Effect of Thermally Induced Deformation in a Supersonic Combustion Facility

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EFFECT OF THERMALLY INDUCED DEFORMATION IN A SUPersonic COMBustion FACILITY

By
Aditya Ajit Gupte

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE AT EMBRY RIDDLE AERONAUTICAL UNIVERSITY DAYTONA BEACH, FLORIDA FEBRUARY 2011

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DEPARTMENT OF
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To My Parents, Teachers and Friends
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Abstract

Nastran and ANSYS finite element analysis (FEA) and Wind-US computational fluid dynamics (CFD) solvers are used to simulate the effect of thermal deformation on the reacting flow developing within the University of Virginia (UVa) Supersonic Combustion Facility (SCF). A detailed thermal-structural model is developed to resolve the temperature distribution and the resulting structural deformation taking place within the scramjet engine flowpath. The predicted thermal deformation is used to refine the CFD model and produce a new set of results for direct comparison with experiment during both ramjet and scramjet modes of operation. Improved agreement between CFD and experiment is afforded by including the thermal deformation effect. The sensitivity of key choices for structural constraints is also evaluated.
Acknowledgements

"The mediocre teacher tells, the good teacher explains, the superior teacher demonstrates, the great teacher inspires."

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Chapter 1

Introduction

The desire for hypersonic flight in the recent years has bought a paradigm shift in research and development. This quest is largely driven by defense desiring faster tactical jets, weapons and future space vehicles [2]. A variety of organizations have broken ground in hypersonic, for example:

1. NASA’s Hyper-X program resulted in a successful test flight of X-43A which attained maximum speed of Mach 9.6 at 110,000 ft

2. FALCON, a joint venture of Defense Advanced Research Projects Agency (DARPA) and United States Air Force (USAF)

3. X-51 Wave Rider, developed by Boeing, Pratt and Whitney Rocketdyne, and managed by the Air Force Research Laboratory (AFRL)

Educational Institutions like the University of Virginia (UVa) and the University of Queensland are also leading efforts in hypersonic research with the Hy-V and Hyshot programs, respectively. Hyshot 2 [3] flight test in Woomera, South Australia in July 2002, demonstrated the world’s first supersonic combustion in an atmospheric flight. However many challenges remain.

High fidelity simulation, including computational fluid dynamics (CFD) and finite element analysis (FEA), plays an increasingly important role in modern hypersonic systems design. Once validated for a small set of test cases, high-fidelity numerical simulation offers the promise of expansive, low-cost virtual testing, detailed flow-field visualization and vital insight in to the complex physics of scramjet propulsion systems. A critical area is the aerothermoelastic problem in hypersonic flight, where the vehicle sees severe aerodynamic heating that can cause structural deformation (for example: bulging, distortion of engine throat, melting of the leading edges, etc.) [4], [5], [6]. Aerothermoelasticity is particularly of interest to re-usable launch vehicles [7], [8] where the cumulative effects of the residual stresses, creep, and material degradation associated with high temperatures must be considered. Active cooling adds a significant complication to analysis of thermostructural effects.
Previous work performed by Goyne [9] simulated the individual components of the UVa dual mode direct connect ramjet/scramjet flowpath using VULCAN. The results concluded that the turbulent mixing as well as the levels of heat release of combustion is under predicted. Bhagwandin [10] simulated the UVa’s direct connect dual-mode scramjet engine using the Wind-US flow solver for three run conditions viz. one fuel off and two reacting cases with different equivalence ratios. The pressure distributions along the flowpath were predicted with reasonable accuracy, except in the exhaust-nozzle region where there was a large region of numerically induced separated flow. A follow-on study by Vyas [11] performed Wind-US numerical simulations of mode-transition and investigated the effect of flow vitiation on the mode transition process. Excellent agreement was found with the experimental results; however, significant discrepancies were observed at the combustor-extender joint, especially at lower equivalence ratios indicative of a scramjet mode. It was speculated that the source of these inconsistencies could be related to the non-uniform temperature distribution across the combustor-extender and/or the difference in the coefficients of expansion between the materials that comprises the combustor and the extender.

