimeters downstream, depending upon the energy of the electron beam.

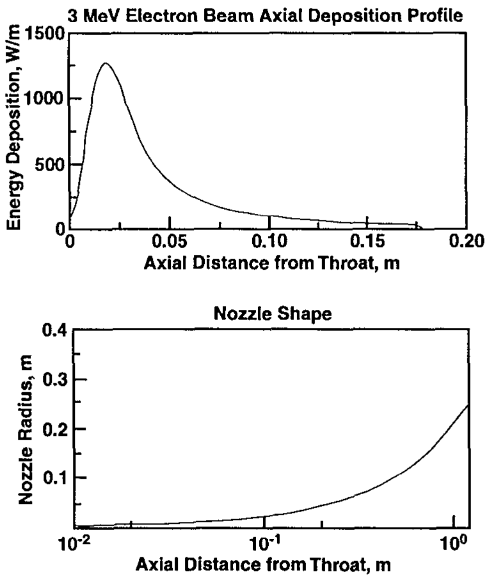

Fig. 7. Nozzle contour for heating profile and power deposition as a function of axial position.

The last iteration in the design process is to implement a fully time-accurate, two-dimensional Navier-Stokes solver to examine the stability of the flow and to predict radial variations in flow properties. Also of great importance is the question of heat transfer to the wall and boundary-layer thickness. In the case of laser energy addition, the two-dimensional code incorporates a ray tracing algorithm which permits the dynamic interaction of the laser with the flow field. In this case (Brown, et al 1996), it is clear that the laser beams are steered by small density variations in the flow in such a manner that, on average, the laser beams uniformly fill the volume. The high temperature, low density, low index-of-refraction boundary layer refracts the laser beams back towards the core of the flow and minimizes wall heating by laser irradiation. This effect may be further enhanced by helium injection along the wall, a step that may need to be taken in any case to suppress heat transfer from the high-enthalpy air.

In the case of the electron beam, the radial heating profile is largely driven by the profile of the electron beam itself. This profile may be controlled to some extent through the electron beam formation process and the magnetic field. In any case, the electron beam must be contoured to keep it from directly heating the walls of the nozzle. Current work is underway to explore the possibility of using a contoured electron beam to heat the core of the flow while leaving a cold annulus of air surrounding that core in order to protect the nozzle wall from excessive heat transfer.

The final design will have to incorporate a model for the boundary-layer growth rate, as well as an understanding of heat-transfer mechanisms under these ultra high Reynolds number, nonideal gas conditions. Experiments are currently underway at Princeton using a 3000-atm, atmospheric temperature, high pressure, blow-down facility to study these questions. The Reynolds number of that facility equals that of the medium- and full-scale facilities, largely because of the relative incompressibility of the air at these pressures and the variation of viscosity with temperature. A major question to be resolved is the recovery temperature at the wall, even in the absence of thermal energy addition. In the nonideal gas regime, the total enthalpy has a significant dependence on pressure. This is an important feature of the MARIAH II concept, since high enthalpy can be achieved in the plenum at relatively low temperatures. As the flow passes through the throat, the total enthalpy remains constant. In the core of the flow the entropy is unchanged, but at the walls entropy increases across the boundary layer. Assuming the transverse pressure is uniform, this could lead to a significant temperature increase, with temperatures achieving levels well beyond the plenum temperature. For example, if the plenum is at 20,000 atm at a temperature of 900 K, the recovery temperature in the throat could be as high as 2000 K. This will have a significant impact on nozzle and throat survivability and may lead to implementation of active nozzle cooling strategies.

ULTRA HIGH-PRESSURE SYSTEM*

Background

The ultra high-pressure system [UHP; $P > 1000$ MPa (145,000 psi)] provides the required mass of air at a plenum condition having as high an enthalpy as possible. The plenum pressure and temperature operating point is a result of a trade-off between mechanical design, materials properties, energy addition capability, and technical risk. The UHP volume is defined by the plenum condition, run time, and the mass flow rate. Run time requirements vary from a few hundred milliseconds for aerodynamic and propulsion performance testing to hundreds of seconds for systems testing. Mass flow rates follow from the size of the test section and

* Portions of this section have appeared in Costantino (1999) [Costantino, Marc, "A Large Volume 2000 MPa Air Source for the Radiatively Driven Hypersonic Wind Tunnel," International Conference on High Pressure Science and Technology, AIR-APT-17, Honolulu, HI, 25-30 July 1999.]

the dynamic pressure at the test article. In general, the UHP subsystem performance is in the direction of high pressure, moderately high temperature, and large volume.

Large volume (> 1 cm^3) UHP design is a mature field, with materials performance as the primary S&T issue. High-pressure equipment operating at 1400 MPa (200,000 psi) and room temperature is available commercially, and fluid pressures up to about 4000 MPa (600,000 psi) are achievable in research laboratories. The limiting factor is the strength of the structural materials containing the pressure. Connecting volumes reliably at pressures above 1400 MPa also is difficult, so that work in the 2000-4000 MPa range has been limited to single manifold systems. Pressure fluid temperatures above about 600 K (327°C) result in degradation of material strength properties. Chemical reactivity of the pressure fluid and the high-performance alloys containing it also must be considered. Since it is common for pressure vessels to operate in the plastic range, fatigue life can be a limiting factor for high cycle applications.

The high pressure, high temperature, large volume, and high oxygen partial pressure requirements for the UHP source results in extraordinary stress management and materials requirements. The primary design challenges for the UHP subsystem of the hypersonic ground testing facility are:

- Connecting UHP volumes
- Materials strength at T > 600K
- Reactivity of oxygen
- Controlling heat transfer from the dense air

Performance Requirements

The UHP conceptual design must demonstrate the technologies for the operating envelope of a practical size facility:

- Mach Number 8 - 15
- Pure air
- Dynamic pressure: 500 - 2000 lbf/ft^2
- Operational time: 1 - 100 sec
- Air mass flow rate: 1 - 100 kg/sec

Trade-offs between the UHP and energy addition subsystems result in a nominal plenum operating point of 2000 MPa and 900 K, with a specific enthalpy of about 2500 kJ/kg (Lemmon et al 1999). The density of air at these conditions is about 1150 kg/m^3, which can be compared to the density of water at standard temperature and pressure (1000 kg/m^3) and liquid nitrogen (807 kg/m^3).

