Ablation/Erosion Facility Employing Multi-Component Flow Concepts

ELMER G. JOHNSON*
Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio
AND
W. N. MACDERMOTT† AND P. A. KESSEL‡
ARO, Incorporated, Arnold Engineering Development Center, Tullahoma, Tenn.

Theme

A REQUIREMENT has arisen in recent years for testing of re-entry vehicle heat shield materials in combined ablation and erosion environments. Such testing can be accomplished for very short time intervals (0.05 sec) in ballistics range facilities. For longer times measured in seconds, however, ablation and erosion tests currently can only be accomplished separately in different wind tunnel facilities. In state-of-the-art ablation facilities, the expansion nozzles are so short that direct drag acceleration of particles in the flow is relatively ineffective. Conversely, in wind tunnel facilities designed for maximum drag acceleration of particles by use of very long nozzles, the Mach number increases to such a degree that stagnation point heating rates are well below the range of interest for ablation testing. An analytical study has been made for a facility configured to produce ablation and erosion environments simultaneously. The proposed approach utilizes a conventional arc-heated ablation facility and a separate light-gas particle acceleration nozzle for generation of the erosion flux. These two components are combined by means of an inertial transfer of particles across a mixing layer formed between the two flows, similar to the process proposed as part of the RHEA (Re-entry Heating Energies Analyzer) facility concept.[1]

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The configurational concept of the proposed facility is shown in Fig. 1. It is proposed that the light gas be helium heated in an electric resistance heater. In this configuration it is essential that the momentum and drag force on the particles be so balanced that the trajectories remain essentially straight lines, even where they pass through regions of cross-flow. Two particle/gas flow computer programs were developed for analysis of the proposed facility: a one-dimensional particle/flow program for a supersonic nozzle with turbulent boundary-layer growth and a two-dimensional program for particle trajectories in a uniform gas flowfield. By use of appropriate thermodynamic and transport properties these programs were adaptable to either helium or high-temperature air. The Crowe relation[2] for smooth sphere drag coefficients was used and the effects of the particles on the gas flow were not accounted for. The range of particle diameters of interest in erosion testing is 10–1000 μ, however the primary interest lies in the vicinity of 100 μ diam.

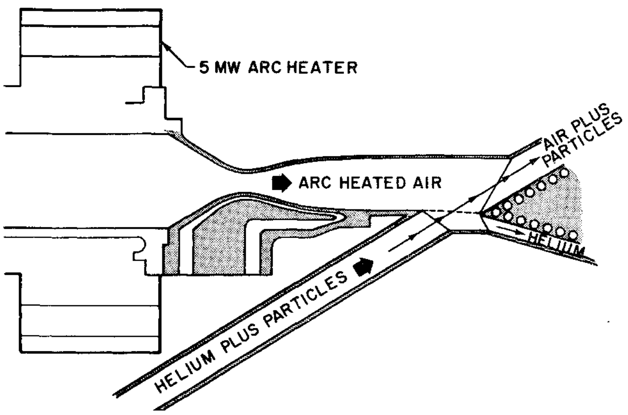
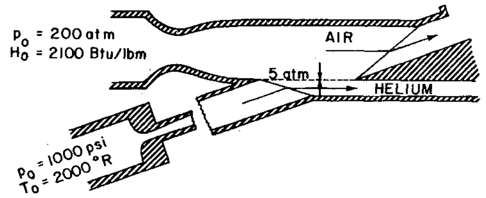


Fig. 1 Ablation/erosion nozzle with ducted injection zone.

An inviscid flow field computer program was developed which permitted calculation of an isentropic expansion followed by an oblique shock in each flow for an equilibrium real gas, with the constraint that static pressures on each side of the mixing layer between flows be equal. Calculated conditions in each of four characteristic flow regions (upstream and downstream of the oblique shocks in the two flows) are given in Fig. 2 for three angles of impingement of the flows; 10, 15, and 20°. Initial conditions in the arc-heated airflow were assumed to be close to state-of-the-art for high impact pressure ablation facilities: a reservoir pressure of 200 atm and a reservoir enthalpy of 2100 Btu/lbm. Corresponding conditions in the helium nozzle were a reservoir pressure and temperature of 1000 psia and 2000°R. The throat diameter of the air nozzle was 0.375 in. and the Mach number was 2.94 to give the desired interface pressure of 5 atm. The Mach number of the helium nozzle



	UPSTREAM OF SHOCK				DOWNSTREAM OF SHOCK				
	M_1	p_1, atm.	T_1, °R	V_{1G}, ft/sec	δ_w, deg	M_2	p_2, atm	T_2, °R	V_{2G}, ft/sec
HELIUM	2.98	2.17	505	9637	10	2.32	5.00	716	8915
p_0 = 1000 psi	3.39	1.33	414	9924	15	2.19	↓	751	8653
T_0 = 2000 °R	3.82	0.82	341	10150	20	2.06	↓	830	8513
AIR	2.94	5.00	3240	7863	10	2.56	9.10	3758	7344
p_0 = 200 atm	↓	↓	↓	↓	15	2.38	11.98	3985	7024
H_0 = 2100 Btu/lbm	↓	↓	↓	↓	20	2.09	15.95	4666	6625

Fig. 2 Results of flowfield calculations for injection nozzle.