The present work uses multi-disciplinary thermo-structural-fluid analysis in order to attempt to resolve the large discrepancy between experiment and Wind-US numerical simulation in the vicinity of the combustor-extender joint. Decoupled FEA-CFD analysis is used to predict structural deformation from FEA and then modify the CFD geometry and grid, and permit Wind-US re-evaluation of the same matrix of the UVa experimental runs [11]. The thermostructural model is based on the experimental configuration of the University of Virginia (UVa)’s supersonic combustion facility (SCF). By accomplishing this primary goal, the study aims to give engine designers further insight regarding the experimental data. The validation of the Wind-US CFD solver for scramjet flowpath application is a secondary goal of this research work.
Chapter 2

Background

2.1 Software Introduction

In order to design the model, CATIA V5, a software cad package was used. The model was exported in the format of a step file which is ready by Femap, a pre and post processor for NeiNastran. A short description of these packages is given as follows.

2.1.1 CATIA V5

CATIA (Computer Aided Three-Dimensional Interactive Application) is a multi-platform commercial software suite developed by the French company Dassault Systemes and marketed worldwide by IBM. The software was created in the late 1970s and early 1980s to develop Dassault’s Mirage fighter jet, then was adopted in aerospace, automotive, shipbuilding and other industries. CATIA provides products for intuitive specification driven modeling for solid, hybrid and sheet metal parts design. CATIA can simply and quickly create linear, curved structures, and plates, using standard or user defined sections. Taking advantage of an optimized user interface, the user can easily create and modify structures thanks to a fully associative design in context capability. CATIA addresses preliminary and detailed design requirements for products such as heavy machinery and equipment, tooling jigs, shipbuilding foundations, manufacturing plant foundations.

2.1.2 Femap and NeiNastran

Femap (Finite Element Modeling and Postprocessing) is an engineering analysis program sold by Siemens PLM Software that is used to build finite element models of complex engineering problems ("pre-processing") and view solution results ("post-processing"). It provided CAD import support, modeling and meshing tools to create a finite element model, as well as postprocessing functionality that allows engineers to interpret analysis results. The finite element method allows engineers to virtually model components, assemblies, or systems to determine behavior under a given set of
boundary conditions and is typically used in the design process to reduce costly prototyping and testing, evaluate differing designs and materials, and for structural optimization to reduce weight. NeiNastran is an engineering analysis and simulation software product of NEi Software (formerly known as Noran Engineering, Inc). Based on NASA’s Structural Analysis program, the software is a finite element analysis (FEA) solver used to generate solutions for linear and nonlinear stress, dynamics, and heat transfer characteristics of structures and mechanical components. Femap uses NeiNastran as one of the solvers for performing calculations.

### 2.2 University of Virginia (UVa) Supersonic Combustion Facility

The UVa Supersonic Combustion Facility shown in Figure 2.1 includes a vertically mounted direct connect, dual-mode scramjet test engine which consists of four major sections: nozzle (supply), isolator, combustor and the extender. The supply nozzle is connected to the oil free compressor and a desiccant air-drying system. A 300 KW, 14 stage electrical heater accomplishes air heating. The heater is capable of delivering vitiate free airflow of about 1200 K to the supply nozzle. The
convergent-divergent supply nozzle delivers a Mach 2 flow to the constant-area isolator. This directconnect nozzle is used to replicate the flow that an inlet would provide an isolator in an actual Mach 5 flight. The isolator ends where the fuel injector ramp begins. The compression ramp has an upward angle of 10 degree and height of the fuel injector at 0.25 inches. The rectangular combustor begins at the point of fuel injection. This is where the fuel mixes with the air and the combustor begins elevating the pressure inside the combustor. The reacting flow enters a 2.9 degree diverging extender nozzle where the remaining combustion takes place. The exhaust plume is caught by a catch cone which directs the exhaust flow out of the building. Each section is water-glycol cooled with approximate flow rates given in Figure 2.1.

Primary experimental data includes:

1. Static pressure transducer readings which describe the axial development along the flowpath

2. Static temperature thermocouple reading at discrete locations along the flowpath

Nominal flow rates are listed in Figure 2.1 of each section. The arrangement of coolant lines differs for each section as illustrated in Figure 2.2. Coolant lines are internal for the isolator, combustor and the extender. Each of the four walls of each section receives coolant flows. Due to the presence of
observation and side windows, coolant lines are routed through corners of north and south combustor walls. The temperature rise of the water-glycol coolant is measured for each individual line and may be converted into regional heat flux.