UHP Design Scheme

The design scheme (Fig. 8) uses classical UHP intensifiers comprised of variable radial support cylinders arrayed in pairs around an axial manifold. For a 10:1 pressure multiplication, opposing intensifier pistons are accelerated by a 200 MPa nitrogen source in about 300 msec to their steady-state speed of about 1 m/sec, compressing the pre-charged 300 MPa, 530 K air adiabatically to 2000 MPa and 900 K into the axial manifold. Four intensifiers, each having an internal diameter (ID) of about 10 cm and a stroke of about 60 cm, provide an operating time of 1 sec at 10 kg/sec flow rate. Eight intensifiers with an ID of about 16 cm and a stroke of 90 cm provide an operating time of 10 sec. A smaller, auxiliary set of UHP intensifiers provides a boundary layer flow of helium, injected immediately upstream of the wind tunnel throat. The total volume, in principle, can be increased arbitrarily by adding radial layers. While the UHP intensifiers must be arrayed in opposing pairs to react the forces along their axis, the total number is determined by the total volume requirement and the economics of building and operating a small number of large vessels or a large number of small vessels. The low pressure nitrogen source drives 200 MPa intermediate intensifiers that simultaneously drive 2000 MPa air and helium intensifiers, and provide the hydraulic pressure for their variable radial support. The radial arrangement around an axial manifold permits connection of multiple 2000 MPa volumes. Four-fold symmetry is

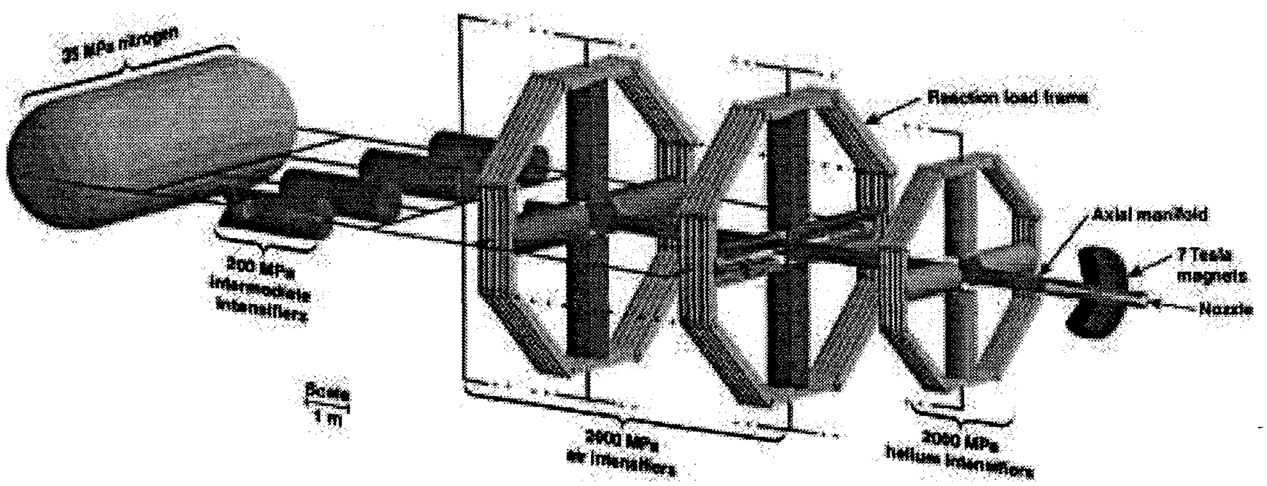

Fig. 8. General design scheme for the air source for a radiatively driven hypersonic wind tunnel.

shown. Six- and eight-fold symmetries are possible. The air source must connect to a nozzle in a 7-20 T magnetic field.

To decrease the environmental, safety, and health (ES&H) risk owing to the large amount of stored energy ($\approx 10^7$ J), the UHP intensifiers are driven by an intermediate set of 10:1 intensifiers which, in turn, are driven by 35 MPa nitrogen contained in an ASME-approved pressure vessel. The intermediate and UHP intensifiers are barricaded and operated remotely during the 1 - 100 sec operation cycle.

The intermediate intensifiers drive both the primary (air) and auxiliary (helium) set of UHP intensifiers and provide the hydraulic load to the variable radial support for those intensifiers. This approach, used by Topchiyan and coworkers (Topchiyan and Kharitonov 1993; Pinakov, Rychkov, and Topchiyan 1981) synchronizes the external radial stress with the internal pressure, which is balanced to result in a controlled radial clearance seal between the intensifier piston and the intensifier inner liner. The use of the variable radial support approach is necessary because, at 900 K, the strength of typical inner liner steels is about 50 – 60 percent of the room temperature value, or about one-half the design internal pressure.

Generating and maintaining the required plenum temperature can be achieved in a number of ways. The present approach employs a packed bed heat exchanger to preheat the initial gas charge to the initial state and makes use of the quasi-adiabatic heat of compression to the final pressure. The air initial state is selected for convenience (at an appropriate entropy) to be within the range of commercial compressors and within service temperatures of organic seal materials. The nominal initial values for the compression path are 300 MPa and 530 K. The compression of the air from its initial value to 2000 MPa occurs quasi-adiabatically in a few hundred milliseconds. The heat flow during this short compression time and the longer operational cycle time depends on the heat-transfer coefficient and the temperature difference between the air and the vessel wall. Estimates of the heat-transfer coefficient using a specific heat, viscosity, and thermal conductivity from Lemmon, et al. (1999), indicate the Biot number for transient heat flow in a hollow cylinder essentially is infinite. Transient heat flow calculations using the code TOPAZ with a constant temperature boundary condition show that, at $t = 1$ sec, significant regions (> bore radius/10) reach temperatures high enough to seriously degrade material properties.

Beginning the compression from an initial point at a higher entropy permits some heat flow to the vessel wall while maintaining the air temperature in the range of 900 K. While this does not improve the flow quality, since the temperature decreases at constant pressure, it does avoid active heating of the vessel wall to decrease the temperature difference between the air and the wall.

The required total volume ($0.01\ m^3 < V < 10\ m^3$) is provided by connecting multiple intensifiers to an axial manifold (Fig. 9). Conveniently, the radial arrangement simultaneously provides the 2000 MPa connectivity between the UHP intensifier volumes and permits assembly of multiple intensifiers into large total volumes. The pressure connection is made by the UHP intensifier end closure, which is free to move axially, by adjusting the stress at the interface between the end closure and the axial manifold to be greater than the air pressure. This is accomplished simply by making the cross-sectional area of the end closure in contact with the axial manifold less than the end inside the intensifier.

