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Ramjet Engine Testing and Simulation Techniques

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Simulation of flow conditions within the operating regime of ramjet engines requires unique ground test capabilities. The blowdown facility is an economical method of meeting the high air mass flow and pressure ratio requirements. Vitiated air heaters provide a flexible and cost-effective method of simulating trajectory temperature variation. Adequate simulation of the inlet flow conditions in freejet tests plays an important role in engine development. Ramjet engine ground test requirements are discussed. Methods of simulating the applicable parameters in direct-connect and freejet tests are reviewed. Techniques and devices that have proved beneficial in meeting aerodynamic simulation requirements are described.

Introduction

THE high specific impulse at high speeds offered by the ramjet engine, together with the demonstrated effectiveness of the integral rocket ramjet concept, has focused increasing attention on this versatile propulsion system. This in turn has kindled new interest in ramjet development testing and simulation techniques. Although supersonic airbreathing test facilities are few in number, there has been a continuous improvement in techniques and capability. A review of the test requirements of the ramjet flight environment follows, and methods and techniques employed to facilitate such testing are discussed.

Operating Regime

The operating regime for subsonic combustion ramjets is illustrated by Fig. 1 and embraces the flight envelopes of the potential applications. The boundaries of the ramjet operating regime are fairly clearly defined by several factors that will be described. Not surprisingly, these boundaries also encompass the flight regime of nonballistic lifting vehicles.

The upper-left-hand boundary of the envelope is specified by combustion limits and limits in useful engine thrust/weight ratio which are associated with operating at low chamber pressures. The limit shown corresponds to a total pressure level P_{t_2} of 10 psia at the combustor entrance with an inlet kinetic energy recovery η_{KE} of 0.9. The inlet kinetic energy recovery is related to the total pressure by the equation

$$\eta_{KE} = 1 - \frac{[P_{t_\infty}/P_{t_2}]^{(\gamma-1)/\gamma} - 1}{[(\gamma-1)/2]M_\infty^2} \tag{1}$$

where P_{t_∞} and M_∞ are the freestream stagnation pressure and Mach number. The ramjet operating limit in this region may also be related to a burner severity parameter, which includes the effect of temperature, as well as pressure.

The lower-right-hand boundary of the envelope shown corresponds to a combustor entrance pressure of 200 psia. Ramjet operating pressure does not necessarily design the combustor of the integral rocket ramjet engine, since the rocket combustion pressure is higher. However, the ramjet pressure can become significant when combined with other loading conditions and considered in light of the reduced material strength at elevated combustor operating temperatures.

The right-hand boundary of the envelope shown is representative of an operating temperature limit for uncooled structures. The Mach-5 limit indicated corresponds to a freestream stagnation temperature in the vicinity of 1800°F.

Ramjet Types

Various types of ramjets can be considered for applications within the ramjet operating regime. This is indicated schematically on Fig. 2 where two pod types and two integral types are shown. The first ramjet engines developed were of the pod type and were accelerated to operating speed by a separate rocket booster.

A normal shock inlet provides adequate performance for low-speed designs operating up to Mach 2. Such designs are fitted with a simple convergent nozzle, which led to the term "flying stovepipe" to describe this combination of sheet metal components. Although simple in concept, the engine operates in the transonic regime, which introduces unique testing problems.

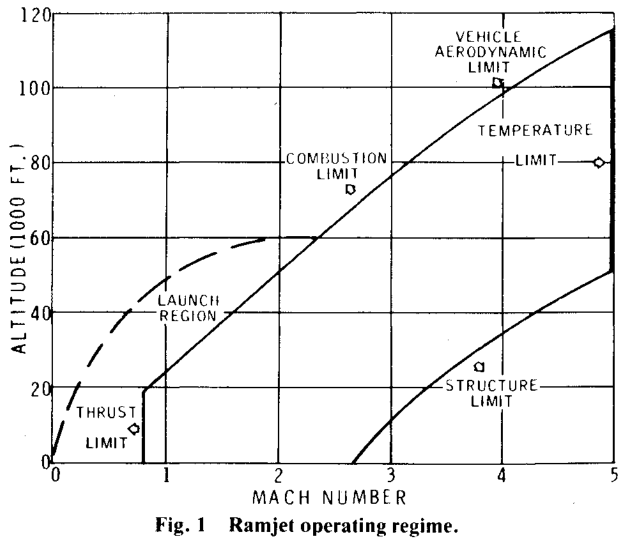

Fig. 1 Ramjet operating regime.

