# Design, Tests, and Verification of a Diffuser System for a Mach 4 Scramjet Test Facility

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## Abstract

RESEARCH directed toward developing the technology for an airframe-integrated modular scramjet engine concept currently being conducted at NASA Langley Research Center, involves experimental investigations of hydrogen-burning scramjet models at simulated Mach 4 and 7 flight conditions. The present concept of the airframe-integrated scramjet engine has modules of rectangular cross section with swept leading edges that produce an asymmetric downward flow that sharply increases locally near the cowl when the scramjet inlet unstarts.

Tests on a heat-sink, hydrogen-burning model representing one module of this concept have been conducted at Langley in a facility which duplicates Mach 7 flight conditions. For Mach 4 tests, an engine test cell is being modified to contain a freejet, blowdown tunnel that will exhaust to the atmosphere. To provide shock-free tunnel flow to the modular scramjet engine and to meet the atmospheric exhaust condition, a diffuser system is required. The available mass flow rates and the size of existing tunnel hardware dictated that the scramjet model block up to 33% of the tunnel nozzle exit area.

A diffuser preliminary design was defined based on published experimental results. However, most of the literature results are not directly applicable to conditions where the model blockage is as high as 33%, and where the model design produces asymmetry by creating a downstream flow that increases when the model inlet unstarts. An experimental investigation was, therefore, undertaken using unheated air and a subscale model of the tunnel-scramjet-diffuser system. A description of the subscale system and some data results obtained during tests with this system are presented. These results were subsequently verified, as a data comparison will show, by "full-scale" engine combustion tests in a Mach 4 facility utilizing a diffuser system based upon the "best arrangement" of the subscale tunnel scramjet-diffuser system.

## Contents

The objective of the subscale experimental investigation was to determine an acceptable nozzle exit, test cabin, and diffuser configuration. This configuration was to provide shock-free flow at the scramjet inlet. Tests were conducted with unheated air at nozzle stagnation pressures from 5-11.6 atm which produced a range of nozzle exit static pressures that simulated pressures at altitudes from 16,764–20,422 m.

The tunnel nozzle-test cabin-diffuser configuration used in the subscale experimental investigation is represented in Fig. 1a. Modifications in the configuration were made by changing the various straight-duct lengths ($L_{st}$), catch cone extensions, internal diameter-sized washers attached to the catch cone entrance, and an oblique nozzle extension. The freejet length ($L_{fj}$) was changed between runs. One size tunnel nozzle was employed; however, in order to represent two different sizes of existing full-scale nozzles, the scramjet flow-through model was enlarged. This model enlargement resulted in an increase in the model blockage of the tunnel nozzle exit area from 20% to about 33%, as indicated in Fig. 1a as A and B, respectively. Two full-scale test cabin sizes were being considered, and both sizes were represented in the subscale tests. Also, a plug could be remotely inserted into and withdrawn from the model internal passage to, respectively, unstart and restart the scramjet model inlet. The data obtained during these subscale tests were in the form of Schlieren and shadowgraph photographs and continuously measured pressures.

During the tests with the various configurations previously described, the total pressure required to start the system, the stability of the flow in the test section and the stability of the flow in the diffuser were determined. The diffuser system was considered started when the tunnel nozzle flow became started (nominally, $p_j/p_{t,j}=0.022$) and when the test cabin pressure became equal to or less than the nozzle exit static pressure. Results of initial tests indicated that the straight-duct length had very little effect upon the starting of the diffuser system and its performance; therefore, a straight-duct length ($L_{st}$) of eight nozzle exit diameters ($D_j$) was used in all remaining tests.

Without the scramjet installed, the basic configuration (prior to any modifications) could be started at a total pressure as low as 5.5 atm for freejet lengths ($L_{fj}$) of 3.0 $D_j$ or less. When the small scramjet model (20% blockage) was installed, a started condition did not occur until the $L_{fj}$ was decreased to a value of 1.75 $D_j$ or less, and the total pressure was about 24% greater than that required for no model installed. The started tunnel flow, however, pulsated and it was

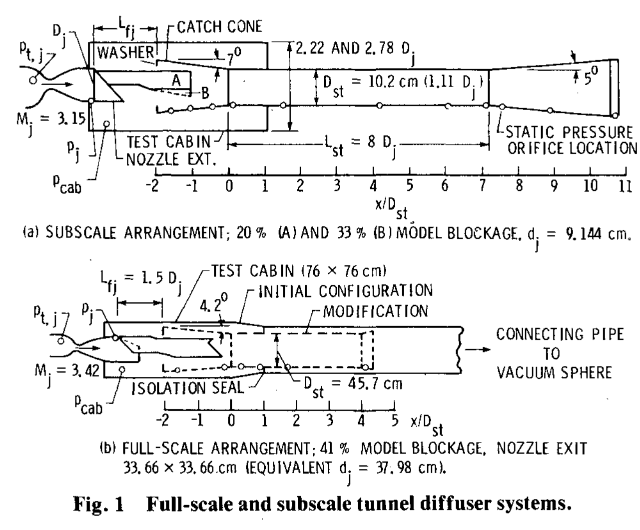


**Fig. 1 Full-scale and subscale tunnel diffuser systems.**

Presented as Paper 78-771 at the AIAA 10th Aerodynamics Testing Conference, San Diego, Calif., April 19-21, 1978; submitted Aug. 9, 1978; synoptic received March 19, 1979. Full paper available from AIAA Library, 555 West 57th St., New York, N.Y. 10019. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.** This paper is declared a work of the U.S. Government and therefore is in the public domain.