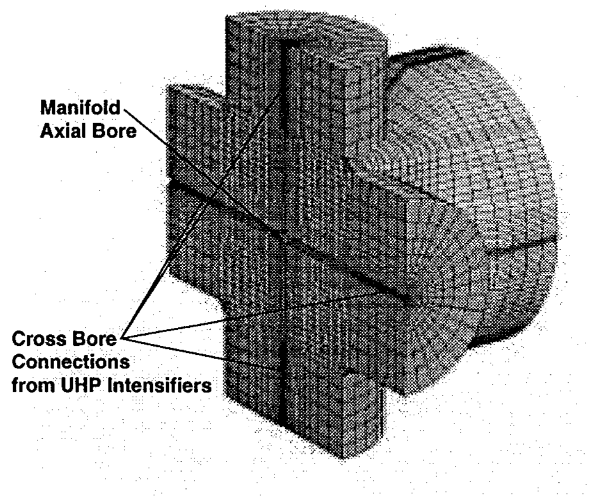

Fig. 9. Connection between 4 UHP intensifiers and an axial manifold.

The stress concentration at the intersection of the cross bores with the axial bore of the manifold is about 3 with respect to the hoop stress, resulting in a von Mises stress that far exceeds the yield point of high-performance steels, even at room temperature. These stresses are reduced to acceptable levels by the symmetric variable radial load owing to the UHP intensifier end closures and by an axial load on the manifold. Elastic Finite Element Analysis (FEA) calculations show that a radial arrangement of UHP intensifiers having twofold symmetry is not adequate to reduce the cross bore stress concentration to acceptable levels. However, fourfold and higher radial symmetries, plus a compressive axial stress, can be used to arbitrarily reduce the stress owing to the stress concentration. The combination of these external mechanical stresses and the thermally induced compressive radial stress is adequate to limit the plastic flow to less than 1 percent in a region very close to the cross bore at room temperature. However, at 900 K and operational times greater than 1 sec, significant regions (> bore radius/10) near the cross bore and axial bore suffer reductions in yield strength and Young's modulus by as much as 50 percent. This presents three distinct problems: (1) loss of structural strength at the vessel wall, effectively increasing the inner radius; (2) generation and growth of critical flaws that limit fatigue life; and (3) loss of dimensional tolerance, which is particularly serious in the clearance between the piston and bore of the UHP intensifier.

While the elastic analysis is useful to identify and manage stresses through geometry, fully coupled elastic-plastic-transient heat flow calculations are necessary to find a realistic response. The elastic-plastic FEA code NIKE3D, coupled to the heat flow code TOPAZ, is used to minimize the plastic strain with respect to the geometry, temperature, and externally applied stresses. Figure 10 is a representative result for P = 2000 MPa and T = 900K.

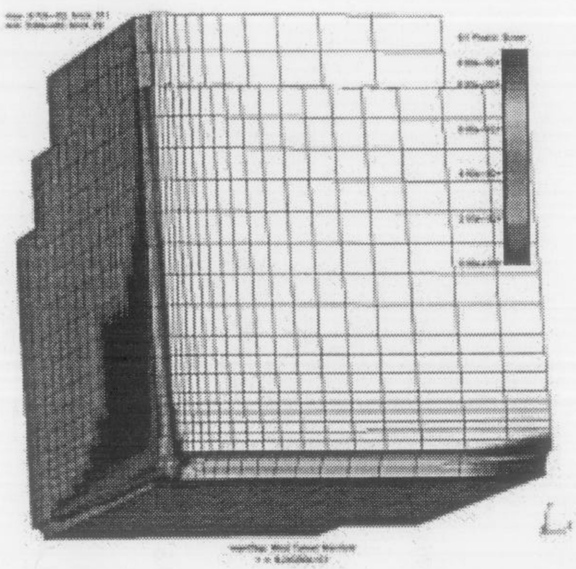

Fig. 10. Cross-bore strain field for VascoMax 300 CVM. P = 2000 MPa, T = 900 K, radial external stress only.

The portion of the wind tunnel nozzle for a distance of approximately one meter downstream of the throat is called the UHP nozzle section. The primary S&T challenges for the nozzle are:

- Containing 2000 MPa air pressure at 900 K static temperature
- Mechanical strength at high temperatures to carry 2000 MPa uniaxial stress
- Chemical reaction with high-pressure, high-temperature air, particularly at hot spots created by energy flux from the energy addition
- Mechanical erosion owing to large shear stresses at the nozzle wall, especially for the nozzle throat
- Surface roughness requirements for flows with $Re = O(10^{10})$
- Injection of cooling film gas to manage the thermal load on the nozzle wall
- Minimizing perturbation of a 7-20 Tesla toroidal magnetic field at the throat (for the e-beam energy addition option)
- Integration with the downstream nozzle section
- Mechanical erosion/heating owing to e-beam or laser flux
- Shape variation owing to thermal and mechanical stresses
- Inspection and replacement costs
- Damage control upon catastrophic failure

Figure 11 shows the conceptual design for the UHP nozzle section in the UHP manifold. The nozzle/throat is part of the end closure for the manifold. Helium is injected into the boundary layer by means of a radial array of UHP intensifiers, similar to the larger intensifiers used for the air supply. In this scheme, the nozzle section is a removable end closure to the UHP manifold. It couples to a downstream section (not shown), that can be removed to permit extraction of the nozzle through the bore of the magnet. The placement of this coupling depends at least on the sensitivity of the flow to nonuniformities at the coupling joint, to the location and integration with other downstream magnets, and to the coupling with the external, axial load frame. This removable section then couples to the remaining downstream nozzle, which is fixed in the laboratory frame of reference.