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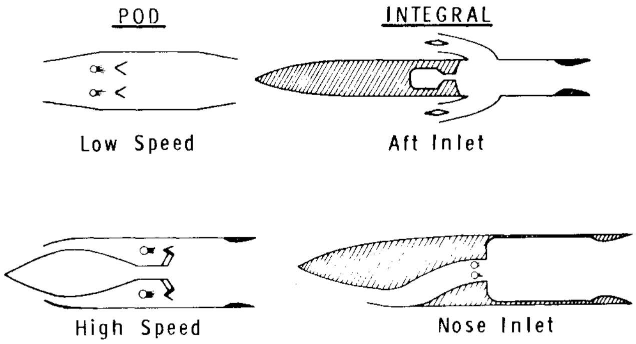

Fig. 2 Types of ramjets.

Pod engines designed for higher supersonic speeds are more complex in design of necessity, in order to achieve good performance. Inlet designs capable of providing efficient supersonic compression are required, as well as convergent-divergent exit nozzles. Additional testing considerations are introduced by these features.

Integral rocket ramjet (IRR) engines are designed to house the booster propellant in the ramjet combustion chamber. This results in a more compact design of lower weight. Transition from the rocket mode of operation to the ramjet mode for designs of this type poses special problems. The IRR designs often combine the propulsion system with the vehicle in such a manner that complete ground testing of the integral ramjet requires including at least a portion of the vehicle forebody geometry as part of the test hardware to provide the necessary flow simulation. Credible IRR systems can be configured with either forward- or aft-mounted inlets of single- or multiple-duct design. With this variety of possibilities challenging problems can be encountered in simulating the engine's operating environment in the test facility.

Development Testing

Like most systems IRR propulsion systems are developed first in component form. Later the components are combined into complete systems for further testing, culminated by a flight rating test. The principal components, which are commonly developed separately, are indicated in Table 1. The major objectives of the development testing are indicated, together with the types of test facilities employed in the process. Full simulation is unnecessary in conducting component development tests. For example, the aerodynamic characteristics and performance of inlets and exit nozzles can be established with reduced-scale models in wind tunnels and similar facilities, which simulate the Mach and Reynold's number but not the temperature, pressure, density, or fluid velocity. This approach is not possible with the combustor, where simulation of the latter parameters is also important. As a result, unique simulation requirements are associated with direct-connect testing and freejet testing involved in the development of the combustor and the complete engine.

Table 1 Ramjet development testing

Components
Inlet
Fuel system
Combustor
Nozzle
Rocket booster
Complete engine
Objectives
Component
Performance
System performance
Operating characteristics
Structural integrity
Heat transfer
Functional compatibility
Facilities
Wind tunnel
Rocket test cell
Fuel system
Test bench
Direct-connect test cell[a]
Freejet test cell[a]

[a] Unique ramjet simulation requirements.

Connected pipe tests are conducted primarily to demonstrate combustor thermal/structural design integrity and combustor performance, using a direct thrust stand measurement or a total pressure/temperature nozzle rake. Precise input conditions of airflow, inlet temperature, and fuel flow to the combustor may be achieved during connected pipe tests using facility-supplied air and fuel flow; consequently, accurate combustor performance correlations may be derived from these tests. In some connected pipe test facilities an entire trajectory time profile may be simulated using computer-controlled valves for airflow, heater fuel flow, and combustor fuel flow.

On the other hand, freejet tests primarily are conducted to verify the functional operation and performance of the integrated propulsion system in a supersonic flowfield. To take full advantage of the freejet tests, the test article should incorporate as many flight designed systems as possible (i.e., vehicle forebody, equipment and telemetry systems, pyrotechnic and ignition systems, inlet fairings, fuel management systems, auxiliary power systems, booster/combustor system, etc.).

Simulation

The temperature and pressure levels associated with full simulation in the ramjet operating regime are illustrated in Fig. 3 as functions of the flight Mach number and altitude. Few test facilities are capable of providing this simulation over a significant portion of the operating regime at mass flow rates high enough to conduct freejet tests of full-scale engines. Power requirements for continuous flow are prohibitive; therefore such facilities are of the stored-air blowdown type. Two of these facilities store 450,000 lb of air at a maximum pressure of 4000 psia and 170,00 lb of air at a maximum pressure of 3000 psia, respectively.[1-3]

There are a number of parameters and flight conditions that are simulated in the test facility, in addition to the temperature, pressure, and Mach number. Table 2 lists several of these. The ratio of the total to static pressure over

