Hypersonic, High-Density Stored Arc-Heated Air Wind Tunnel

W. B. Boatright,* A. P. Sabol,† R. B. Stewart,‡ G. M. Stokes,§ and W. B. Olstad¶
NASA Langley Research Center, Hampton, Va.

Theme

PRESSURIZATION of a large ceramic-lined tank with arc-heated air, and its subsequent discharge through a hypersonic nozzle, offers a technique for obtaining high mass flow, true-temperature flight duplication in the Mach number 8 to 10 region. This use of long-term energy storage and its more rapid release can provide a ground facility which will be especially useful for hypersonic airbreathing propulsion testing. Ceramic-filled storage heaters can be used in large facilities to provide true-temperature duplication up to slightly in excess of Mach number 7. Conventional electric arc-heated hypersonic tunnels can furnish true-temperature duplication to much higher Mach numbers but, with the high mass flows which occur in a facility of a size suitable for small engine testing, the power requirements for the arc heater are formidable.

Calculations of the heat transfer from the arc-heated air to the tank walls show that with about 5 Mw power input to the air, then a facility with a test core diameter of 0.7–0.9 m (2.5–3 ft) and a test duration of 5–25 sec (depending on nozzle size and stagnation pressure) can be realized. The actual feasibility calculations include a more accurate determination of the power to the air based on a given arc-heater design and pressure history of the air in the tank. Heat-transfer calculations from the air to the tank walls show that conduction losses are negligible, radiation losses amount to about 6%, and the dominant heat loss mechanism is by natural convection.

During the test period when the previously arc-heated air is discharging from the tank through the nozzle, the stagnation pressure can be held constant by injecting a secondary gas into the tank at the upstream end. This fluid piston technique can also be used to increase the stagnation pressure above that obtainable with an arc heater. Analyses of the use of combustion-heated gas mixtures for the secondary gas indicate that the fluid undercutting problem (oblique interface) associated with the fluid piston concept can be overcome.

Contents

Figure 1 shows schematically the facility components. For the 20-Mw power supply considered in the example calculations, the ceramic-lined tank is a horizontal cylinder 1.1 m diam (3.5 ft) by 12.2 m long (40 ft). The arc heater operating at a mass flow of about 0.9 kg/sec (2 lb/sec) and an enthalpy of 5.8×10^6 to 6.8×10^6 joules/kg (2500 to 3000 Btu/lb) pressurizes the tank to 100 atm in about 2 min. Using the injection of secondary gas to hold the stagnation pressure constant, this charge of air in the tank will furnish an ideal test duration of 22 sec for a 0.76-m-diam (2.5-ft) nozzzle. If the pressure of the air in the tank were raised from 100 atm to 200 atm by the injection of the secondary gas, then the ideal test duration would be 11 sec. Ideal test duration assumes no mixing between the arc-heated air and the secondary gas, and no fluid undercutting. In practice, the interface between the two gases will not be a thin line, but considerable interface mixing can be tolerated and still provide useful test durations. The quantities listed at the bottom of Fig. 1 are typical values of flow and energy into and out of the tank. Flow exhausting from the tank at 9 kg/sec (20 lb/sec) at 3200°K would represent 35 Mw of power into the gas if an arc heater were directly connected to the nozzle. Based on typical arc-heater efficiencies, this corresponds to a required power supply in excess of 100 Mw.

The purpose of the ceramic lining on the tank walls is to permit a high wall temperature and minimize the heat loss during the pressurization period. Use of stabilized zirconia oxide bricks permits a wall temperature of about 2220°K (4000°R).

Prediction of History of Air Enthalpy in Tank

One critical item in proving feasibility of this concept is the determination of the history of the net enthalpy in the tank during pressurization considering the power and mass input and the simultaneus heat loss to the walls. An arc heater of known characteristics could be attached to the upstream end, but the example calculation considers the design shown in Fig. 1 with a pair of ring electrodes inside the tank and the arc rotated by a magnetic field. A recently developed empirical formula based on measurements from seven different types of arc heaters can be used to predict the arc voltage. Knowing arc voltage and current determines power to the arc. Efficiency (power to the air/power to the arc) is assumed to vary from 80% at the start of pressurization to 45% near the end. The example calculation also assumes a constant mass flow into the tank and a linear density increase. The pressurization period is divided into equal time increments (100) and for each increment the power input less the heat loss by radiation and natural convection is computed. Knowing the resulting enthalpy and density, a new pressure is determined. The calculation is then repeated at each time increment iterating on the pressure and the history of the enthalpy of the air in the tank is thus determined.

The evaluation of radiation loss is based on the assumptions that density varies linearly with time, specific heat C_v is constant,

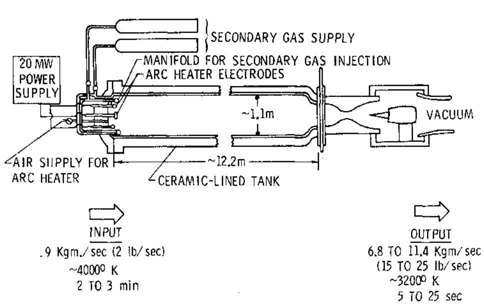

Fig. 1 Schematic showing stored-arc-heated-air concept.

