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Paper Session I-B - Computational Fluid Dynamics Analysis of Space Shuttle Vehicle and Exhaust Plume Flows at High Altitude Flight Conditions

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COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF
SPACE SHUTTLE VEHICLE AND EXHAUST PLUME FLOWS
AT HIGH-ALTITUDE FLIGHT CONDITIONS

by

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ABSTRACT

Computational fluid dynamics (CFD) analysis has provided verification of Space Shuttle flight performance details and is being applied to performance predictions with Advanced Solid Rocket Motors (ASRM's) scheduled to begin operation in 1997. Advancements in CFD methodology described herein have allowed definition of exhaust plume flow details completing the capability for 'nose-to-plume' simulation. CFD predictions of the Space Shuttle vehicle aerodynamic performance at Mach 3.5 and 107,000 ft with ASRM's confirm no adverse effects for high-altitude flight conditions.

INTRODUCTION

Results of CFD analysis are presented in this paper for the Space Shuttle at high-altitude flight conditions. They are a part of the aerodynamic and aeroheating performance verification for the vehicle with the new ASRM's scheduled to begin operations in 1997. The ASRM's are utilized with the same forward and aft skirts and nose cone frustum as the SRM's. They are aerodynamically 'cleaner' with fewer factory and field joints. They have 4 inches greater diameter but the same length as the SRM's.

Combined efforts at Rockwell Space Systems Division in Downey, California, and in Huntsville, Alabama, together with the NASA Johnson Space Center (JSC), Ames Research Center (ARC), and Marshall Space Flight Center (MSFC), have resulted in highly-detailed Space Shuttle CFD grids for simulating the aerodynamic flow and exhaust plume effects. The Space Shuttle vehicle Orbiter, External Tank (ET), Solid Rocket Motor (SRM), Space Shuttle Main Engines (SSME's), and surrounding flow field have been modeled with over 2.5 million grid points to capture the surface

pressure and temperature and shock waves, flow separation regions, wakes, and exhaust plumes. Grids were developed for the vehicle both with the present SRM's and with ASRM's.

New and more detailed aerodynamic simulations have added refinements to our knowledge of how the Space Shuttle flies. These simulations have been made on supercomputers at NASA/JSC, ARC, MSFC, and Rockwell's facility at Seal Beach, California. Refined definition of Shuttle's airloading and base recirculation plume effects has helped to reduce small aerodynamic uncertainties. Reducing these uncertainties will help us realize all of the 12,000 lb payload capability increase we have planned with the ASRM's.

Our simulations have focused on: 1) airloads in transonic flight altitudes near 37,000 ft where we throttle the SSME's for maximum dynamic pressure (max q), and 2) high-altitude supersonic flight above 90,000 ft where we experience maximum aerodynamic heating and base heating. This paper focuses on the high-altitude supersonic flight and brings to light some flow details more clearly than we have seen with flight instrumentation, tracking cameras, or in subscale model testing/experimentation in the wind tunnels and altitude test chambers.

HIGH-ALTITUDE FLIGHT CONDITIONS

The ascent trajectory for the Shuttle is controlled by the maximum aerodynamic loads at the medium altitudes (during max q) and later by the Shuttle vehicle elements thermal protection system (TPS) capability to withstand aerodynamic and exhaust plume (base) heating. Heating considerations include the integrated effect of the total time to ascend in the atmosphere to orbit or any of the possible abort options for a

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trans-Atlantic or return-to-launch site landing. A longer burn time of nearly 10 seconds and slightly increased thrust-to-weight ratio for the ASRM's will allow a trajectory reshaping that eliminates the need for SSME throttle-down.

The Orbiter TPS (tiles and advanced insulation blanket) and SSME nozzle external insulation are designed for re-entry, but must also provide adequate protection for aeroheating and base heating during high-altitude ascent. As the ambient pressure decreases when the vehicle ascends to about 90,000 ft and higher, the SSME and SRM plumes expand to where they intersect and cause hot gas recirculation into the Orbiter and ET base region. The three SSME plumes interact with one another to form a closed region of recirculating exhaust plume gases that pressurize the Orbiter base as the flight ambient pressure continues to diminish to vacuum.

The aeroheating is a forebody aerodynamic boundary layer friction phenomenon. Shock waves interacting with the boundary layer cause local conversion of some of the flow energy to high recovery air temperatures (exceeding 1500° F), changing the friction and causing locally high convective heating.

Simulation results are shown in this paper for the Shuttle flying with ASRM's at Mach 3.5 and 0 deg angle of attack at 107,000 ft altitude. Here the ambient pressure is 17.5 psfa and the temperature is -20°F and the exhaust plume spreading results in formation of oblique shocks at the plume intersections. The wake expansion at the Orbiter base at these conditions results in a base pressure of about 9 psfa. The pressure recovery at the plume intersections becomes strong enough to recirculate plume gas from the outer boundaries of the SSME plumes back to the heat shield. Exhaust gases from both the SSME's and the SRM's are recirculated to the ET base.