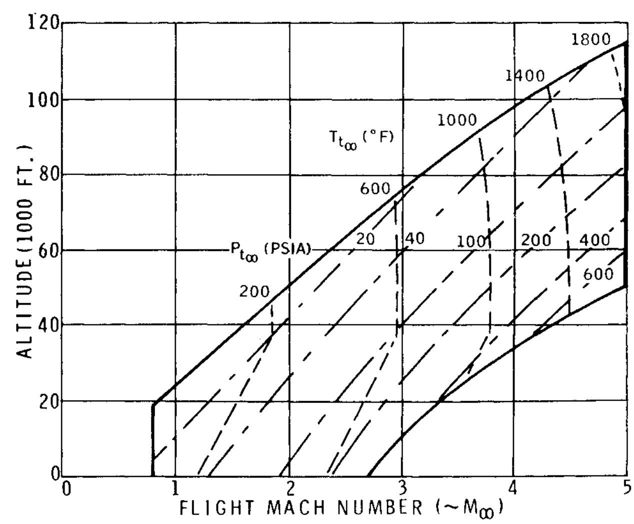

Fig. 3 Ramjet simulation requirements.

Table 2 Parameter simulation

Stagnation pressure
Stagnation temperature
Mach number
Pressure ratio
Air mass flow
Trajectory conditions
External heating
Maneuver loads
Angle of attack
Forebody flowfield
Transition sequence

the Mach number range indicated varies from 1.5 to 600. Techniques for reducing the static pressure, as well as for supplying the desired total pressure, are necessary. Test facility mass flows range from 8 to 1900 lb/s. One of the more challenging problems is to provide temperature simulation at the higher mass flows.

Missile propulsion systems are designed for short-life-cycle single-mission operation. Therefore it is desirable to provide the capability to vary the test conditions with time consistent with the variation encountered on representative flight trajectories. Conditions of interest include the external convective and radiation heat transfer and maneuver loads applied to the hot structure, as well as internal flow simulation of the mass flow, temperature, pressure, and combustion processes.

Provision to test at angle of attack is required, since this parameter can have a significant effect on the operation and performance of the engine, particularly when the flow is supersonic. Generally, the engine will be affected by variations produced in the vehicle flowfield by angle of attack. Simulation of the flow conditions produced at angle of attack by the vehicle forebody at the entrance to aft-mounted inlets is a major test challenge.

The IRR propulsion system operates first as a rocket until the ramjet operating speed is reached and the booster propellant consumed. Following this, a transition to ramjet operating occurs, involving the ejection of ancillary components, such as nozzle inserts and duct covers, which differentiate the two operating modes. The transition process consists of a series of related and closely timed events. Successful implementation of the transition sequence requires that each event occur as planned. Duplication of this process in the test facility also presents an interesting challenge.

Simulation of the stagnation pressures associated with the lower altitudes and higher Mach numbers of the ramjet operating envelope (Fig. 3) is impractical in a continuous-flow facility. The power requirements are prohibitive at the mass flow rates necessary to test full-scale engines. As an illustration, a representative 40-in. wind tunnel operates at pressure levels that occur only at the upper third of this envelope, and the total installed horsepower is 92,500. The power problem is circumvented for ramjet ground tests by using intermittent facilities that operate on stored air. At one facility the foregoing wind tunnel compressor system is supplemented by two additional stages of compression driven by a 7000-hp motor to charge the storage tanks with 450,000 lb of air at 4000 psi in 70 min. In this case the relatively high power level available contributes to a comparatively short pumping time.

In an intermittent facility pressure simulation is dependent primarily on the design of the storage system, heater, and ducting. Heater design to provide test capability in the vicinity of the low-altitude boundary of the flight envelope has presented a major simulation problem. This test region is important because typical flight trajectories will tend to follow a high acceleration path along this boundary, and also because this is the most severe structural environment in which the engine must operate. A major advance in test technique, which facilitates simulating low altitudes and high Mach numbers, was provided by the SUE heater. This sudden-expansion vitiated air burner with oxygen replenishment was originally developed for ramjet testing and has since been adopted by several facilities for other types of testing.

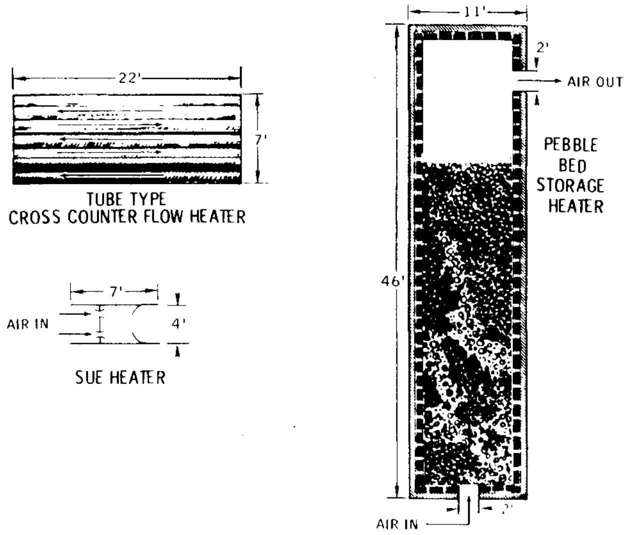

Fig. 4 Types of air heaters.

