LMSC-HREC TR D390661

NASA CR-141626

SUMMARY OF NOZZLE-EXHAUST PLUME FLOWFIELD ANALYSES RELATED TO SPACE SHUTTLE APPLICATIONS

FINAL REPORT

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JANUARY 1975

CONTRACT NAS9-13429

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AERODYNAMIC SYSTEMS ANALYSIS SECTION
JOHNSON SPACE CENTER, HOUSTON, TEXAS 77058

(NASA-CR-141626) SUMMARY OF NOZZLE-EXHAUST PLUME FLOWFIELD ANALYSES RELATED TO SPACE SHUTTLE APPLICATIONS (Lockheed Missiles and Space Co.) 21 p HC $3.25 CSCL 21B

N75-16625

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FOREWORD

This report presents a summary of the results of work performed by the Lockheed-Huntsville Research & Engineering Center under contract to the NASA-Johnson Space Center (JSC), Houston, Texas. The NASA-JSC Contracting Officer's Technical Representative for the study was Mr. Barney B. Roberts of the Aerodynamic Systems Analysis Section.

Studies conducted under this contract represent a coordinated effort of several organizations. Experimental data used in data correlation were obtained from test programs conducted at Marshall Space Flight Center. Lockheed-Huntsville personnel conducted the analytical studies and data comparisons. Mr. Morris M. Penny served as Project Engineer for the technical studies.

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Section 1
INTRODUCTION

Considerable attention is currently being directed toward exhaust plume problems associated with the design of the Space Shuttle vehicle. Current configurations utilize a combination of liquid and solid propellant booster motors to provide vehicle thrust during the launch phase. Solid propellant motors are then used to effect separation of the booster motors from the orbiter. Interaction of the exhaust plumes (both during the launch phase and stage separation) with the external surroundings produce hostile environments which must be considered in the respective design phases.

Plumes formed by the exhaust gases of the solid propellant rocket boosters and the orbiter main engine propulsion system interact with the freestream air flowing over the vehicle surfaces, thereby affecting the vehicle aerodynamic characteristics. In particular, plume-induced separation of the boundary layer on the vehicle aft surfaces occurs. Performance of the aerodynamic control surfaces (such as elevons and control surfaces on the vertical fin) located in the separated flow region is adversely affected resulting in a reduction of the vehicle aerodynamic control effectiveness. Also affected is the vehicle base drag. The extent of the influence of the propulsion system exhaust plumes on the vehicle performance and control characteristics is a complex function of vehicle geometry, propulsion system geometry, engine operating conditions and vehicle flight trajectory. Therefore, the magnitude and significance of the plume/vehicle aerodynamics interaction must be determined for each launch vehicle system being considered.

This is ascertained from scale model launch vehicle test programs. These, in general, utilize "cold" gas simulations of the various exhaust plumes. Appropriate similarity parameters are selected and applied to determine the model requirements to match the prototype plume shapes at the various trajectory points being considered. Thus, in addressing the problem of exhaust plume shape simulation, three basic problem areas must be considered. These are: (1) defining the full-scale exhaust plume characteristics; (2) selecting and applying the appropriate similarity criteria to determine model requirements; and (3) analysis of test data (includes nozzle calibration data). The studies conducted under this effort were directed primarily toward items (1) and (3).

For applications associated with plume simulation, the full-scale data normally required are the plume initial expansion angle and the corresponding plume shape over a region of interest. Once the test data are reduced, the respective vehicle performance data are usually correlated with respect to the plume initial expansion angle. Consequently, for full-scale design applications one simply needs the full-scale initial plume angle as a function of the vehicle trajectory.

Calculation of the orbiter exhaust plumes are rather straightforward since these result from the operation of liquid propellant motors. However, the flow in the booster exhaust plumes is complicated by the presence of particles in the flow. These are primarily aluminum oxide particles resulting from the reaction of aluminum and oxygen in the motor chamber and nozzle. The particles are accelerated through the nozzle-plume flow field due to the drag exerted by the surrounding gas. During the gas flow expansion through the nozzle and plume flow field, the gas cools rapidly. However, since the particles are accelerated by the gas, the particle temperature is not reduced by the flow expansion process. Instead, the particles cool by heat conduction and radiation to the surrounding gas as the gas cools. The particles are thus hotter than the exhaust gas. Therefore, to correctly determine the exit plane properties and consequently the exhaust plume shapes, the effect of the interaction of the particles with the gas exhaust must be treated.