Figure 2.2 shows the various cooling channels in the different parts of the facility. Figure 2.3 shows the various materials and location of the windows in the different parts of the facility. The supply nozzle, isolator, west wall of the isolator and extender are made with Nickel 200. The inner isolator walls are coated with 0.4mm of zirconia coating. The north and south walls have side windows that do not span the entire width of the wall in the combustor. The west wall is the fuel injector wall. The fuel injector wall of the combustor section is made of Nickel 200, unlike the other walls and coated with zirconia to protect the inner walls from high temperatures. It also has internal parallel cooling channels. The east wall is opposite to the fuel injector wall. Here an observation window spans the entire width of the wall. All windows have a ceramic blank insert. The black bold lines show the flowpath perimeter for each face while the solid black lines are external cooling channels and dotted lines are embedded in the wall. The arrow shows the direction of the flow through the cooling channels.
Chapter 3

Constraints and Boundary Conditions

Figure 3.1: Catia Model of the UVa SCF
3.1 Assumptions

The assumptions made for the thermo-structural analysis are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Young Modulus, E (Pa)</th>
<th>Shear Modulus, G (Pa)</th>
<th>Poisson's Ratio, $\nu$</th>
<th>Expansion Coefficient, $\alpha$ (1/K)</th>
<th>Thermal Conductivity, $k$ (W/m-K)</th>
<th>Specific Heat, $C_p$ (J/kg-K)</th>
<th>Density, $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel 200</td>
<td>200 Gpa</td>
<td>76 Gpa</td>
<td>0.31</td>
<td>$f(T)$</td>
<td>$f(T)$</td>
<td>26.07</td>
<td>8908</td>
</tr>
<tr>
<td>Stainless Steel 304</td>
<td>193 Gpa</td>
<td>73.6 Gpa</td>
<td>0.32</td>
<td>$f(T)$</td>
<td>$f(T)$</td>
<td>500</td>
<td>8000</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>72 Gpa</td>
<td>31 Gpa</td>
<td>0.16</td>
<td>$5.5*10^{-7}$</td>
<td>$f(T)$</td>
<td>45.3</td>
<td>2230</td>
</tr>
<tr>
<td>Copper</td>
<td>110 Gpa</td>
<td>48 Gpa</td>
<td>0.34</td>
<td>$f(T)$</td>
<td>1.4</td>
<td>0.385</td>
<td>8940</td>
</tr>
<tr>
<td>Zirconia</td>
<td>200 Gpa</td>
<td>-</td>
<td>-</td>
<td>$12*10^{-6}$</td>
<td>$1.675$</td>
<td>-</td>
<td>5680</td>
</tr>
</tbody>
</table>

1. The surface of the isolator where the facility nozzle is connected is considered to be fixed
2. In order to simulate the condition of 4 bolted flanges, the nodes between the flanges are merged
3. The nodes between the surfaces where the nickel and the steel walls are connected in the combustor are merged in order to simulate the effects of two different parts connected by bolts
4. The outer walls of the isolator, combustor, and extender are assumed to be adiabatic. Thermal radiation is neglected
5. Based on the limited available thermocouple data, isothermal conditions are imposed on the internal walls of the isolator, combustor, and extender. For the baseline model, the temperature on the inner walls of the observation and side windows are assumed to be at 1200 K. The temperature on the inner walls of the isolator, combustor, and extender are chosen to be 500 K. The temperature on the coolant tubes was assumed to be at 350 K
6. The coolant temperature rise from the different walls of the facility was used to calculate the heat removed from each walls of the facility for each section, and then the average heat flux absorbed by each coolant line. Then, heat flux is fixed along the curved inner surface area of
Figure 3.2: Thermal Conductivity Data for Nickel 200 and Stainless Steel 304
Figure 3.3: Coefficient of Thermal Expansion of Nickel 200 and Stainless Steel 304
the coolant tubes in the thermo-structural model to match the total experimentally-measured heat absorption by the coolant tubes.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temp Rise</th>
<th>Heat flux</th>
<th>Heat flux/Unit area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustor, Injector wall</td>
<td>9.75 K</td>
<td>3.35 kW</td>
<td>-595 kW/m²</td>
</tr>
<tr>
<td>Combustor, North Side wall</td>
<td>3.98 K</td>
<td>1.41 kW</td>
<td>-345.7 kW/m²</td>
</tr>
<tr>
<td>Extender, Injector wall</td>
<td>10.24 K</td>
<td>3.70 kW</td>
<td>-736 kW/m²</td>
</tr>
<tr>
<td>Extender, North Side wall</td>
<td>10.44 K</td>
<td>3.57 kW</td>
<td>-710.228 kW/m²</td>
</tr>
</tbody>
</table>

7. The material data for Nickel 200 and Stainless Steel 304 was considered to be non-linear with temperature. Due to the large temperature range considered, temperature dependent data for thermal conductivity, specific heat capacity, and thermal expansion are used to obtain more accurate thermal response, and thermal deformation. Material data is given in Table 3.1, Figure 3.2 and Figure 3.3.