Heaters

The advantages of the SUE heater can be seen by comparing it with other types of heaters. Three of the principal types in use are illustrated in Fig. 4. It is evident that the SUE heater is more compact than the other types. This permits it to be installed in close proximity to the freejet nozzle in articulating ducting used to facilitate angle-of-attack variations during the test. The tube heat exchanger type of heater illustrated can supply clean air up to about 1200°F. However structural and maintenance problems, as well as heat transfer considerations, limit the maximum operating temperature. Higher temperatures can be achieved by adding a vitiated air heater downstream. The stored-energy heater is capable of supplying clean air at temperatures exceeding the testing requirements discussed. Problems that have been encountered in adapting this type of heater to full-scale engine testing include disintegration of the refractory materials of construction and matrix flotation at high mass flow rates. Also, a significant period of time is required to bring the storage heater up to temperature before testing can begin.

The SUE heater eliminates several of the problems associated with other heater types and provides a wind range of test simulation. It can be installed and maintained for a fraction of the cost of other heaters.

The principal problem associated with vitiated air heaters is that the resulting air, after combustion heating and oxygen replenishment, contains higher mass fractions of water vapor and carbon dioxide than normal air. Fortunately, this has proved to be only a minor problem in ramjet engine testing.[4]

Mach Number Simulation

A series of axisymmetric convergent-divergent nozzles is generally employed to simulate representative flight Mach number within the engine's operating envelope. The nozzle contour to obtain a given Mach number is defined by the method of characteristics, corrected as necessary for boundary-layer displacement thickness. The test capability provided by these fixed nozzles is extended by other techniques, as illustrated in Fig. 5.

Multiple-inlet configurations have been tested with a multiple freejet nozzle arrangment. This approach leads to a reduction in the facility air mass flow rate required to simulate the supersonic inlet environment for test purposes.

At the high temperatures associated with flow in the hypersonic regime, consideration must be given to protecting the freejet nozzle from the hot gas. Film cooling is a practical method of dealing with this problem.

In one configuration that has proved suitable, cooling air is introduced through two annular slots located upstream of the nozzle throat. The resulting film is adequate to protect the nozzle over the full length of the expansion bell without introducing disturbance in the supersonic section. Such a nozzle is cheaper to produce than one containing cooling water passages.

A simple but effective axisymmetric variable-Mach-nubmber nozzle for transonic freeject testing is obtained by welding a rolled up cylinder of commercially available perforated sheet metal to a sonic nozzle section. The test Mach number desired at the exit of the cylindrical section is obtained by operating at the corresponding pressure ratio. The principal of operation is the same for transonic slotted wind tunnels. The ratio of bleed air to test air increases with Mach number. This ratio is 0.18 at Mach 1.5, and 0.69 at Mach 2. Beyond this the ratio increases rapidly to 3.61 at Mach 3. From this it is seen that the technique becomes impractical at the higher Mach numbers.

Pressure Ratio

The ratio of total pressure to static pressure increases rapidly with test Mach number. Simulation of the static pressure at altitude requires that the cell pressure be reduced. Practical methods of lowering the cell pressure include connecting the cell to a vacuum tank, an ejector, or a powered exhauster system. A large vacuum sphere is often used for high-altitude hypersonic simulation, since the sphere can be evacuated to very low pressures between runs and the facility mass flow is low. This method is less practical for large facilities.

The air ejector is useful if a sufficient quantity of stored air is available. This technique is employed in one leading facility. For many test conditions a large fraction of the stored air is used to drive the ejector.

Power-driven exhausters are most useful when they can be operated either in series or in parallel. The choice depends on whether low cell pressure or high mass flow is the primary requirements of the test. The use of exhausters overcomes the limitation in run time associated with the vacuum sphere and split use of the stored air associated with air ejectors. In another prominent facility five J-46 turbojet engines are used to drive ten J-33 compressors as exhausters in both series and parallel arrangements.[2,3]

The methods described can be supplemented by other techniques to provide a further reduction in static pressure and increase in pressure ratio. The simplest is to operate the freejet nozzle filled but overexpanded. The flow leaving the nozzle is deflected toward the axis through an oblique shock, which replaces a Mach line as the downstream boundary of the test rhombus. As the pressure ratio is reduced, this shock becomes stronger, separates the nozzle boundary layer, and moves into the nozzle destroying the simulation.