During staging of the Space Shuttle, the exhaust plumes from the solid propellant motors used to effect the maneuver are directed at the orbiter. Portions of the orbiter surfaces are thus subjected to impingement of the exhaust plume. The impingement results in heating to the surfaces subjected to the impingement as well as forces and moments acting on the vehicle. This problem is further complicated by the presence of particles in the exhaust. For complete impingement loads and heating analysis, the particle trajectories through the flow must be known.

Work during the performance of the subject contract has been directed toward computer program development and analytical support of various plume related problems associated with the Space Shuttle. Computer program development has been concentrated in three primary areas: (1) two-phase nozzle-exhaust plume flows; (2) plume impingement; and (3) support of exhaust plume simulation studies.

A nozzle-exhaust plume computer code was developed to treat the flow of a chemically reacting gas-particle mixture. A computer code was developed to examine the applicability of a streamline divergence technique to analyze heating rates to surfaces subjected to exhaust impingement. Two thermodynamic codes were developed to provide variable thermodynamic properties for the simulant gas currently used in exhaust plume simulations.

During the performance of the contract several studies were conducted to provide full-scale data for defining exhaust plume simulation criteria. Model nozzles used in launch vehicle test were analyzed and compared to experimental calibration data. These studies are discussed in Section 2 (Task Summaries along with computer codes developed. Each task performed under this contract was documented at the conclusion of the respective task. Consequently, the following section provides a summary of each respective task.

Section 2
TASK SUMMARIES

Tasks performed under this contract were directed toward: (1) development of computer codes to treat gas-particle flows; (2) exhaust plume impingement; and (3) support of exhaust plume simulation studies.

The following discussion summarizes the various tasks performed under this contract.

2.1 GAS PARTICLE FLOWS

Gas-particle flows in nozzle-exhaust plume flow fields have received considerable attention during the development of the Space Shuttle. Solid propellant formulations are used in the booster and stage separation motors. Interaction of the exhaust plumes with the external surroundings produces a hostile environment which must be considered in design applications. The solid propellant boost motors significantly affect the vehicle base environment. During the separation of the orbiter and booster motors the exhaust plumes from the separation motors impinge on the orbiter. The exhaust impingement results in heating to the surfaces subjected to the impingement as well as forces and moments acting on the vehicle. The presence of particles in the flow further complicates the analysis by increased heating and enhances other possibilities such as erosion.

A series of computer codes has been developed to treat the supersonic flow of chemically reacting gas mixtures. These are described in the following paragraphs.

Supersonic Flow of Chemically Reacting Gas-Particle Mixtures (Refs. 1, 2 and 3)

The solution for chemically reacting supersonic gas-particle flows was formulated. This solution is incorporated in a nozzle-plume computer code which utilizes a streamline-normal technique. The gas particle flow solution is fully coupled in that the effects of particle drag and heat transfer are treated. The gas and particles exchange momentum via the drag exerted on the gas by the particles. Energy is exchanged between the phases via heat transfer and radiation (optional).

Gas thermodynamics and transport properties can be obtained from any one of several assumptions. These are:

1. Ideal gas (constant specific heats, molecular weight, etc.)
2. Equilibrium chemical properties in the gas phase
3. Equilibrium/frozen chemical properties in the gas phase
4. Non-equilibrium chemical kinetics in the gas phase.

Items 1 through 3 are input to the computer code via precomputed tables. Equilibrium chemical properties for the gas phase calculations are obtained from a modified version of the NASA-Lewis Chemical Equilibrium Computer (CEC) code (Ref. 4). Frozen properties are obtained by specifying where chemical "freezing" occurs. Equilibrium calculations are made to this point with the flow assumed to be chemically frozen thereafter. Non-equilibrium chemical kinetics are assessed by specifying the reacting gas chemical species, the reaction rates, initial concentrations and the appropriate thermodynamic data.