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Index categories: Research Facilities and Instrumentation; LV/M Simulation; Entry Vehicle Testing.

* Director, Fluid Mechanics Research Laboratory. Fellow AIAA.

† Propulsion Wind Tunnel Facility.

‡ Propulsion Wind Tunnel Facility. Associate Member AIAA.

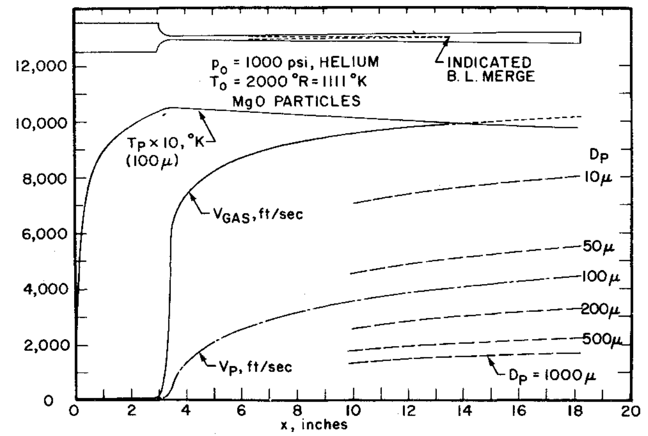

Fig. 3 Gas velocity, particle velocity, and temperature in helium acceleration nozzle; $D^* = 0.119$ in.

expansion varied with the flow impingement angle. The 20° impingement case was selected for further detailed analysis of the proposed facility.

To maximize performance of particle acceleration nozzles it has been found necessary to use drastically elongated nozzles. In the present case, the geometry assumed was a throat diameter of 0.119 in., a divergence half-angle of 0.5° and a length of 18.2 in., which was determined by the location at which the calculated static pressure was 0.82 atm upstream of the helium shock, Fig. 2. Because of the large length-to-diameter ratio, there is a distinct possibility of merging of the nozzle boundary layer and the aerodynamic calculation indicates merging several inches upstream of the nozzle exit, Fig. 3. If merging is actually encountered in practice, and if it results in significantly reduced acceleration performance, the nozzle divergence may be increased to avoid it. The calculated particle velocity distributions are also shown in Fig. 3. The final helium gas velocity is 10,150 fps. The particle velocities at the exit are 8000 fps–1700 fps for magnesium oxide particles having diameters of 10–1000 μ.

The trajectories of particles crossing the four flowfield

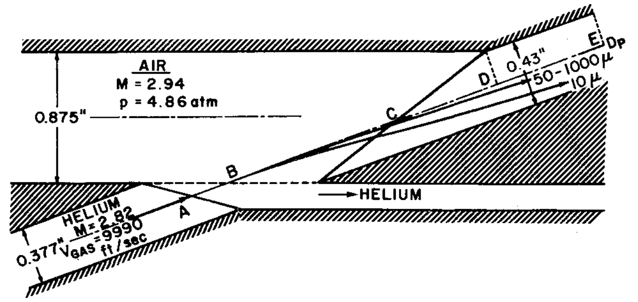

Fig. 4 Particle trajectories in ablation/erosion nozzle.

regions of Fig. 2 were computed by numerical integration of the equations of motion in two dimensions, using for initial velocities the values obtained in the helium nozzle calculations. It was desired that these calculations establish a range of particle diameters for which the particle momentum is sufficient to ensure transfer of particles from the helium flow to the airflow without introducing an unacceptable degree of dispersion. The calculations show that for a diameter range of 50–1000 μ there is a strong tendency for the trajectories to converge to a single curve, Fig. 4. Particles in this range of diameter deflect only 0.05–0.06 in. normal to the axis of the helium nozzle and the velocity vector is rotated by only 1.3–1.5°. Below this diameter range, an increasing degree of divergence from linear paths occurs, as shown in the figure for 10 μ particles. These results appear to establish the feasibility of operation of the proposed facility with particles of the desired diameter (100 μ) and with particle velocities of the order of 4500 fps. Higher performance would of course be indicated for operation with higher stagnation temperatures in the helium or by conversion to use of hydrogen as the light gas.

References

[1] Johnson, E. G. and von Ohain, H. J. P., "Generation of Ultra-High Enthalpy Gases through Multi-Component Flow Techniques," AIAA Paper 72-167, San Diego, Calif., 1972 (available as ARL 72-1000).

[2] Crowe, C. T., "Drag Coefficient of a Particle in a Rocket Nozzle," *AIAA Journal,* Vol. 5, No. 5, May 1967, pp. 1021–1022.