The limiting pressure ratio for a filled nozzle is a function of the nozzle exit Mach number. A further reduction in operating pressure ratio can be achieved by bleeding the boundary layer near the nozzle exit or by designing the nozzle to recompress a portion of the flow, as shown in Fig. 6. The latter method is more applicable at hypersonic speeds where the diameter of the test rhombus is larger than required for the test.

Other useful techniques illustrated include the use of a freejet shroud or an exhaust diffuser. The freejet shroud operates on the principle of diffusing the flow from supersonic to subsonic velocity through a shock train in the annular passage between the shroud and the test article. Shrouds of this type can be employed at angle of attack by inserting a pie-shaped section in the flanged joint between the shroud and the nozzle.

Exhaust diffuser designs make use of the freejet and engine exit gases as the primary flow in an ejector-diffuser combination to reduce the cell pressure at the freejet nozzle exit. The ejector or exhausters draw off air downstream of a sealed bulkhead, which splits the cell. The flow in the diffuser increases in pressure through a series of shock waves and leaves the diffuser at subsonic velocity.

Figure 7 illustrates the effectiveness of the techniques described in reducing the operating pressure ratio below the isentropic ratio for a fully expanded nozzle. The curves shown are based on measured test values. The pressure ratios associated with diffusing the air through a normal shock and

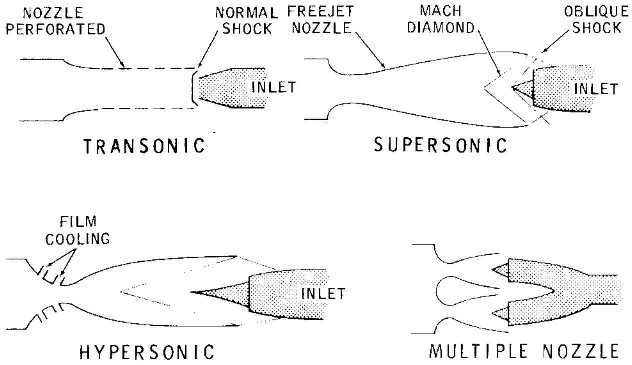

Fig. 5 Freejet nozzles.

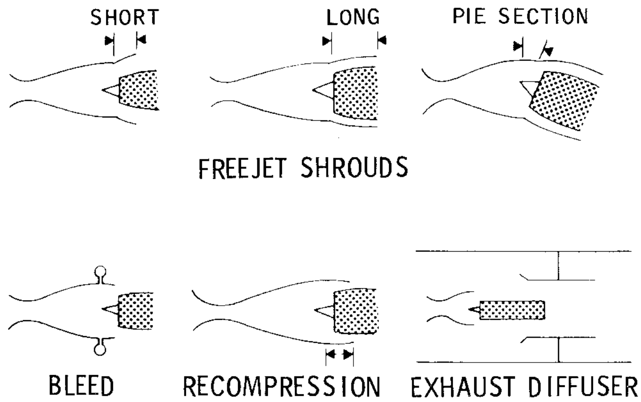

Fig. 6 Pressure ratio (techniques).

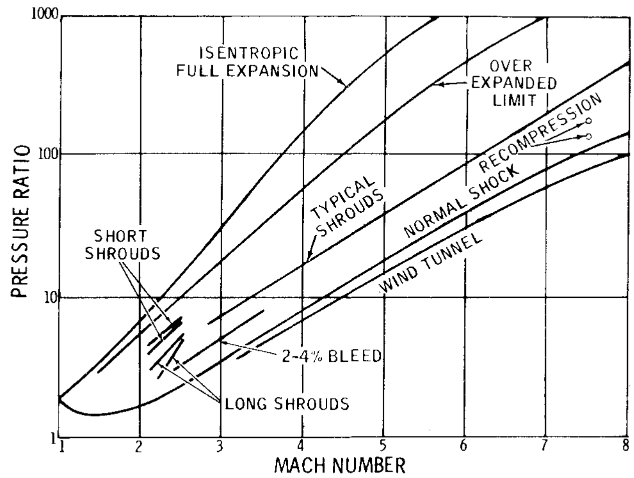

Fig. 7 Pressure ratio (performance).