The heat transfer between the gas and particle phases is obtained from semi-empirical expressions which have been modified for rarefaction effects. Particle drag is computed from either expressions derived from Kliegel or Crowe. Particle thermodynamic data are obtained from the JANNAF thermochemical tables.

The basic mesh construction for the flow solution is along streamlines and normals to the streamlines for axisymmetric or two-dimensional flow. The analysis gives detailed information of the supersonic flow and provides for a continuous solution of the nozzle and exhaust plume flow fields. Boundaries for the flow are either the nozzle wall or the exhaust plume boundary.

Chemical Equilibrium Calculations for Gas-Particle Flow (Ref. 4)

Gas phase thermodynamic and transport properties are obtained from the NASA-Lewis CEC code. Modifications (Ref. 4) were made to treat the gas phase expansion in the coupled gas particle solution. These modifications were made so that the thermochemical data used in the gas phase are consistent with the assumptions used in the development of the gas-particle governing flow equations.

The CEC code was modified as follows. The usual combustion solution is performed. All condensed species are removed from the list of products of combustion. A new mass balance is made and the energy, etc., remaining in the gaseous species is calculated. The gas phase expansion is then performed without the condensed particles. From the chamber results,the particle loading relative to the gas can be determined.

Experience in thermodynamical modeling of rocket exhaust flows has indicated that many chemical systems experience a transition from equilibrium to frozen chemistry during the expansion process. The code contains a pressure preeze option which allows the user to specify a pressure ratio (chamber to local static) at which chemical freezing occurs. Expansion properties are computed using equilibrium chemistry up to the specified pressure ratio and the remainder of the expansion completed with frozen chemistry. Once the gas properties are calculated the transport properties are then computed.

One-Dimensional Gas-Particle Flows (Ref. 5)

Supersonic gas-particle flow solutions utilizing a method-of-characteristics solution are initiated along some data surface which must be everywhere supersonic. Information required to initiate the solution are the gas data (i.e., velocity, flow deflection angle, etc.) and the particle velocity temperature and limiting streamline locations.

As a minimum the particle velocity and temperature along with the limiting streamline locations should be known. Determining the lags permits an assessment of the gas flow losses (work required to accelerate the particles from the chamber to the supersonic start line) and the energy exchanged between the gas and particle phases. For applications utilizing plume data, the two-dimensional effects in the throat region become of secondary importance since these effects tend to be "washed out." Consequently a one-dimensional solution should provide an adequate starting condition for the nozzle-plume solution.

A fully coupled one-dimensional solution for gas-particle flows was formulated and a computer code developed. The solution is coupled via the momentum and energy equations. Particle distributions are represented as a series of discrete sizes and/or chemical species. The gas is assumed to be in chemical equilibrium, frozen or have constant thermodynamic and transport properties with no mass exchange between the phases. The solution is initiated at a specified condition. Analytical functions are used to describe the geometry from which the variation in area ratio is obtained. The work performed by the gas in accelerating the particles and the heat given up by the particles are a function of the relative distance over which the expansion occurs. Thus, the gas-particle flow is defined at specified area ratios and axial stations relative to the initial data plane. At each axial station the gas and particle properties are solved iteratively. The solution is continued until a specified gas Mach number is reached. Particle trajectories are then traced through the region of interest by numerically integrating the particle equations of motion. The complete solution then consists of one-dimensional gas-particle properties and particle limiting streamline locations at a specified data surface.

2.2 EXHAUST PLUME IMPINGEMENT (REF. 6)

Most current theories used in predicting convective heat transfer rates on body surfaces subjected to exhaust plume impingement do not utilize an adequate outflow correction theory. When a plume impinges on a surface at some angle of inclination, there is an outflow-induced thinning of the boundary layer, and a corresponding increase in the convective heating rates to the surface. Application of current methods for predicting convective heat transfer (without an adequate outflow correction theory) often results in the predicted heating rates being considerably lower than the experimentally measured heating rates. Without an outflow analysis to determine the severity of the thinning of the boundary layer and the corresponding increase in convective heating rates it is very difficult to make experimental-theoretical comparisons. Under such circumstances, experimental-theoretical comparisons can result in erroneous conclusions. For example, convective heating rates are determined by both turbulent and laminar theory. The convective heating rates determined by turbulent theory are found to compare more favorably with experimental data than by laminar theory. The conclusion is then made that the experimental data are turbulent which may actually be laminar. When proper outflow correction theory is applied, such erroneous conclusions can hopefully be avoided. The results determined by laminar theory and by turbulent theory should compare favorably with the laminar and turbulent data, respectively.