CFD METHODS

Computational Grids

The protuberances and element interconnect structure have appreciable influence on the aerodynamic flow and are important features of the analysis of the forebody. Great care has been put into computational grid generation to get the necessary detail (see Figure 1) into the simulation. The forebody, for the purposes of this discussion, is that major portion of the vehicle

length up to the maximum in aerodynamic cross-sectional area. A maximum aeroheating zone is associated with compressions in the shocks between the ASRM and ET at the forward cross beam attach. Approximately 450,000 grid points were used in the Orbiter base region to capture the SSME and body flap details. The upper engine (No. 1) is canted upward at 16 deg while the two lower engines (2 and 3) are canted upward at 5 deg and outward at 2 deg. The external surfaces of the SSME's, body flap, and Orbital Maneuvering System (OMS) pods are shown.

CFD Code Solver

The CFD code solves for all of the flow variables in each grid cell. The grid cells are finite-volume tetrahedrons that are sized to grow exponentially from close to the vehicle surface outward to the free-stream flow. The solutions presented in this paper were obtained using Rockwell's viscous USA CFD code. This code automatically captures shock waves, flow separation regions, and wakes and computes the three components of flow velocity, and the pressure, density, and temperature everywhere in the flow field. The code also computes finite-rate chemistry and gas species concentrations and energy, which are important for accurate simulation of the exhaust plumes mixing with air.

Shuttle flight simulation results were processed on local departmental workstations for graphical displays of solution output. The plot routines compute isocontours of derived parameters such as local Mach number, temperature, and pressure and fluid particle traces through three-dimensional space.

Finite-Rate Chemistry

The flowfield is treated block-style in zones permitting separate treatment of the air and the exhaust plumes in the base region and downstream. The forebody flow is air treated as a perfect gas with constant ratio of specific heats, γ , of 1.4. However, in the base flow zones, the air is treated as a mixture of 79 percent N_2 and 21 percent O_2 by volume mixing with combustion products in the exhaust plumes. In the case of the SSME plume flow shown in this paper, the code solves for the densities of four combustion

product species -- H_2 , O_2 , H_2O , and OH -- as well as of the N_2 from the free-stream air. Free O_2 from the atmosphere finds its way into the engine compartment and is available to support continued combustion of the free H_2 recirculated to the base, provided the local mixture ratio and pressure are in the flammable range.

Mole fractions of SSME combustion products computed by the code at each exit plane are 73.0 percent H_2O , 25.2 percent H_2 , 1.7 percent OH , and 0.1 percent O_2 . The exhaust flow is mostly steam with γ varying from 1.2 at the plume outer boundaries to 1.3 at the plume core centerlines. Dissociation and recombination as well as continued combustion with atmospheric air are a function of local temperature, pressure, and mixture ratio in the plume and base region.

Turbulence

Turbulence effects are treated with a simple algebraic model in the forebody zones and a differential equation mixing-length model in the base and exhaust plume zones. The modeling shapes the velocity shear profiles in the forebody boundary layer, wake regions, and exhaust plumes. Turbulence influences the degree of plume-air mixing in the base and the resulting gas temperatures for base heating. The gas mixing and diffusion rates play a large part in the results.

RESULTS

Forebody

Pressure isocontours are shown for the Shuttle forebody surfaces in Figure 2 and on the vehicle vertical plane of symmetry and on a plane perpendicular to that through the booster motors. Shock waves on the nose of the ET, Orbiter, and ASRM cone frustrums are clearly evident. The ASRM shock wave impinges on the Orbiter and ET. There is a set of reflected shock and expansion waves in the Orbiter-ET forward bipod attach structure area. There is a shock compression system between the ASRM and the ET at the forward attach structure location. There are strong shocks on the Orbiter nose and canopy. These are the major features of the forebody flow seen in Figure 3 and primary locations of aeroheating.

Close-up views of the shock compression system at ASRM-ET attach structure are shown in Figure 3. Temperature in the airflow at the vehicle element surfaces reach $1000^\circ F$ maximum temperature just forward of the attach beam on both the ET and the booster surfaces. The associated aeroheating rates are as expected and well within the capability of the TPS on both the ET and the ASRM. The transition from the forward skirt to 4 inches increase in ASRM diameter is benign and produces no flow disturbance.

Static pressures computed along the forebody surfaces, when compared to pressures measured in wind tunnels with the ASRM's versus wind tunnel model pressures with the SRM's, have confirmed there are no adverse aerodynamic or aeroheating effects with the ASRM's.