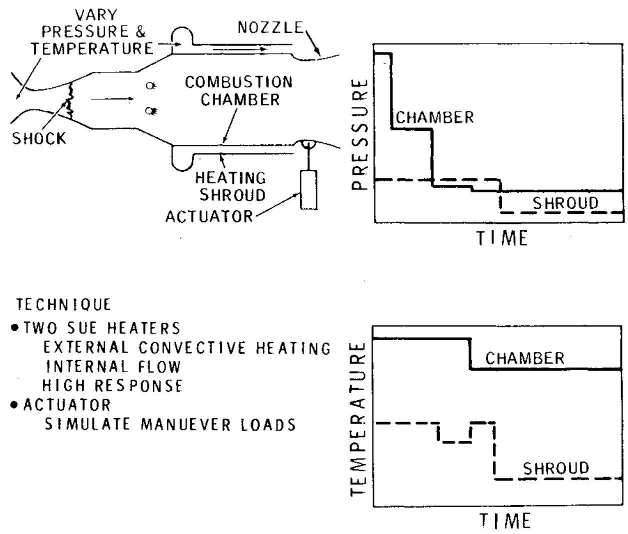

Fig. 8 Trajectory simulation.

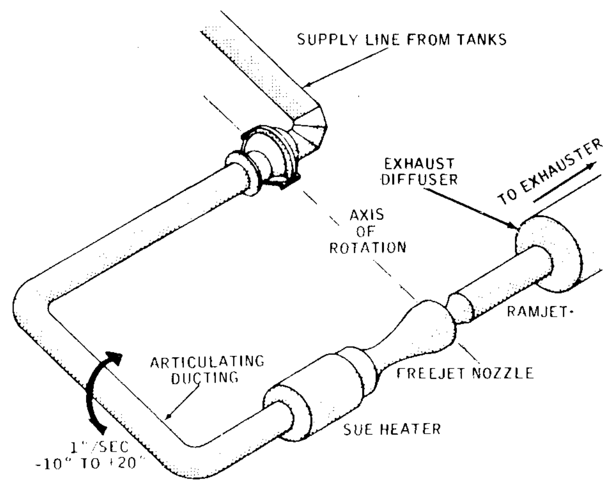

Fig. 9 Angle of attack.

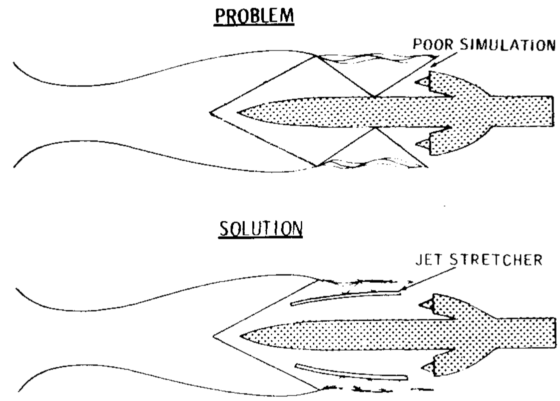

Fig. 10 Forebody flowfield (aft inlet zero angle of attack).

typical wind tunnel operation are shown for comparison. Some of the methods reduce the pressure ratio substantially. The data for short and long shrouds at the lower Mach numbers indicate the spread in performance observed when operating between 0- and 7-deg angle of attack. Short shrouds are not so effective but do not require axial realignment with the engine at angle of attack. Bleed flow at the lower Mach numbers and recompression at hypersonic Mach number are both seen to produce a substantial reduction in the operating pressure ratio.

Facility Mass Flow

The mass flow requirements for testing ramjets depend on the size and configuration of the engine and also on the flight condition being simulated. The mass flow per square foot of flow area in the test facility for the operating regime of Fig. 1 reaches a value of 230 lb/s. This maximum value corresponds to the low-altitude high-Mach-number operating condition. In general only intermittent facilities can provide mass flow rates high enough for freejet testing of full-scale engines at the lower altitudes.

Two of the leading ramjet test facilities have test flow capabilities up to or exceeding 1200 lb/s. The maximum values depend on temperature and pressure requirements.

A substantial portion of the engine development can be conducted using a direct-connect test arrangement. In this method of testing the inlet is eliminated and the combustor is connected to the facility air supply. The facility air flow required is much less than for freejet testing. This extends the available run time and makes it possible to simulate time-dependent flight trajectory conditions. Figure 8 illustrates the direct-connect test arrangement schematically. The inlet is replaced by a duct containing a choked throat, followed by a supersonic expansion and a diffuser normal shock train similar to the internal shock structure of the inlet. This permits the fuel flow to be varied at constant air flow to simulate supercritical operation of the ramjet and inlet. A heavy-duty combustor can be used to investigate the fuel injector, flame-holder, and exit nozzle components. The technique is extended to develop flight-weight combustors and combustion chamber insulators by providing an external heating shroud. External heated air flowing through this shroud under controlled conditions of temperature and pressure can be used to match the calculated external heat transfer for representative flight trajectories. Hydraulic actuators can be used to apply simulated maneuver loads to the hot structure at appropriate times during the course of the test.