The computer program utilizing the streamline divergence has been developed to: (1) demonstrate the capability to trace inviscid surface streamlines and calculate "outflow corrected" laminar and turbulent heating rates on a body subjected to rocket exhaust plume impingement (it is capable of analyzing impingement due to any supersonic flow field); and (2) improve the existing convective heat transfer prediction techniques (which do not apply outflow correction theory).

2.3 SUPPORT OF EXHAUST PLUME SIMULATION STUDIES

Computer Codes to Calculate Thermodynamic Data for Air and Freon (Ref. 7)

Scale model testing which requires simulation of the prototype plume shape generally employs a "cold flow" test approach in obtaining the scale model plume. Air is most commonly used since air supply systems are readily available at most test facilities. However, air does not exhibit the desired flow properties under all test conditions which then in such cases necessitates the use of other simulant gases. Freon 14 (CF_4) has been found to exhibit expansion properties similar to those of the Space Shuttle main engines and thus is a candidate for use as a simulant gas in Space Shuttle scale model test programs.

Previous investigators have found these gases not to behave as an ideal gas (constant ratio of specific heats, etc.) nor obey the perfect gas law when expanded supersonically. Consequently, analytical studies which treat the supersonic expansion of these gases should include the effects of the non-standard equation of state as well as the variation of specific heat ratio with pressure and temperature.

Computer codes have been developed to calculate the thermodynamic properties of these gases for isentropic expansions from given plenum conditions. Thermodynamic properties for air are calculated with equations derived from the Beattie-Bridgeman nonstandard equation of state. Thermodynamic properties for Freon 14 are calculated with equations derived from the Redlich-Quang nonstandard equation of state.

Utility of the programs for use in analytical prediction of model rocket nozzle flow fields was enhanced by arranging card or tape output of the data in a format compatible with the Lockheed-Huntsville method-of-characteristics (MOC) computer program.

Operating Instructions for the NASA-MSFC Heater System (Ref. 8)

This document describes the operation of the NASA-MSFC high-pressure, high-temperature heater system. The system is capable of supplying 40 pounds of gas heated to a temperature of 650°F at a pressure of 2000 psia. The document provides a description of the operating techniques to be followed when the heater is equipped with a three-way mixing valve located downstream of the cold and hot tank. Manufacturers' brochures describing the component parts of the system are included in the Appendixes. Mechanical and electrical drawings of the heater may be obtained from E. H. Simon of MSFC, S&E-AERO-AEG.

The NASA-MSFC gas heater was designed and built by the CALSPAN Corporation (formerly the Cornell Aeronautical Laboratory, Inc.), to flow gas at a maximum flow rate of 4 pounds per second over a temperature range from ambient to 650°F at pressures up to 2000 psia. The heater will maintain the maximum conditions for at least 10 seconds.

Any non-corrosive gas or gas mixture may be used with the heater provided that adequate heating procedures are followed.

Plume Simulation Technology Pretest Analysis (Ref. 9)

This study generated data in support of the experimental program conducted to parametrically investigate the sensitivity of vehicle base environment to exhaust plume characteristics. Examination of these data indicate that the variations in the plume initial angle and shape of the "prototype" system does encompass the anticipated range of the corresponding Space Shuttle exhaust plume characteristics. Values of the mixing parameter ρu to be obtained with the test system do not cover the prototype range This arises from the large difference between maximum chamber temperature for the experimental program and the combustion temperature for a full-scale system. However, this is not considered to be detrimental to the program goals since an order of magnitude variation in ρu is possible. Parametric variations in ρu over the available range will result in the data required to determine trends and parameter sensitivities.

Plume characteristic values for the "simulant" system of nozzles that use air as the simulant gas do encompass the range of data generated for the "prototype" system flowing CF_4. These data show that "prototype" plume characteristics (δ_j, plume shape, ρu, etc.) can be matched while varying air nozzle geometry and operating conditions parametrically. Therefore, the objective of conducting a parametric, controlled assessment of the sensitivity of base environment to changes in the simulation parameters can be met.

