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A Large Volume 2000 MPa Air Source for the Radiatively Driven Hypersonic Wind Tunnel

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A Large Volume 2000 MPa Air Source for the Radiatively Driven Hypersonic Wind Tunnel

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An ultra-high pressure air source for a hypersonic wind tunnel for fluid dynamics and combustion physics and chemistry research and development must provide a 10 kg/s pure air flow for more than 1 s at a specific enthalpy of more than 3000 kJ/kg. The nominal operating pressure and temperature condition for the air source is 2000 MPa and 900 K. A radial array of variable radial support intensifiers connected to an axial manifold provides an arbitrarily large total high pressure volume. This configuration also provides solutions to cross bore stress concentrations and the decrease in material strength with temperature.
[hypersonic, high pressure, air, wind tunnel, ground testing]

1 INTRODUCTION

Hypersonic (> Mach 8) ground testing of aerodynamic shapes, engines, and airframes requires simulation of air flow at the altitudes and times of interest. Conventional methods of creating the entropy-enthalpy conditions of the hypersonic flight envelope require passing through temperatures as high as 6000K. As a result, the concentrations of NO_x contaminants preclude true measurements of combustion chemistry. Further, these methods provide a gas flow limited to about 100 milliseconds. Miles, *et al.*, [1] proposed a thermodynamic path that takes advantage of the real gas properties of dense air to reach the test condition thermodynamic state along a path that remains below about 2500K. In this scheme, ultra-high pressure (UHP) (>1000 MPa), moderate temperature (900K < T < 1500K) air, stored in a large volume (> 0.01 m^3) expands adiabatically, then is heated approximately isobarically by laser, microwave, or electron beam energy; and finally expands adiabatically to the entropy-enthalpy state at the desired flight condition. High enthalpy and low entropy states in the air supply minimize the amount of radiative energy required. Proof-of-principle experiments have demonstrated energy addition to a supersonic air flow using CO_2 laser [2] and electron beam [3] radiation sources. This paper is a description of a design for an air source for the radiatively driven hypersonic wind tunnel.

The performance goals for the full-scale hypersonic facility are:

- Mach Number 8 – 15 (2270 – 4260 m/s at 30,000 m altitude)
- Pure air
- Dynamic pressure: 500 – 2000 lbf/ft^2
- Operational time: 1 – 100 seconds
- Air mass flow rate: 1 – 100 kg/s
- Total enthalpy: 10^7 J
- Flow quality: _ P/P < 0.05

The target design parameters for the present air source are:

- P = 2000 MPa
- T = 900K
- Air mass flow rate = 10 kg/s
- Operational time > 1 s

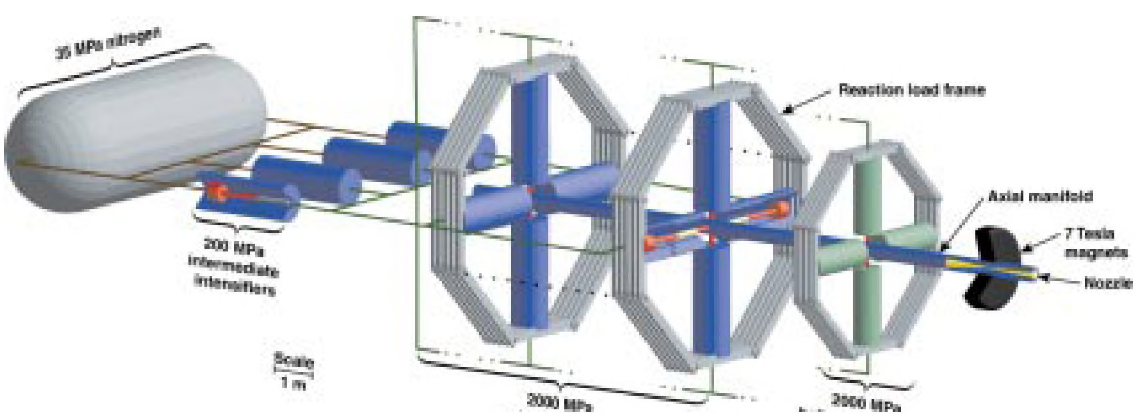

Figure 1 General design scheme for the air source for a radiatively driven hypersonic wind tunnel. A low pressure nitrogen source drives 200 MPa intermediate intensifiers that simultaneously drive 2000 MPa air and helium intensifiers, and provide the hydraulic pressure for their variable radial support. The radial

The high pressure, high temperature, large volume, and high oxygen partial pressure results in severe stress management and materials requirements. The primary design challenges are:

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- Connecting 2000 MPa volumes
- Materials strength decrease at 900K
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- Reactivity of oxygen
- Controlling heat transfer from the dense air

2 DESIGN CONCEPT

2.1 *General Design Scheme*

The design scheme (Figure 1) uses classical UHP intensifiers comprised of variable radial support cylinders arrayed radially in pairs around an axial manifold. For a 10:1 pressure multiplication, opposing intensifier pistons are accelerated by a 200 MPa source in about 300 milliseconds to their steady state speed of about 1 m/s, compressing the pre-charged 300 MPa, 550 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 s at 10 kg/s flow rate. Eight intensifiers with an ID of about 16 cm and a stroke of 90 cm provide an operating time of 10 s. 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.