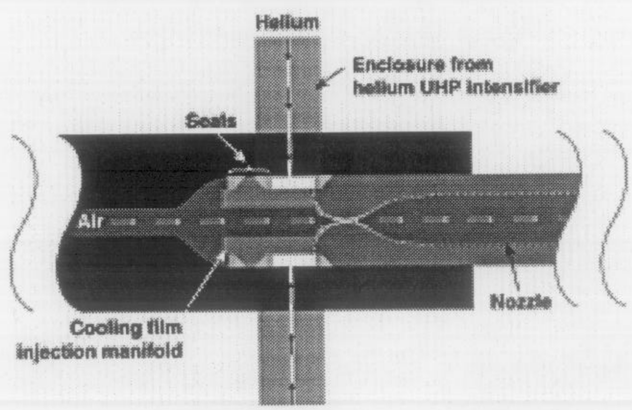

Fig. 11. Cartoon of the nozzle end of the axial manifold.

The settling chamber at the end of the manifold serves three purposes: (1) to permit the fluid flowing through the approximately 2-cm-diam manifold bore at approximately 30 m/sec to settle to mechanical equilibrium at a fluid speed of about 1 m/sec into the nozzle; (2) to provide space and a means to inject helium into the boundary layer at the entrance to the nozzle; and (3) to couple the UHP nozzle to the UHP axial manifold. This region of the manifold is externally supported by the radial array of the intensifiers used to inject the helium. The internal helium shroud serves to isolate the helium from the air, both to prevent air from entering the helium intensifiers and from helium entering the settling chamber, except in an annular region tangent to the nozzle inlet.

The present design for the UHP nozzle is a compound pressure vessel, about 10 cm in OD, having at least three layers. All nozzle layers must be made of materials that are compatible with the time-dependent magnetic field strength and uniformity required at the throat. The innermost layer is an easily replaceable thin-walled liner, about 0.5-1 cm wall thickness, with a cylindrical external surface and an internal surface having the desired inlet, throat, and outlet nozzle profiles. Ideally, the material for this layer can be electroplated onto a mandrel having the desired profile and that serves as a substrate for a protective surface layers applied using chemical, vapor, or physical deposition. These layers are tailored to provide chemical protection, mechanical strength, thermal expansion matching, and epitaxial matching. The boundary of the external surface of this thin-walled liner can carry longitudinal or helical ducts for rear surface cooling.

The second and third layers of the nozzle are primarily for strength, with the material selected for optimum yield strength with acceptable magnetic properties. This selection promises to be difficult, since even the best titanium-based alloys (13 V, 11 Cr, 3 Al, bal Ti) have yield strengths of the order of only 1400 MPa. Use of an external winding of a non-magnetic organic, such as a carbon filament, can provide an external compressive radial stress to compensate for the low metal strength, providing thermal expansion coefficients can be matched adequately well. This external winding also can be accomplished synergistically by using the magnet windings as the external pressure vessel winding. Usual superconducting magnets have the Nb_3Sn superconductor imbedded in a copper matrix for thermal inertia and mechanical support. Since the superconducting properties of Nb_3Sn are stress sensitive, NbTi may be required for the superconducting material. Replacing the copper with a thermally similar, but stronger, material may permit winding the magnet directly onto the UHP nozzle body. Finally, the thermal gradient $dr/dT < 0$ provides an additive, compressive stress in the nozzle.

The conceptual design for the helium (or other suitable fluid) cooling film injection addresses several issues: (1) generating helium at a pressure at or above the air pressure in the settling chamber and synchronized with it; (2) providing a total volume of cooling gas (assumed to be O (10 percent) of the air flow volume) that is commensurate to the total air volume; (3) providing a variable radial support to the UHP manifold end closure region that is synchronized with the pressure in the settling chamber; and (4) providing a means of injecting the helium in a continuous annular ring just upstream of and tangent to the nozzle inlet.

Nozzle survivability continues to present the highest technical risk for the UHP driver. The chemical reactivity depends on the reactants, their activities, and the temperature. Also, mechanical erosion is expected to be very high. None of these quantities is known adequately well for the boundary-layer condition. The design planning assumption is that the inner nozzle wall will have a thermal and diffusion barrier layer, either through its natural composition and initial oxidation (as in formation of Cr_2O_3, BeO, Al_2O_3, etc.) or a barrier laid down using a chemical, vapor, or physical deposition process.

SUPERSONIC THERMAL ENERGY ADDITION

Three approaches have been studied for the addition of thermal energy to the supersonic flow. These include microwaves, lasers, and electron beams. While microwaves may be feasible in the long run, there are several unresolved technical hurdles that have led us to de-emphasize the consideration of microwaves in the present study. These include the lack of a satisfactory mechanism for coupling microwave energy into air in a controllable fashion, complexities associated with passing microwave energy into the wind tunnel without initiating breakdown, and questions of wind tunnel scale in relation to the wavelength of currently available high-power microwave sources.

Both energy addition with lasers and electron beams are being pursued. These studies have led to two experiments at the 10-kW level over the past two years. Both of these experiments have demonstrated that thermal energy can be added to supersonic flow in a controllable fashion, leading to a significant increase in total enthalpy and stable flow conditions.

The laser experiment was conducted using a 10-kW CO_2 laser facility at the Air Force Research Laboratories in Dayton, Ohio. The air flow was seeded with a small amount of sulfur hexafluoride, which is a strong absorber of 10.6-micron CO_2 radiation. Figure 12 is a diagram of the experimental setup at that facility. Run times were typically a second or more, and the data acquired included shadowgraph movies, as well as static pressure measurements along the nozzle, and pitot probe and total temperature measurements at the exit. Figure 13 shows the static pressure measure-

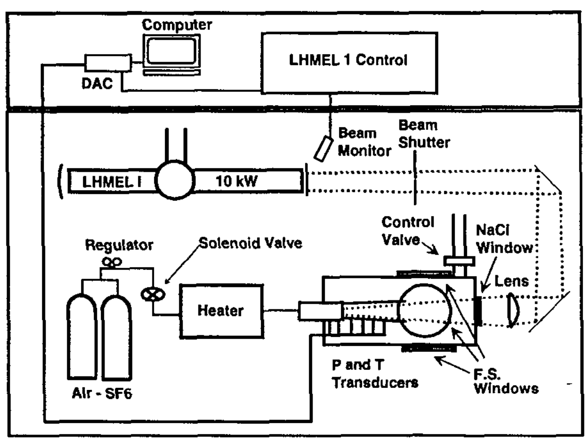

Fig. 12. Diagram of the 10-kW CO_2 laser-heated wind tunnel.

ments along the wall, both with and without laser energy addition, and Fig. 14 shows the change in shock angle observed in the shadowgraph images. In this experiment, as with the following one using electron beams, the energy addition led to a predicted reduction in the Mach number, since the temperature of the flow increased. The change in Mach angle indicates that Mach number dropped from 4.2 to 3.9. This agrees with predicted results if 8 kW of laser energy is assumed to have been absorbed. Shadowgraph images taken at video framing rates showed that the flow stability with energy addition was approximately the same as it was without energy addition (Morgan, et al 1998).