Comparisons of ideal and real gas calculations indicate the ideal gas calculation to be applicable over a portion of the chamber pressure and temperature ranges to be considered in the parametric studies. However, at the combination of higher pressures and low temperatures real gas effects are significant. Due to the wide range of chamber pressure and temperatures as well as ambient pressures to be considered, real gas calculations should be used for all calculations. This will ensure that real gas effects are considered where applicable and not require that an additional study be conducted to determine the range of applicability of the ideal gas analysis.

Analysis of SRM Model Nozzle Calibration (Ref. 10)

This study was conducted to support three Space Shuttle launch vehicle test programs. Model nozzles were designed to simulate the prototype exhaust plume shapes. Air was used as the simulant gas. Calibration tests were conducted to verify the nozzle operating conditions. Experimental data consisted of nozzle wall pressure distributions and schlieren photographs of the exhaust plume shapes. Analytical data were generated using a method-of-characteristics solution.

Exhaust plume boundaries, boundary shockwave locations and nozzle wall pressure measurements calculated analytically agree favorably with the experimental data from the IA12C and IA36 test series. For the IA12B test series condensation was suspected in the exhaust plumes at the higher pressure ratios required to simulate the prototype plume shapes. Nozzle calibration tests for the series were conducted at pressure ratios where condensation either did not occur or if present did not produce a noticeable effect on the plume shapes. However, at the pressure ratios required in the power-on launch vehicle tests condensation probably occurs and could significantly affect the exhaust plume shapes.

The following general conclusions were reached during the course of this study:

- The nozzle used in the IA12B calibration test did not perform as expected. It is suspected that the performance difference resulted from a deviation of the nozzle geometry from design baseline. Model inspection data were not available to substantiate this, however. The effect on the plume simulation at the required pressure ratios was considered to be slight.
- The nozzles used in the IA12C calibration tests performed as expected.
- The nozzles used in the IA36 calibration tests performed as expected.
- Use of schlieren photographs in the evaluation of the calibration data taken for a plume expanding to ambient conditions provides a good assessment of plume boundary shock location. However, due to the relatively large width of the viscous mixing zone, a certain amount of interpretation is required to ascertain an equivalent location of the inviscid plume boundary. Since the method used to interpret the optical data directly influences various aspects of the study results, additional effort has been undertaken to better define the mixing region at the plume boundary. The results of this additional effort were reported in Reference 12.
- The use of dry unheated air as the simulant gas in the nozzle calibration and launch vehicle tests can result in the liquefaction of the constituents of the air (nitrogen and oxygen) in the exhaust plumes. Techniques for predicting the onset of the liquefaction and its effect on the plume boundary shape are not available for use in readily assessing these effects for the test program. However, examination of vapor pressure data and Mollier curves for equilibrium air and oxygen indicate that conditions suitable for liquefaction to occur do exist in the exhaust plumes. It is also evident that the chamber pressure used in the launch vehicle test (higher by a factor of three over the calibration test chamber pressures) will aggravate the liquefaction problem.
- To prevent the introduction of "unknowns" into the plume simulation problem, it is therefore recommended that future nozzle calibration tests be conducted with nozzle supply pressures equal to that which will be used during the testing. It is also recommended that provisions for heating the air be provided so that the liquefaction problem can be eliminated.

- The experimental calibration data utilized in this study were obtained with one nozzle of each pair provided for the IA12B, IA12C and IA36 launch vehicle tests. A cursory dimensional inspection was made for both nozzles in each pair to determine if the nozzles were geometrically matched. A decision to test only one nozzle in each pair was made based on the inspection results. Although this approach is probably adequate it is recommended that both nozzles to be used in simulating the SRM plumes be calibrated prior to future launch vehicle aerodynamic tests.