8. For the baseline model, ten-noded tetrahedron elements with element size of 2 mm were used in order to generate the mesh in Femap. A uniform mesh was made over the entire geometry. In ANSYS, tetrahedron elements were used, along with refinement in order to refine the mesh in key areas such as the coolant tubes and near joints. This was done in order to evaluate grid sensitivity. Figure 3.4 shows the isotropic grid generated in Femap. Figure 3.5 shows a coarse version of the mesh generated by ANSYS. The total number of nodes for each mesh was approximately 200,000.

9. Contact elements were used at the isolator-combustor and the combustor-extender joints. This was done to accommodate potential sliding along the joints. The sliding along the joints was assumed to be small; hence, a linear static structural analysis was considered.

3.2 Analysis Procedure

The procedure for thermo-structural analysis is given as follows:

1. CATIA, a CAD package was used to model the various parts of the Scramjet Combustion Facility. The model was saved in *.stp (step) format and imported into Femap and ANSYS.

2. Once imported into Femap, the model geometry was cleaned for any sliver or spikes generated while translating the geometry from CATIA. Intersecting surfaces are created in order to have proper mapped meshing between the solids.
Figure 3.4: Femap Generated Mesh for Nastran (Medium Grid Shown)
Figure 3.5: Mesh Generated for ANSYS (Coarse Version of the Mesh Shown)
3. Isotropic material cards are made according to the material data available from MIL-Handbook [1]. Solid properties are defined from the material cards.

4. Meshing attributes are assigned to different parts of the geometry. These attributes define the materials that are assigned to the different parts of the geometry.

5. A uniform mesh sizing is given to the different parts of the geometry. The geometry is then meshed by using tetrahedron elements. Midside nodes are enabled in order to obtain better accuracy.

6. Once the geometry is meshed, the various constraints and boundary conditions mentioned in the previous part are applied.

7. Contact elements are created between the isolator-combustor and the combustor-extender joint.

8. The NeiNastran solver is used to conduct steady state thermal analysis. The result obtained from the solver gives the temperature distribution over the entire model. This temperature distribution is given as an input to static structural analysis.

9. The results obtained from the static structural analysis gives the total deformation taking place in the model. The deformations are measured at key areas: observation window, side window, isolator-combustor and combustor-extender joint.
Chapter 4

Baseline Results

4.1 Steady State Heat Transfer Analysis

Exterior Wall Temperatures – Clean Air

Figure 4.1: External Wall Temperature Data from UVa

Figure 4.1 shows the External Wall temperatures obtained at the thermocouple locations from UVa under Clear Air (non-vitiated) combustion conditions. Figure 4.2 and Figure 4.3 illustrates the steady state temperature distributions obtained for the baseline model. NeiNastran was used as the
Figure 4.2: Nastran Computed Steady State Temperature Distribution

The results show very high temperature on the inner walls of the observation window and side windows. However as we move away from the inner walls, the temperature decreases because of the effect of the coolant tubes. A key step in obtaining an accurate temperature distribution was to have minimum error in convergence. This was made sure by having proper contact and merging of nodes at the walls and the flanges. At the sliding joint, there is no direct transfer of heat at the joints except at the flanges. Hence the temperature on the combustor and the extender at the sliding joint are different.

4.2 Static Analysis

Figure 4.4 shows the static displacement distribution obtained with the temperature distribution and heat fluxes applied to the model. The thermal-structural analysis is uncoupled under the assumption that the structural deformation does not appreciably affect the heat loads. When observed closely, a forward facing step is observed along the combustor-extender joint (east wall) and a small
Figure 4.3: Section Cut of the Model Showing Temperature Distribution of the Windows