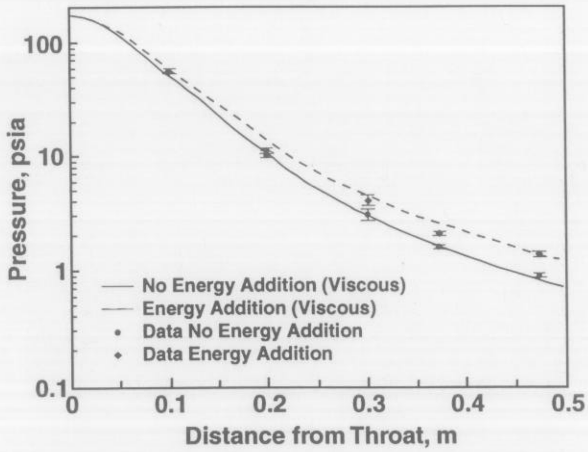

Fig. 13. Static pressure measurements along the wall, both with and without laser energy addition.

a. No energy addition

b. Energy addition

Fig. 14. Shadowgraph of flow around pitot pressure and total temperature probe at the nozzle exit, flow from right to left.

Electron beam energy addition experiments were conducted at Sandia National Laboratories using their 0.9-MeV HAWK accelerator. A diagram of the layout for those experiments is shown in Fig. 15. In this case, the electron beam was operated with an energy on the order of 30 kW, but only ran for a millisecond or so.

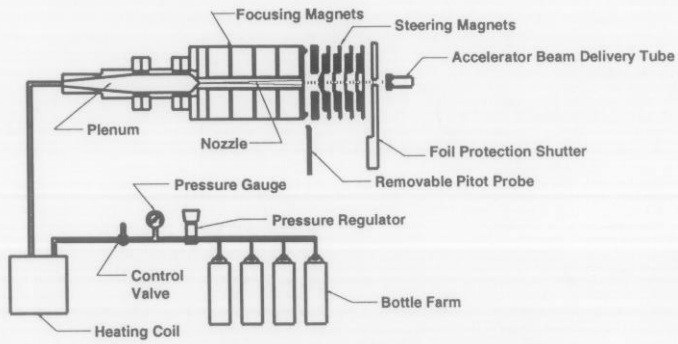

Fig. 15. Diagram of experimental layout.

Once again, shadowgraph images were used to study shock angle variation and flow stability, but, this time, in the 10-100 kHz rate. These images were taken using a new fast-framing CCD camera built by Princeton Scientific Instruments and on loan from the Air Force Research Laboratory. Illumination was with a continuous wave argon-fluoride laser. Static temperature measurements were made using a new LITA technique that measures the speed of sound over an approximately 300-nsec time interval at a point in the flow (Barker, Grinstead, and Miles 1999a). Flow velocity was measured using laser-induced breakdown. More conventional measurement devices intended to measure static pressure along the nozzle, total temperature, and pitot pressure, were less useful since they were subject to large background noise during the electron beam pulse arising from electron beam-generated X-rays. Figure 16 shows shadowgraph images before and during the electron beam pulse. The electron beam heated the flow for 750 microseconds; approximately 90 kW enters the nozzle. The observed Mach number

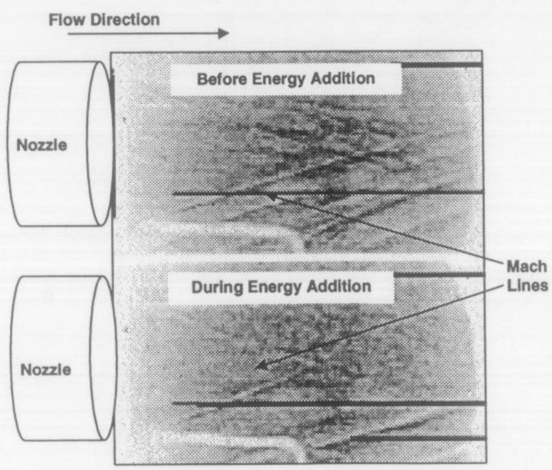

Fig. 16. Shadowgraph image of e-beam heated flow.

changed from Mach 3.9 to 2.7. This change corresponds to an estimated energy deposition into the flow of approximately 10 kW. A direct comparison with the computational model is difficult, since much of the electron beam energy was deposited in the wall, so a curve of the electron beam energy deposition profile in the gas could not be established with reasonable accuracy. Nevertheless, shadowgraph images indicated that a stable, higher enthalpy flow was generated with electron beam energy addition (Barker et al 1999b).

Both of these initial experiments are far from the regime where a test-scale wind tunnel will operate. In order for these energies to produce a significant change in the static enthalpy of the flow, the entropy in the plenum must be very low compared to predicted test facility conditions. Pressures were held on the order of 1200 psi, and the plenum temperature varied between room temperature and 400 K. The major reason for increasing the plenum temperature was to avoid condensation in the unheated flow.

Follow-on experiments using laser energy addition are not currently planned due to the limited availability of higher power laser sources. Follow-on electron beam experiments are currently in the planning stages and are anticipated to step to the 100-kW level for the next set of experiments, followed by experiments at the 10-MW level. The major objective of the 100-kW experiments is to exercise the technology necessary to focus electron beams into an appropriately scaled nozzle, contour the electron beam so there is minimal wall heating, and demonstrate uniform and stable addition of large amounts of enthalpy into supersonic air. Control of the electron beam profile is expected to allow the energy to be deposited in the core of the air flow while maintaining an annulus of cold air to minimize wall heating problems. The 10 MW experiment is expected to simulate the full specific enthalpy of a medium-scale test facility.