Adjustment of Model Nozzle Operating Conditions to Compensate for Condensation Effects in Exhaust Plume Flow Fields (Ref. 11)

A post-test analysis was performed of a Space Shuttle main engine model nozzle flowing "cold" air or nitrogen and a Space Shuttle solid rocket motor model nozzle flowing "cold" air. Operating conditions were investigated at which the condensation of oxygen and/or nitrogen was possible in the model nozzle exhaust plume flow fields. Experimental exhaust plume boundaries obtained from schlieren photographs were nondimensionalized and compared with analytical inviscid plume boundaries generated with a method-of-characteristic solution. At the higher chamber to ambient pressure ratios, the experimental exhaust plumes were larger than the corresponding analytical exhaust plumes due to the presence of condensed species in the supersonic expansions. For these operating conditions, the analytical chamber pressure to ambient pressure ratio necessary to match the experimental exhaust plume shape analytically was determined. The analytical pressure ratio required for matching the experimental exhaust plume shape was plotted versus the corresponding experimental pressure ratio for each nozzle. The data were sufficiently collapsed on the plot for each nozzle to provide working curves for the purpose of adjusting the experimental operating conditions to compensate for larger exhaust plume shapes resulting from the condensation of oxygen and/or nitrogen in the nozzle exhaust plume.

The following conclusions and recommendations were reached as a result of the analysis.

- At the low operating pressure ratios ($P_{chamber}/P_{ambient}$ = 178 - 318 for the SRM 3.0-A nozzle and $P_{chamber}/P_{ambient}$ = 186 - 435 for the SSME 1.2-A nozzle), there was no evidence of condensation affecting the exhaust plume boundary to any significant extent.

- At the moderate operating pressure ratio ($P_{chamber}/P_{ambient}$ = 329 - 507 for the SRM 3.0-A nozzle and $P_{chamber}/P_{ambient}$ = 524 - 861 for the SSME 1.2-A nozzle) the increase in exhaust plume size due to the presence of condensation was relatively small for several radii downstream of the nozzle exit plane.

- The results indicate that relatively large corrections in pressure ratio are necessary at the higher operating pressure ratios to adjust the size of the exhaust plume boundary to compensate for the presence of condensed species in the "cold" gas flow fields.

- A plot of matching analytical pressure ratio versus experimental pressure ratio as represented in Figs. 42 or 43 of Ref. 6 would be valid for only one nozzle configuration.

- The plots of matching analytical pressure ratio versus experimental pressure ratio as represented in Figs. 42 and 43 were derived from data acquired by expanding the nozzle flows into a quiescent ambient environment. The results have not been validated for nozzle expansions into a nonquiescent ambient environment.

- It is recommended that a similar analysis be conducted with nozzles expanding into a nonquiescent environment before this data or this technique is used for adjusting exhaust plume size due to condensation in nozzle flow fields expanding in a nonquiescent environment.

Interpretation of Schlieren Photographs of Exhaust Plumes (Ref. 12)

This study investigated the method for interpreting nozzle exhaust plume boundary and internal boundary shock locations from schlieren photographs of nozzle flows exhausting into a quiescent environment. The nozzle used to demonstrate the method was a subscale Space Shuttle solid rocket motor model using air as the working fluid. Comparisons of the experimentally measured exhaust plume boundaries and internal boundary shock locations were made with analytical data computed from an inviscid method-of-characteristics solution. The comparisons were made for low chamber to ambient pressure ratios to minimize condensation and other real gas effects in the nozzle exhaust plume.

The shear layer present at the boundary of the exhaust plume and ambient environment was found to measurably affect the interpretation of the experimental plume boundary location but did not affect the location of the internal boundary shock over the region of interest. The shear layer was analytically defined using a viscous mixing computer code. Calculated shear layer widths and radial pitot pressure distributions within the shear layer agreed in magnitude and trend with the experimental measurements.

The method developed for interpreting the exhaust plume boundary and internal boundary shock locations from schlieren photographs compensates for the presence of a viscous shear layer at the boundary of the exhaust plume and ambient environment. Excellent agreement was obtained between experimentally measured plume boundary and internal boundary shock locations using an inviscid method-of-characteristics solution. This method should be used when analyzing nozzle exhaust plume shapes from optical data.

The following conclusions and recommendations were developed during the course of this analysis.