To decrease the Environmental, Safety, and Health (ES&H) risk owing to the large amount of stored energy (_ 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 s operation cycle.

The intermediate intensifiers drive both the primary and auxiliary set of UHP intensifiers and provide the hydraulic load to the variable radial support for those intensifiers. This approach, used by Topchiyan and coworkers [4, 5], synchronizes the external radial stress with the internal pressure, which are balanced to result in a controlled radial clearance seal between the intensifier piston and the 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% of the room temperature value, or about one-half the design internal pressure.

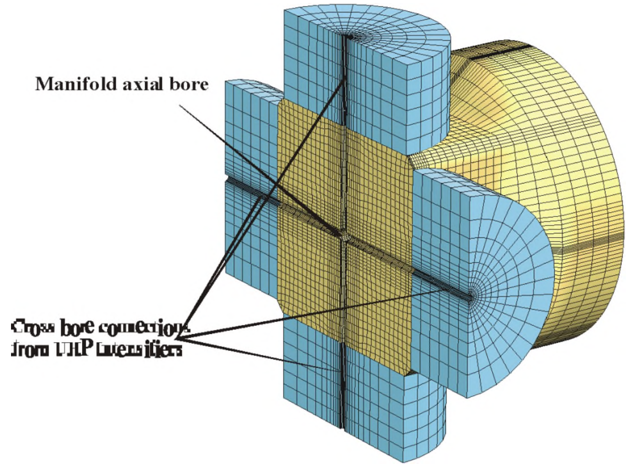

Figure 2 Connection between 4 UHP intensifiers and an axial manifold. The external radial stress at the intensifier end plug-manifold interface simultaneously provides a 2000 MPa pressure seal and an external radial stress to reduce the cross bore stress concentration.

2.2 *Thermal Management*

The objectives of thermal management are to maintain the air temperature at 900 K and to keep the material in contact with it as cool as possible so that mechanical properties are not degraded. The heat flow from the air must be kept as close to zero as possible, primarily to maintain the pressure-temperature condition in the plenum to meet flow quality requirements, but also to minimize the temperature rise of the structural material in contact with the air.

The compression of the air from its initial value to 2000 MPa occurs quasi-adiabatically in a few hundred milliseconds. The air initial state, *e.g.*, 300 MPa and 530 K, is selected for convenience (on an appropriate adiabat) to be within the range of commercial compressors and within service temperatures of organic seal materials. 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.*, [6] 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 1 s significant regions (> bore radius/10) reach temperatures high enough to degrade material properties seriously.

Beginning the compression from an initial point on a higher adiabat 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. Heating the inner liner to a temperature near 900 K results in relatively constant air temperature, but requires resistive heaters mounted at the interface between the ceramic sectors and the inner liner to heat the liner. However, this ensures that the liner material properties are degraded to 900 K.

2.3

Stress Management

The required total volume of the order of 0.01 m^3 is provided by connecting multiple intensifiers to an axial manifold (Figure 2). 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.

The stress concentration at the intersection of the cross bores with the axial bore of the manifold is about 3, with a resulting 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 two fold symmetry is not adequate to reduce the cross bore stress concentration to acceptable levels. However, 4-fold and higher radial symmetries, plus a compressive axial stress can be used to reduce the stress concentration arbitrarily. 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% in a region very close to the cross bore at room temperature. However, at 900 K and operational times greater than one second, 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%. 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 3 is a representative result for P = 2000 MPa and T = 900K.

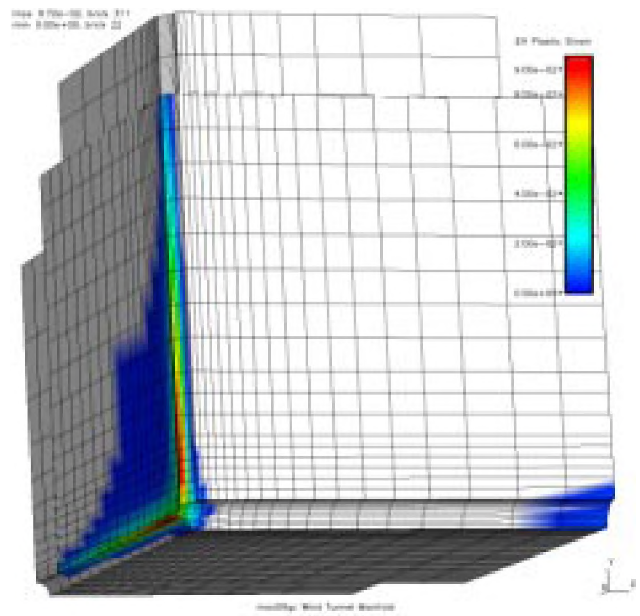

Figure 3. Crossbore strain field for VascoMax 300 CVM. P = 2000 MPa, T = 900 K. Radial external stress only.

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