Orbiter Base Region

Temperature isocontours are shown in Figure 4 looking upstream into the Orbiter base region. The plume boundaries are evident and on the plane between Engines 2 and 3, there is a discriminating streamline where the two plumes intersect. The detail diagram in Figure 4 illustrates the discriminating streamline and the turning of low-velocity plume gases at the plume outer boundaries back toward the base. This is the characteristic feature of the high-altitude base recirculation phenomenon. It does not occur until the vehicle is at a high-enough altitude for the plumes to expand to the point of forming these discriminating streamlines.

Computed gas temperatures at the bottom center of the base heat shield reach $2500^\circ F$. Computed pressure at the base was 7 psfa and proportional to: 1) the 216 psfa recovery pressure and $5000^\circ F$ temperature computed in the oblique shocks at the discriminating streamlines at the plume intersection and 2) to the air expansion in the wake at the Orbiter base. The computed average base gas temperature and pressure agree well with flight data. Gas particle traces are shown in Figure 5, and it is evident that the flow between Engines 2 and 3 streams inward to the lower half of the base heat shield and then turns outward radially and becomes entrained in the Orbiter wake.

These effects of base recirculation flow details confirm basic theory and altitude test chamber model experimentation although a complete

simulation with OMS pod and vertical tail shocks was not done.

The local gas mixture and finite-rate chemical reactions in this CFD analysis account for the real gas properties variation as plume gases mix, diffuse, dissociate, recombine, and react with air. The computed species concentrations by volume in the lower half of the base heat shield are 38.8 percent N_2 , 36.0 percent H_2O , 14.6 percent H_2 , 9.8 percent O_2 , and 0.8 percent OH. The variation is seen in the specific heat ratio, γ , varying for 1.2 (all exhaust gases at the plume edge) to 1.4 (all air at the wake edge). This chemically-reacting feature in the base flow is a significant CFD methodology advancement.

SUMMARY

'Nose-to-plume' CFD predictions of the Space Shuttle vehicle aerodynamic performance at Mach 3.5 and 107,000 ft with ASRM's confirm no adverse aerodynamic or aeroheating effects on the vehicle forebody. The primary shock compression systems of the ET-booster forward attach structure produce recovery temperatures and aeroheating well within the capability of the TPS on these elements. The predicted Orbiter base recirculation flow field gives base pressures and temperatures that agree well with flight data. Advancements made in CFD methodology account for plume gases mixing with air. These CFD results provide an advancement in knowledge above that which was possible from flight, tracking camera, and wind tunnel and altitude chamber experimental test data.

ACKNOWLEDGEMENT

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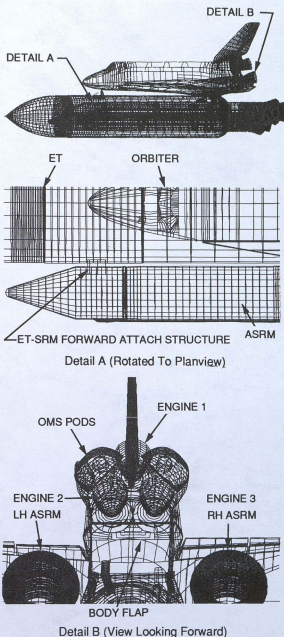


Figure 1. A Fine-Detailed Grid Was Constructed Around This Shuttle CAD Model

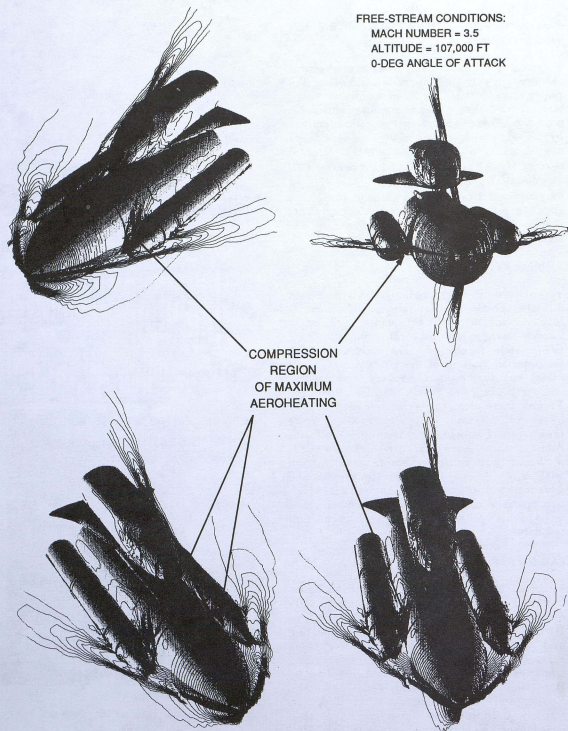


Figure 2. Pressure Contours From the CFD Solution at Mach 3.5 Show the Shock Waves and Regions of Locally High Compression