MHD ACCELERATOR AUGMENTATION ISSUES

An MHD accelerator is a device for accelerating a gas by applying a Lorentz body force (J X B force) to the flow. The device therefore requires (a) a static magnetic field applied transverse to the flow direction, and (b) a current flow across the duct. The body force per unit mass (i.e. acceleration) is proportional to the product of the current which is applied across the duct and the applied magnetic field. The primary advantage of MHD compared to other energy addition methods is that it is capable of adding some fraction of the input electrical power directly as push work. This part of the input energy does not increase the entropy, a decisive advantage for this application, whereas the portion added as Joule dissipation does increase entropy. At the same time, MHD performance is constrained by the requirement that the entropy of the gas as it exits the MHD duct be equal to the specified test section entropy. Since entropy increases by the mechanism of Joule dissipation, the latter requirement imposes limits on how much Joule dissipation can be tolerated through the MHD system while still achieving the targeted test section conditions.

Requirements

The purpose of the MHD acceleration augmentation is discussed in the introduction. The flight Mach number, dynamic pressure, and altitude define the total enthalpy and entropy goals to be achieved in the test section of the MSHWT. The MHD augmentation will be constrained by the channel inlet flow enthalpy and entropy, gas conductivity, wall heat-transfer limitations, boundary layer growth rates, and the thermodynamic energy addition process used. The inlet enthalpy and entropy conditions are defined by the thermal energy addition processes upstream of the MHD channel. Broadly speaking, the purpose of the MHD research is to define the "best" envelope of MHD augmentation within these constraints, and to perform demonstration experiments to validate the proposed design concepts.

To clarify these statements, consider a flow in an MHD channel with velocity U in the x (streamwise) direction, with an imposed magnetic field B in the z (transverse) direction. We consider a Faraday configuration, for which the streamwise current flow is (ideally) zero. Then the electrical power input per unit volume is $\langle J \cdot E \rangle = \langle J_y E_y \rangle$, where the brackets denote a cross-sectional average. Note that J_y is the current density (amps/cm^2) and E_y (volt/meter) is the electric field in the y direction. The push work is the work done on the gas, and is equal to $\langle J_y UB \rangle$. The conversion efficiency η is defined as the ratio of the push work to the total electric power input:

$$\eta = \frac{\langle J_y UB \rangle}{\langle J_y UB + J_y^2/\sigma \rangle}$$

Note that the second term in the denominator is the Joule dissipation. Devices such as arc heaters add energy exclusively by means of Joule dissipation. Such devices cannot supply push work and thus have a conversion efficiency of zero. For MHD to be useful, it will be necessary that the system have a reasonably high conversion efficiency; otherwise, the device offers no essential advantage over an arc heater. As discussed by Macheret, et al. (1997), the conversion efficiency is related to the load factor $K = E_y/UB$ by the simple relationship $K = 1/\eta$.

In the absence of heat transfer and viscous dissipation, the rate of entropy increase and Joule dissipation are related by the expression

$$\dot{m} T \frac{dS}{dx} = A(x) \langle J_y^2/\sigma \rangle$$

In the last expression A(x) is the cross-sectional area of the channel at station x.

It is also to be noted that the net acceleration, a, is given by

$$a = \frac{J_y B}{\rho} - \frac{1}{\rho}\frac{dP}{dx}$$

The above relationships essentially determine the requirements for the MHD accelerator. Let us summarize the MHD accelerator requirements.

1. Because the entropy in the test section is fixed, and because the rate of entropy rise through the MHD channel is proportional to the Joule dissipation, it will be necessary to limit Joule dissipation through the MHD channel. The entropy rate equation above suggests that there are two strategies for minimizing the entropy rise through the MHD channel: (a) operate at low transverse current densities, or (b) operate at high conductivities. In practice, both strategies must be pursued to achieve the necessary matching of the exit entropy to the test section entropy.

2. Minimization of Joule dissipation implies that the accelerator must work at high conversion efficiencies, η. Since η is inversely related to the load factor, high conversion efficiencies imply that the load factor, $K = E_y/(UB)$, must be close to one throughout the MHD channel.

3. The expression for acceleration shows that to achieve high acceleration, it will be desirable to operate at low mass densities.

4. For reasons of material integrity, it will be very desirable to maintain low static temperatures through the MHD channel. Active cooling in the walls and/or injection of a buffer gas into the boundary layer are options for thermal management of the boundary layer and wall temperatures.

5. Additionally, the MHD accelerator must provide an airstream that has minimal and known levels of dissociated species and contaminants. It must also provide reasonable flow uniformity in the test section.

Historically, requirement (1) has been difficult to achieve. To obtain significant acceleration over a reasonable length, channel designers have relied on moderate B fields and high current densities. Most MHD accelerators designed for continuous operation have also relied on the injection of an alkali metal seed to achieve the necessary conductivity levels. To ionize the seed, the gas must be heated to temperatures of 2800 K or higher, which raises serious materials issues. The MHD accelerators operated at the Central Aerohydrodynamics Institute (TsAGI) in Russia, for example, were seeded with NaK, a eutectic mixture of sodium and potassium, and were run at current densities in the range 30 –50 amp/cm^2, magnetic fields of less than 3 Tesla, and static temperatures approaching 4000 K. The high current densities resulted in large Joule dissipation and a relatively low conversion efficiency. While substantial velocity increases were demonstrated, the high Joule dissipation and resulting high exit entropy levels appear to preclude this type of MHD channel from being used to achieve the high total enthalpies and modest entropy levels required for advanced engine testing. This point has been discussed in some depth in the literature (Baughman et al 1997; Simmons and Nelson 1998).

For this reason, the MARIAH II program has recently focused on an alternate method for sustaining the required conductivity through the MHD accelerator. The method relies on injection of high-energy electrons into the airstream. The primary advantage is that this method achieves the required conductivity nonthermally, through the production of secondary electrons, which eliminates the requirement for an alkali metal seed. This in turn eliminates the need for high temperatures in the MHD channel.