Index categories: Research Facilities and Instrumentation; Air-breathing Propulsion; Supersonic and Hypersonic Flow.

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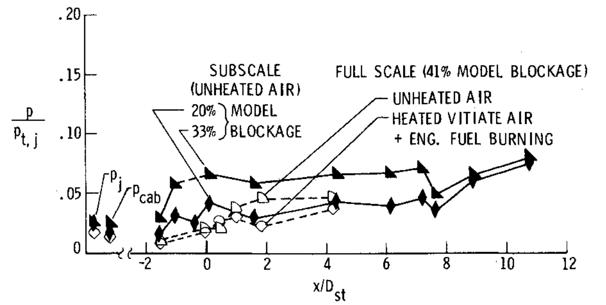


**Fig. 2 Pressure distributions within full-scale and subscale tunnel-diffuser systems.**

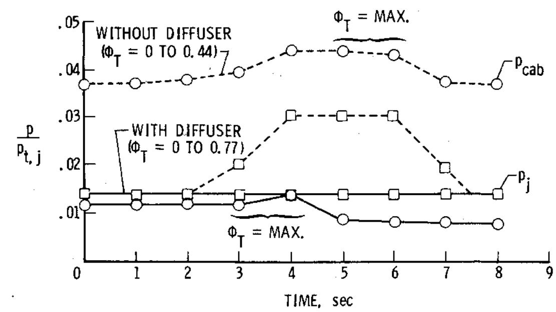


**Fig. 3 Test cabin and nozzle exit pressure variation with time and fuel equivalence ratio increase (time zero, $\phi = 0$); full-scale tests.**

at this point the several modifications to the catch cone and nozzle were investigated. A best nozzle exit-scramjet-catch cone arrangement was concluded to be the one utilizing an oblique nozzle extension and a catch cone with an entrance washer; this best arrangement is the one represented in Fig. 1a.

A reduction in the test cabin size appeared to have very little effect upon the performance of the diffuser system. A started condition with the installation of the larger scramjet model (33% blockage) required an additional increase in total pressure of about 8% above that required for when the smaller scramjet model was installed.

Insertion of the plug inside the scramjet models resulted in an unstarted inlet, which greatly disturbed the test cabin/diffuser flowfield and caused the diffuser flow to become subsonic. However, the test cabin pressure increased only slightly for both model sizes, and the tunnel nozzle exit static pressure was unaffected at the freejet lengths of 1.5 and 1.75 $D_j$. Withdrawal of the plug resulted in an immediate restart of the diffuser system flow to the same condition prior to the inlet unstart.

To summarize the results of the subscale tests, the best arrangement yielded acceptable diffuser pressure recovery and starting characteristics, stable diffuser pressure distributions, and unaffected tunnel nozzle flow when the scramjet model inlet was unstarted. Typical pressure distributions within the subscale diffuser system are presented by the solid-symbol curves in Fig. 2. To project the degree of applicability of these results to actual engine tests, an analysis based on satisfying continuity indicated that the performance of the best arrangement should be sufficient for testing a hydrogen-burning scramjet with 20% blockage. (Hydrogen burned in the scramjet will increase the diffuser duct flow temperature about 80% at Mach 4.) The analysis indicated that for an engine blockage as high as 33%, the performance of the best arrangement exhausting to atmosphere may not be sufficient to allow the engine to burn the hydrogen fuel stoichiometrically. With an ejector system or a vacuum system attached to the diffuser, even larger blockage engine models may be feasible.

The determination of the validity of subscale test results to full scale occurred during hydrogen-burning scramjet engine tests at Mach 4.0 simulated flight conditions using a full-scale engine module (20.3 cm high and 16.3 cm wide) with 41% blockage. The original nozzle-scramjet-test cabin setup at the General Applied Science Laboratory, Westbury, New York, exhausted directly into a facility vacuum system without benefit of a diffuser. This setup is represented by the solid lines in Fig. 1b. During early tests, facility-engine interactions were experienced where the test cabin pressure ($p_{cab}$) and the tunnel nozzle exit static pressure ($p_j$) increased with time, as shown by the dashed curves in Fig. 3, from the no-fuel level (at time 0-1.0 s) to a higher level as the total fuel equivalence ratio ($\phi_T$, weight flow of hydrogen divided by weight flow of hydrogen required for stoichiometric combustion) was increased. These pressure increases occurred as fuel was injected and were soon followed by an engine unstart. Since an engine unstart could also be caused by combustor-inlet interactions independent of the test cabin pressure, interpretation of the data was, therefore, impossible.

To eliminate the facility-engine interaction, a catch cone-diffuser arrangement based on the best arrangement of the subscale tests was installed in the full-scale setup, as shown by the dashed lines of Fig. 1b. Incorporated in the full-scale arrangement is a relatively larger straight-duct diameter ($D_{st}$) than used for the unheated flow subscale tests to allow for the effect of heat addition from burning hydrogen fuel in the scramjet. This catch cone-diffuser arrangement resulted in the elimination of the scramjet-facility interaction, as indicated by the nearly constant level trends, solid-line curves in Fig. 3, of the test cabin and tunnel nozzle exit pressures as the $\phi_T$ was increased to a value of 0.77.

Pressure distributions with the 41% model blockage and unheated flow (Fig. 2) indicate a general trend similar to that obtained for the subscale tests, but the level was lower than for the subscale data for 33% model blockage. With the heated tunnel flow and hydrogen fuel injected in the scramjet for stoichiometric conditions, the pressure trend is actually at a lower level than for the subscale data with 20% model blockage. These results confirm that a diffuser system based on the subscale best arrangement is suitable for hydrogen-burning scramjet tests.