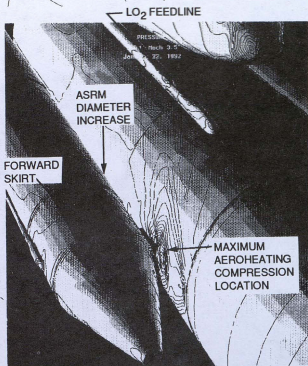
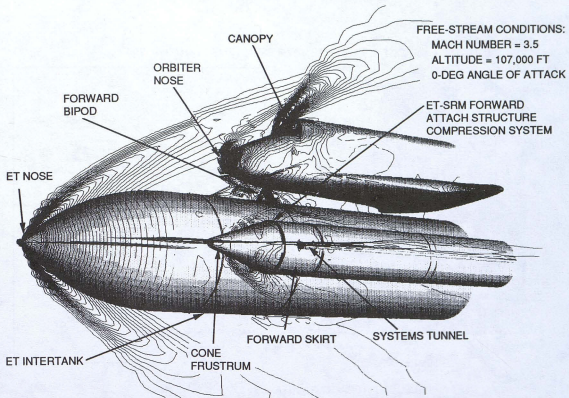


Figure 3. Close-Up Views of the Pressure Contours On the Shuttle Vehicle Forebody at Mach 3.5 Show the Shock Waves and Maximum Aeroheating Locations

CONDITIONS:
 FREE-STREAM MACH NUMBER = 3.5
 ALTITUDE = 107,000 FT, PRESSURE = 17.5 PSFA, TEMPERATURE = -20°F

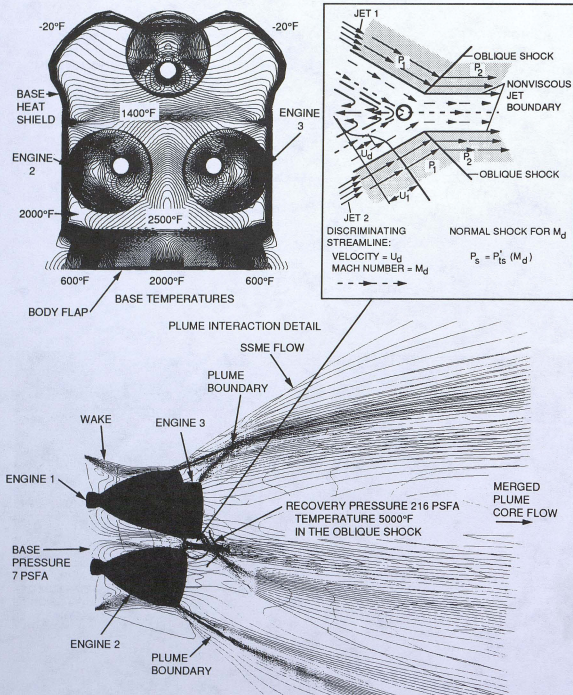


Figure 4. SSME Multiple Plume Interactions Cause Hot Gas Recirculation and Heating of the Lower Half of the Base and Body Flap

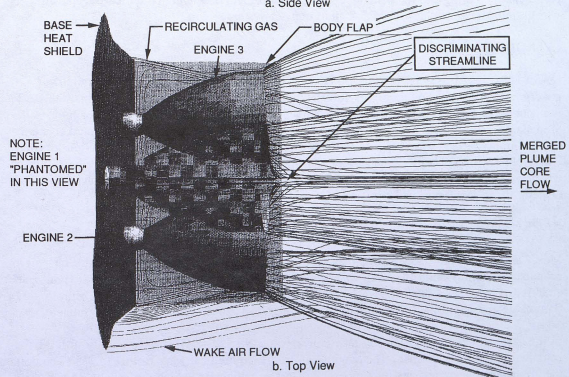
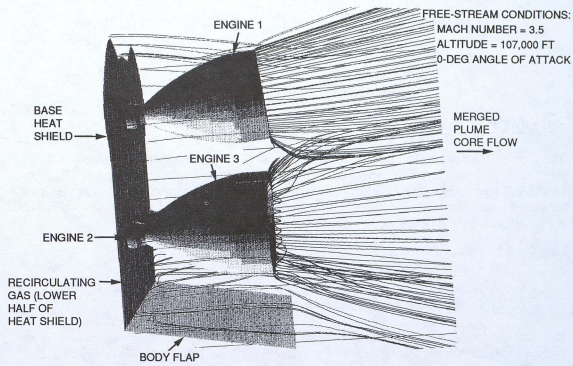


Figure 5. These Plume Gas Particle Traces From the CFD Solution Show Recirculation Into the Lower Half of the Base