A schematic diagram of an MHD channel utilizing electron beam seeding is shown in Fig. 17. Electron beam radiation would be introduced into the gas along an axis perpendicular to the sidewalls. Impact ionization of the primary electrons with the air molecules would induce a nonequilibrium level of secondary electrons in the gas, thus creating the necessary electrical conductivity. For such a nonequilibrium scheme to be useful and predictable, the recombination and electron attachment issues must be addressed and an overall analytical model for the ionization kinetics must be developed and experimentally validated. As discussed by Macheret, et al. (1997), the rates for these processes are strongly dependent on the neutral particle number density, as well as the electron beam current and beam energy. Many of these issues have been addressed (Macheret, Miles, and Nelson 1997;

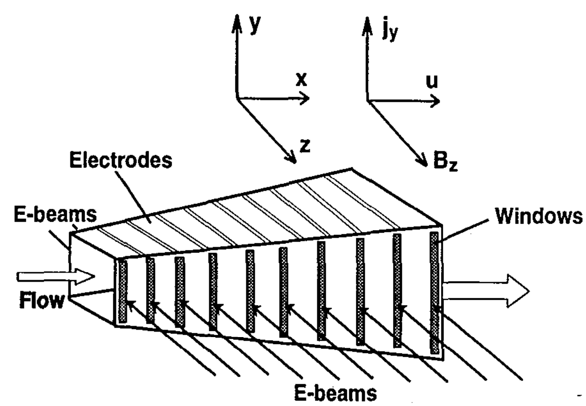

Fig. 17. Schematic diagram of an MHD channel utilizing electron beam seeding.

Schneider, Macheret, and Miles 1999), both of which present detailed analytical models of the ionization and recombination kinetics for electron beam-induced plasmas.

An experimental effort described by Reed et al. (1999) has been initiated at Sandia National Laboratories for measuring the electrical conductivity induced by electron beams passing through a static test cell filled with air. The purpose of these experiments is to validate theoretical models of electron beam-induced conductivity (Macheret, Miles, and Nelson 1997; Shneider, Macheret, and Miles 1999).

MHD Accelerator Critical Technical Issues

Operating Regime of MHD Accelerators – Several strategies have been considered for achieving the the modest entropy, high total enthalpy levels required for advanced engine testing. As discussed earlier, the first is to start the process at very low entropies by working at very high plenum pressures. The TsAGI MHD program is instructive in this respect. The Russian MHD accelerators were operated successfully at static pressure of 1 – 4 atm and at static temperatures above nearly 4000 K. However, the exit entropy levels were much too high to achieve the performance goals needed for hypersonic air-breathing propulsion testing. To overcome this problem, the channel inlet entropy must be much lower, and/or the Joule dissipation must be minimized.

The constraint on entropy precludes operation at high temperatures and moderate pressures, as has been done in MHD channels with electric arc preheating at stagnation pressures up to approximately 100 atm. Operation of seeded MHD accelerators at very high static pressures and high temperatures has been suggested but never demonstrated, nor believed possible because of materials limitations and chemistry issues. Low static temperature (below 500 K), low static pressure (< 1atm) operation of MHD accelerators is a potentially attractive option, provided sufficient electrical conductivity can be achieved. But this likewise has not been demonstrated. For any given inlet entropy, a higher inlet pressure and temperature would provide a higher thermodynamic efficiency toward achieving the desired test conditions.

Electrical Conductivity Issues – Electrical conductivity must be sustained in the gas flow through the accelerator at a level sufficient to ensure electromotive force acceleration. External means of establishing and maintaining conductivity are expected to be required.

Channel Boundary-Layer Issues – Overheating of the channel walls is a major issue. Wall recovery temperature, heat loads, and thermal boundary-layer management must be addressed. The degree to which the boundary layer is an issue depends on channel inlet conditions, the boundary-layer electrical conductivity, and the mode of operation in the MHD accelerator. Both velocity and thermal overshoots in the boundary layer are to be avoided. Thermal overshoots can result in high electrical conductivity near the electrode walls and sidewalls. This may in turn cause interelectrode shorting axially along the electrode walls as well as transverse shorting in the sidewall boundary layers. The latter effect, if sufficiently pronounced, can produce relatively high accelerating MHD forces in the boundary layer compared to that in the core flow, clearly an undesirable situation. Tailoring the flow conductivity to prevent over-acceleration of the boundary layer on the electrode walls is probably required.

Flow Quality – An important issue and requirement for a test and evaluation facility is that the gas delivered to the test section must be near true air, implying minimal dissociation and contamination. A spatially and temporally uniform core flow in the test section is also required.

Electron Beam Issues – Establishing electrical conductivity by electron beam seeding is the option currently being pursued. Electron beams have been demonstrated as ionizers in MHD generators, but in a different working gas (argon, seeded with Cs). Major issues with respect to electron beams are described below.

- Sustained Conductivity – The conductivity must be sustained volumetrically, not merely locally. Because of the strong tendency of the electrons to recombine with positive ions, it will be necessary to employ many electron beams, spaced at short intervals down the channel, as shown in Fig. 17. The number of beams required must be determined as a part of the research program.
- Beam Injection Methods – The beam must be introduced across the sidewall, and must either pass through the magnet poles or originate inside the magnet at the inner sidewall.
- Foil Window Integrity – Electron beams are generated in a near vacuum. Consequently, foil windows are used to isolate the vacuum region from the working region. These foils are necessarily thin, and heat up extremely rapidly from the high beam flux. To maintain foil integrity, the electron pulses must be of short duration, typically a few milliseconds to a few tens of milliseconds. Alternatively, continuous operation is possible if the current densities through the foils are below about 30 mA/cm^2. Advanced window designs such as cooled foils, aerodynamic windows, or the "plasma porthole" technology pioneered by A. Hershcovitch and his colleagues offer the possibility of extending the pulse duration and/or operating the window in a continuous mode at current densities in excess of 30 mA/cm^2. A pulse duration of 1 sec or more must be demonstrated as a part of the technology development program.

- Magnetic Fields – Note that, from the above formula for acceleration, one would deduce that the highest possible magnetic field should be used, since this maximizes acceleration and appears to incur no additional Joule dissipation penalty. While the conclusion is correct, it neglects a host of other effects which arise when the Hall parameter (Σ = :B, : being the mobility) exceeds a certain critical value. For example, the heat transfer away from a current filament is greatly inhibited by the presence of an magnetic field, and the effect becomes intensified the greater the magnetic field. Electrons tend to travel in a helical pattern around the magnetic field lines; this prevents them from dissipating thermal energy by migrating away from the current filament and colliding with less energetic (cooler) neutral particles. The net effect is that current filaments become more unstable as the magnetic field is increased. These instabilities can cause constricted arcs to form, greatly increasing the Joule heating and creating hot spots in the flow. Other undesirable effects due to high magnetic fields and high Hall parameters include shorting along the sidewalls and the formation of current concentrations along the leading and trailing edges of electrodes. Also, we note that even in the absence of constriction and shorting, MHD performance may be reduced at high magnetic fields because of the so-called "ion slip" effect (Rosa 1987).