- A viscous shear layer of measurable thickness is present at the boundary of the exhaust plume and the ambient environment. The inviscid MOC solution of the exhaust plume flow field does not account for the viscous shear layer thickness in the calculation of the exhaust plume boundary. In order to compare the inviscid exhaust plume boundary generated analytically with the experimental plume boundary, an approximate location of an inviscid experimental plume boundary has been outlined and should be used in analyses requiring the interpretation of plume boundaries from optical data.

- Interpretation of the half of schlieren photographs taken with a horizontal knife edge containing an outer diffuse dark region should be avoided. The half of horizontal knife edge schlierens containing sharp definite lines should be used for interpretation of the experimental boundary shock and exhaust plume boundary.

- Schlieren photographs of poor quality (lack of sharp definition, clouding caused by smudged tunnel windows or schlieren system optics, etc.) should not be used for interpretation of nozzle exhaust plume boundaries or boundary shocks.

- The internal boundary shock appears on schlieren photographs as a sharp well defined line which is easily interpreted. The internal boundary shock is not affected by viscous mixing phenomena over the region of interest, and in the absence of condensation effects provides consistent correlation between experimental and analytical flowfield data.

Model Nozzle Design for the Space Shuttle Reaction Control System Simulation (Ref. 13)

This study was conducted to support a Space Shuttle reaction control test program. A 0.01-scale model of the Space Shuttle was selected for operation in the Langley Research Center Unitary II wind tunnel and 31-inch hypersonic wind tunnel. Model nozzles employed a "cold" gas simulation of the full-scale RCS reaction control motor operating in various flight regimes.

Similarity parameters for the RCS simulation were momentum ratio and pressure ratio. Model nozzles were designed by using an iterative one-dimensional analysis based on momentum and pressure ratio matching between the prototype and model nozzles.

Five groups of model nozzles were designed for RCS system simulation corresponding to trajectory conditions at approach flow Mach numbers of 2.5, 3.0, 4.0, 7.0, 16.0, 22.0 and 29.2. Three baseline model nozzles were designed by matching full-scale momentum and pressure ratio. The nozzles were designed to simulate the following conditions: (1) full-scale approach flow Mach numbers of 2.5, 3.0 and 4.0 at a tunnel Mach number of 4.0; (2) full-scale approach flow Mach numbers of 7.0 and 10.0 at a tunnel Mach number of 10.3; and (3) full scale approach flow numbers of 16.0 and 22.0 at a tunnel Mach number of 10.3. Two additional model nozzles were designed by matching full-scale pressure ratios for full-scale approach flow Mach numbers of 7.0 and 6.0 at tunnel Mach numbers of 4.0 and 10.3, respectively, and for a full-scale approach flow Mach number of 29.2 at a tunnel Mach number of 10.3.

2.4 FULL-SCALE SOLID ROCKET MOTOR CALCULATIONS

Definition of SRM Exhaust Plumes for Nozzle Area Ratios of 5 and 7 (Ref. 14)

This study was conducted to support a Space Shuttle launch vehicle test program. A "cold" gas simulation employing air was used to simulate full-scale exhaust plumes.

Of interest in the test program was the effect of nozzle area ratio on launch vehicle aerodynamics. For correct simulation of the full-scale exhaust plume interaction with vehicle aerodynamics, adequate knowledge of the full-scale exhaust plume flow fields is necessary. To define the SRM exhaust flow field and operating characteristics, an analysis was conducted of the full-scale SRM plume boundaries employing nozzles with area ratios of 5 and 7. The engines were assumed to be operating at various trajectory conditions.

Definition of SRM Exhaust Plume Initial Expansion Angles (Ref. 15)

The exhaust plume initial expansion angle has been found to be a correlating parameter for predicting vehicle base drag resulting from the plume interaction with vehicle aerodynamics. This study generated SRM nozzle and exhaust plume data for five points of the launch vehicle trajectory.

Nozzle-exhaust plume flowfield properties were computed using the Lockheed-Huntsville two-phase flow computer code (RAMP). Gas thermodynamic and transport properties were calculated from chemical equilibrium considerations. Exhaust plumes were computed for the nozzle exhausting to the specified atmospheric condition at the respective trajectory points. The plume initial expansion angles were then correlated with respect to the corresponding chamber to ambient pressure ratio.

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