Angle of Attack

Freejet testing at angle of attack is facilitated by the use of articulated ducting, as illustrated by Fig. 9. The test facility air flow is rotated, rather than the ramjet engine. This technique provides several advantages. It is beneficial to keep the axis of the ramjet exit nozzle aligned with the axis of the facility exhaust diffuser to minimize the problem of cooling the diffuser. Maintaining this alignment also deflects much of the external flow, as well as the internal engine flow, into the diffuser axially to maintain high ejector pumping effectiveness. Furthermore, there are many lines connected to the engine in a typical test setup. These include instrumentation lines, fuel lines, and water-cooling lines. If it is not necessary to rotate the engine for testing at the various angles of attack, the need to change the test installation between runs is eliminated, thereby simplifying the procedure significantly. Also, this approach simplifies the design of the thrust stand and the method of mounting the engine in the test cell, since a single arrangement provides for all angles of attack.

Although the articulated ducting is heavy, a rotation rate of 1 deg/s is achieved with ease, and the angle of attack can be changed during the run, which offers testing advantages. The relatively compact size and light weight of the SUE heater permit installation in the rotating duct in close proximity to the freejet nozzle. This minimizes the length of ducting subject to the high heater exit temperature.

Forebody Flowfield

In most cases the vehicle forebody will influence the flow conditions at the engine inlet, and it is desirable to simulate the effects of the vehicle forebody in freejet tests of the

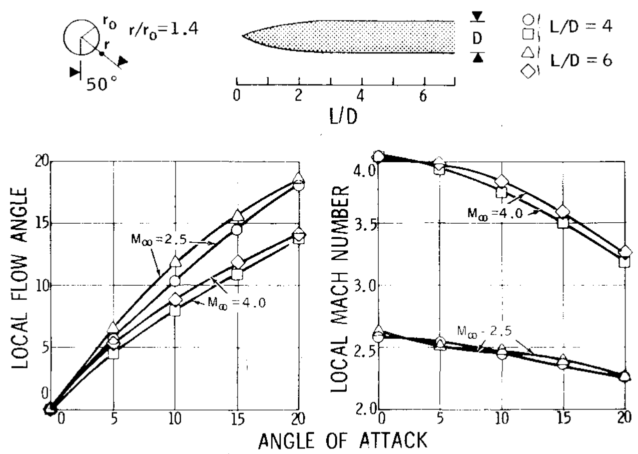

Fig. 11 Forebody flow conditions (L/D of 4 and 6).

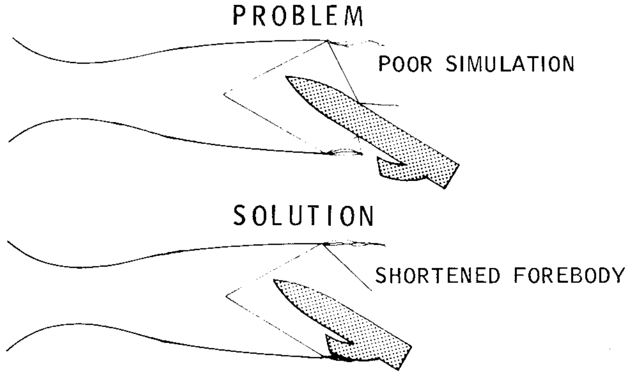

Fig. 12 Forebody flowfield (aft inlet at angle of attack).

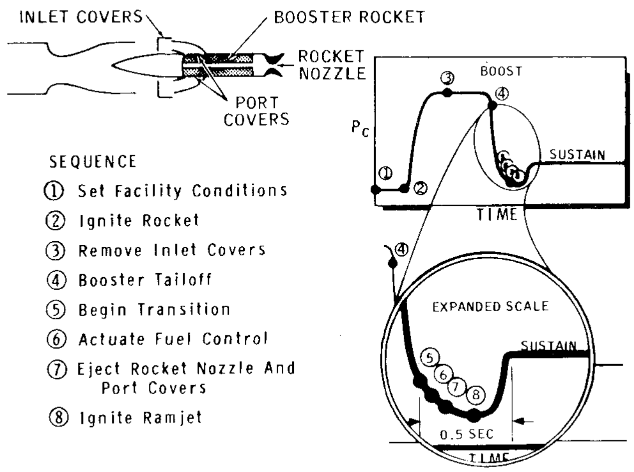

Fig. 13 Transition testing.