  Thus, from a practical standpoint, there is a limit on the maximum allowable magnetic field. Presently, it is not known what this limit is for electron beam-induced plasma. A major goal of the research program is to establish this limit through analysis and experiment.

To resolve these MHD issues it will be necessary to demonstrate a fully integrated MHD accelerator system. The experiment will consist of an electron beam and window system, a magnet, an MHD accelerator, and a driver system. These experiments will demonstrate operation of a nonequilibrium electron beam-seeded MHD accelerator system at a scale close to that of a pilot scale facility, perhaps one-quarter scale. Long duration runs are not essential, hence the driver may consist of a reflecting shock tunnel or other impulse facility.

SYSTEMS INTEGRATION

Systems Integration includes all of the tasks and activities necessary to ensure that major components of the MSHWT (such as the ultra high-pressure supply system, the nozzle subsystems, the radiant energy addition subsystem, the MHD subsystem, etc.) are compatible with each other in terms of scale, operating regime, and stability of operation and, most important, that the total system meets its performance requirements. The system integration studies span the full 8-year program.

In general terms, systems integration issues, like most others, are resolved either through analysis, experiment, or cost considerations. The following discussion first presents a list of the key systems issues, then defines what analytical tools are required to adequately address the systems issues, and finally a suggested list of demonstration experiments necessary to resolve key systems issues.

Analytical Tools

Several analysis tools must be employed to provide predictions of systems performance. Simulation tools which address the various energy addition options are currently under development at Princeton University. Simplified (one-dimensional) MHD codes are presently available for simulating the gas dynamics and energy addition processes up to the nozzle exit. Additional code development is underway to simulate the kinetics of electron beam interactions in air. A multidimensional computational tool is also being developed at Princeton to simulate the MHD accelerator. This code relies on a two-dimensional Navier-Stokes solver for the gas dynamic simulation. A separate set of subroutines is called for computing the MHD processes and electron beam ionization kinetics (Macheret, Schnieder, and Miles 1999).

Additionally, there is a need for a simplified (i.e., one dimensional/algebraic) model of the facility system. The code should be designed to perform sensitivity and trade studies. For example, one should be able to simulate the effect of adding laser power vs. the effect of adding the same amount of power in the MHD accelerator on the final test section conditions. Another example would be simulating the effect of MHD energy addition on the required reservoir pressures. Such a code will be useful for predicting overall system performance to first order. Development of this code should draw freely upon experimental data from subsystem/ component testing, as well as algorithms and models developed for simulation codes that model individual subsystems.

Key Systems Demonstrations

Certain experimental demonstrations at the system level must be carried out prior to design of the MSHWT. This testing will be done at a reduced scale and will have the two objectives of establishing the credibility of the analytical simulations and resolving scaling and performance issues. Table 1 summarizes both the testing accomplished to date, as well as the tests presently planned for the balance of the program.

Interface Issues

The term "interface issues" refers to the fact that the basic systems comprising the hypersonic wind tunnel must interact at key interfaces, and must do so across a range of condi-

Table 1. Summary of System Testing for the MARIAH II Program

Test Name	Objectives	Primary Interfaces	Remarks
10 kW Laser Energy Addition Test	Demonstrate laser energy deposition in a supersonic air stream.	Nozzle – Laser Beam	Completed 12/97
30 kW Electron Beam Energy Addition Test	Demonstrate electron beam energy addition in a supersonic flow.	Nozzle-electron Beam Magnet – Nozzle	Completed 7/98
Static Cell Conductivity Tests	Measure the electrical conductivity induced by an electron beam passing through a static test cell.	Electron Beam – Window	Phase I completed 7/99 Phase II to commence 1/00
100 kW Electron Beam Energy Addition Tests	Demonstrate stable energy absorption at high power. Demonstrate beam contourng and focusing. Measure chemistry effects.	Nozzle-electron Beam Magnet – Nozzle	Testing to commence 11/99
MHD Sidewall Demonstration Experiment	Design and fabricate an MHD Sidewall section for electron beam seeding. Demonstrate multiple beam injection and electron beam seeding.	Electron Beam – Window	Testing to commence mid 2000.
Checkout of the A-2 UHP Facility	Design verification tests.	Nozzle - UHP	Early 2002
10 MW Electron Beam Energy Addition Tests	Demonstrate electron beam energy addition and beam contouring at prototypic conditions.	Magnet – Nozzle – Electron Beam	Late 2002
MHD Accelerator System Demonstration	Demonstrate (in an impulse facility) a subscale MHD accelerator that uses electron beam seeding.	Electron Beam – Window Nozzle – MHD Accelerator Magnet – Accelerator MHD Power Supply - Accelerator	Testing to commence in 2003. Test planning to commence in 2001.

tions. This implies that the designer of a particular component, say the MHD accelerator, must take into account the range of conditions that may be coming into the accelerator from the nozzle. In this case, it will be necessary to demonstrate (proabably experimentally) that the MHD accelerator can accommodate a range of inlet conditions and provide the desired exit conditions (total enthalpy, entropy, density). Another example is the interface between the nozzle and the steering magnet for the various electron beam energy addition experiments. The requirement here is that the magnetic field strength must be matched carefully to the wall contour and the electron energy to ensure that the electrons do not deposit substantial energy on the interior nozzle wall. The primary interfaces involved in each of the systems experiments are shown in Table 1 above. Most of these interface issues can only be resolved experimentally.

SUMMARY AND CONCLUSIONS

This paper describes a research program designed to develop technology for a true temperature Mach 8-15 hypersonic wind tunnel. The approach circumvents problems of conventional stagnation heating by adding thermal energy downstream of the nozzle throat to achieve a test Mach number of 12. A test Mach number of 14.5 is achieved with magnetohydrodynamic augmentation. The total approach involves a number of S&T issues including ultra-high pressure gas physics and compression, very high Reynolds number flows and boundary layer properties, nozzle materials, laser and/or electron beam thermal heating, electron beam gas ionization, MHD, and numerous systems engineering integration issues. Experiments have demonstrated thermal energy addition by laser and electron beams is possible. Experiments are planned to measure flow quality at high power, nozzle flow properties, demonstrate nozzle survivability, and demonstrate MHD augmentation.

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