Presented as Paper 71-254 at the AIAA 6th Aerodynamic Testing Conference, Albuquerque, N. Mex., March 10–12, 1971; revision submitted March 31, 1971; synoptic received August 19, 1971; revision received October 21, 1971. Full revised paper available from National Technical Information Service, Springfield, Va. 22151, as N71-76326 at the standard price (available upon request).

Index category: Research Facilities and Instrumentation.

* Head, Advanced Facilities Research Section, Hypersonic Vehicles Division. Member AIAA.

† Aerospace Technologist, Hypersonic Vehicles Division.

‡ Aerospace Technologist, Hypersonic Vehicles Division. Member AIAA.

§ Aerospace Technologist, High-Speed Aircraft Division.

¶ Head, Advanced Entry Vehicles Branch, Hypersonic Vehicles Division. Member AIAA.

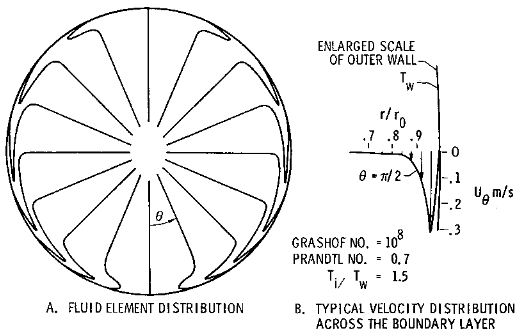

Fig. 2 Tracing of computer solution plots of fluid element displacements and velocities 9 sec after flow initiation.

and that the gas emits but does not absorb. The energy equation becomes

$$(d/dt)(\delta C_v VT) = \dot{m}C_v T_e - \delta V \dot{q}_R \tag{1}$$

where δ denotes density, t is time, V is volume, T_e is temperature of air entering tank and $\dot{q}_R$ is the rate of loss of energy from the air per unit mass by radiation. Charts of Ref. 1 are used in the evaluation of $\dot{q}_R$.

Preliminary two-dimensional calculations of natural convection loss were made based on

$$N_{\mathrm{Nu}} = 0.372 N_{\mathrm{Gr}}^{1/4} \tag{2}$$

where N_{Nu} = Nusselt number and N_{Gr} = Grashof number. The form of this equation has a sound theoretical basis,[2] and a more in-depth analysis being performed by the third author indicates that the constant in Eq. (2) is slightly conservative. This more rigorous analysis consists of finite-difference solutions to the Navier-Stokes equations for the internal flow in a horizontal cylinder with a uniformly cooled wall. Typical results illustrating the flow configuration are shown in Fig. 2, where in the sketch at right, azimuthal velocity U_θ is plotted as a function of the radial position nondimensionalized by the tank radius r_o. T_w denotes wall temperature and T_i the initial air temperature. Results such as these have been obtained for Grashoff numbers from 10^5 to 10^9 and the constant in Eq. (2) evaluated in each case.

Performing the calculation procedure which considers the total coupled problem of energy input and heat loss furnishes a prediction of the time history of the air enthalpy in the tank as illustrated in Fig. 3. Results with and without clean air radiation

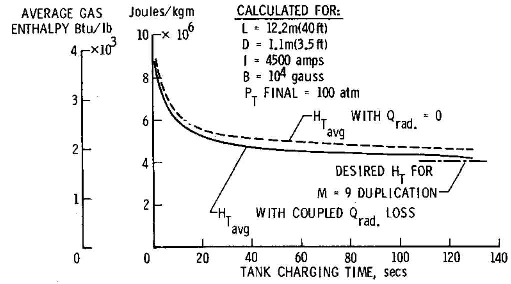

Fig. 3 History of average air enthalpy in tank during pressurization.

loss are shown. (An additional uncertain radiation loss due to electrode contaminants and NO formation is not included.) The final enthalpy at the end of the 2-min pressurization period exceeds that for $M = 9$. These results do not consider any increase in temperature due to any further compression of the gas using the fluid piston concept.

Use of Fluid Piston

If the secondary gas is more dense than the previously arc-heated air, then fluid undercutting will significantly decrease test duration. A hot secondary gas will not only permit a closer match of the densities, but will alleviate the thermal shock problem on the ceramic liner. Stoichiometric propane-air combustion results in a secondary gas which is heavier than the test air. However, if 10% helium, which has been heated to 1111°K (2000°R), is added to the propane-air mixture, then the density will match the test air. Alternately, hydrogen-air combustion used as the secondary gas will match densities to within 10%. By enriching this mixture with oxygen, the densities can be matched. Even with a perfect match, however, there will still be problems of interface mixing.

A number of research problem areas require further effort in order to assure feasibility and optimize the design, but the results show promise of providing a facility which would be especially useful for airbreathing propulsion.

References

[1] Allen, R. A., "Air Radiation Graphs: Spectrally Integrated Fluxes Including Line Contributions and Self-Absorption," CR-556, Aug. 1966, NASA.

[2] Hermann, R., "Heat Transfer by Free Convection From Horizontal Cylinders in Diatomic Gases," TM 1366, 1954, NACA.