engine. A problem is encountered when the inlets are located in an aft position on a relatively long vehicle forebody (Fig. 10). Flow disturbances originating at the freejet boundary enter the vehicle flowfield upstream of the inlets and destroy the flow simulation. The problem can be overcome by means of a "jet stretcher" for tests at zero angle of attack. This device is contoured to conform to the shape of a bounding stream tube downstream of the vehicle's nose shock and upstream of the inlet. The required shape is calculated by the method of characteristics for supersonic flow with corrections for the displacement thickness of the boundary layer. The jet stretcher provides a shield that prevents freejet boundary disturbances from entering the vehicle flowfield upstream of the inlet. The device provides flow simulation at the inlet with a much smaller freejet nozzle and facility mass flow than required otherwise – hence the term "jet stretcher." Practical use of the device is confined to zero or small angles of attack, since the stream tube boundary at angle of attack is not axisymmetric and since additional flow aberrations are introduced by the boundary-layer cross flow caused by the circumferential pressure gradient. Major complexities in applying the jet stretcher to higher angles of attack are introduced by the aerodynamic considerations.

Two practical approaches to the aft inlet flow simulation problem at angle of attack have been suggested. One of these is based on the observation that flow conditions at various stations on the cylindrical portion of an ogive-cylinder body are quite similar. This is illustrated by the data of Fig. 11.[5] Here the measured Mach number and flow angularity are compared at stations 4 and 6 diameters downstream of the ogive tip. The length of the ogive is 3 diameters. The point of comparison in the flowfield is located 50 deg from the bottom centerline at a body radius ratio of 1.4, which is representative of a possible dual-cheek inlet installation. Since the flow conditions are similar at the two stations, the installed engine performance with the inlet located at either station will be similar. This implies that an aft inlet configuration can be tested in the freejet with a shortened forebody, as indicated in Fig. 12, with little change in installed performance. If the freejet testing is supplemented by wind tunnel tests of the inlet with both forebody lengths, the difference in measured inlet performance can be applied to correct for the small deviation in installed engine performance when measured in the freejet with a shortened forebody.

The second approach involves the capability to estimate installed engine performance on the basis of the predictable effect of known flowfield conditions at the inlet entrance on the engine performance. If this method is adopted, engine performance is established with an isolated inlet independent of the vehicle flowfield. The full effect of the forebody on the local flow conditions is applied to determine the installed performance from the isolated inlet performance. This method is similar to that employed with a shortened forebody, except that the engine performance correction requirements are larger. Measuring the performance of the isolated engine is considerably simpler than measuring installed engine performance, regardless of forebody length. Therefore, the method offers attractive advantages in terms of cost effectiveness.

Transition Testing

At the conclusion of development, it is appropriate to demonstrate the complete integral rocket ramjet propulsion system. All of the components have been proved by separate tests in suitable facilities, and freejet tests of the combined components, including the inlet, have been completed. Demonstration of the sequential functional capability of the components of an IRR propulsion system is carried out by means of a transition test, as illustrated by Fig. 13.

The objective of this test is to establish that transition from the rocket mode to the ramjet mode of operation will take place as planned, free of functional interface problems. Although exact simulation of the accelerating engine environment cannot be achieved in the ground test, a near facsimile is possible.

A freejet nozzle is selected to match the desired end-of-boost Mach number. The complete IRR system is installed in the cell and tested sequentially substantially as indicated by the figure. Inlet covers are installed to isolate the rocket motor from the freejet air blast until the rocket ignites and the chamber pressure is established. These covers may differ from the flight configuration for testing convenience.

Aside from possible secondary effects of axial acceleration, which are absent, the process of transition from rocket to ramjet operation is duplicated closely. The events associated with transition occur within a period of a few hundred milliseconds, which is necessary to minimize the deceleration period in flight between the two modes of operation.

Following successful completion of the transition test series, the propulsion system is ready for flight test. Beyond this, ground test facilities also may be required for flight support and production quality assurance testing.

Conclusions

Simulation of the ramjet flight environment involves an air supply capable of covering wide ranging conditions of mass flow, pressure, and temperature in the transonic to hypersonic regime. The ramjet ground test requirements are detailed. Specialized facilities have been developed to meet all or part of these needs. The high mass flow rates necessary for freejet testing of full-scale ramjet engines within the simulated flight regime of interest can be provided by specific intermittent facilities. A number of test techniques are described that have been developed to extend the range of test capability and simulation that can be provided.

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