<table>
<thead>
<tr>
<th>Location</th>
<th>Experimental Data (K)</th>
<th>Analysis data (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream(Combustor)</td>
<td>475-500</td>
<td>490-500</td>
</tr>
<tr>
<td>OW Flange(Combustor)</td>
<td>380-400</td>
<td>400-406</td>
</tr>
<tr>
<td>Upstream(Extender)</td>
<td>375-400</td>
<td>370-430</td>
</tr>
<tr>
<td>Downstream(Extender)</td>
<td>350-375</td>
<td>380-396</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison Between Experimental Data Obtained from UVa and Analysis Data
Figure 4.4: Nastran Computed Static Displacement Distribution
Baseline Results: Key Area of Deformation

FORWARD FACING STEP AT THE COMBUSTOR-EXTENDER JOINT

Extender

Step Height
Max = 0.13 mm
Min = 0.09 mm

Combustor

Figure 4.5: Rearward Facing Step Between the Isolator and Combustor
Figure 4.6: Forward Facing Step Between the Combustor and Extender
rearward facing step along the isolator-combustor joint (east wall). The maximum step height at the isolator-combustor joint was measured to be 0.05 mm and the minimum step height was measured to be 0.012 mm. The maximum height at the combustor-extender joint was measured to be 0.13 mm and the minimum step height was measured to be 0.09 mm. The step height was measured by taking the difference of the z displacements of the nodes across the joint. Figure 4.5 and Figure 4.6 illustrates the various step heights between the joints. The reason for the steps to occur is related to the high temperatures present in the metal at the edges of the observation and side windows, and the difference in the coefficients of expansion between the dissimilar metals along the joint. Because of high temperatures, the stainless steel warps in the negative z direction, whereas nickel warps in the positive z direction. The stainless steel at the observation window appears to bow outward strongly to about 0.23 mm because of the high temperatures present on the internal surfaces. This deformation goes all the way up to the combustor-extender joint thus exposing the extender and creating a forward facing step. Also when observing the outer wall, it is seen that the combustor has bowed outwards thus expanding on the side walls. At the west wall, where the nickel-nickel connection is present, a smaller deformation is observed because the same materials are present along the joint, and the temperatures are moderate (500 K).
Chapter 5

Sensitivity Analysis

5.1 Grid Sensitivity Analysis

Grid sensitivity analysis was carried out on the model using the baseline boundary conditions and constraints. The number of nodes was varied from 77,000 to 600,000 and the corresponding step height across the combustor-extender joint was measured for each grid level. The grid was kept uniform over the entire model. One of the reasons for the grid sensitivity analysis was concern that
there is insufficient grid to resolve the non-linear temperature effects on the thermal and structural analysis. The grid is refined until the step height became constant with further increase in grid (as shown).

5.2 Temperature Sensitivity Analysis

Figure 5.2: Temperature Sensitivity Analysis

A temperature sensitivity analysis is carried out on the model. The temperature on the inner walls of the observation window and the side window is varied from 750 K to 1200 K due to the lack of thermocouple data available on the windows. The maximum temperature was set by the melting point condition of the material, and the minimum temperature based on data from nearby thermocouples. Thus, the sensitivity of step height to window temperature is evaluated.

5.3 Comparison with ANSYS Results

Figure 5.3 and Figure 5.4 show the results obtained from ANSYS steady state thermal and static structural analysis. The baseline boundary conditions and constraints and a medium grid of 200,000 nodes is used to carry out the analysis. The purpose of using ANSYS is to verify the
Figure 5.3: Steady State Thermal Analysis Results from ANSYS
Figure 5.4: Static Structural Analysis Results from ANSYS
results obtained in Nastran. Also there is a more efficient, direct coupling between the steady state heat transfer and static structural module from ANSYS using the ANSYS Workbench. The steady state temperature distribution and structural deformation obtained from ANSYS is similar to that obtained from Nastran. A forward facing step was obtained between the combustor-extender joint and a rearward facing step was obtained between the isolator-combustor joint. The maximum forward facing step was 0.127 mm and the maximum rearward facing step was 0.042 mm. Figure 5.5 and Figure 5.6 shows the rearward and the forward facing steps obtained from the static structural analysis from ANSYS. The difference between the ANSYS and the Nastran step height results is within 2-3 percent.
Figure 5.6: Forward Facing Step obtained from ANSYS
Chapter 6

CFD Analysis

As explained earlier, the impetus for this investigation is to determine the source of the large discrepancy for the axial pressure profile between Reynolds-Averaged Navier Stokes (RANS) simulations and experimental data in the vicinity of the combustor-extender joint, as documented in [11]. Consequently, the Wind-US CFD model developed in Ref [11] has been modified to incorporate a forward-facing step similar to that predicted in the present effort by the Nastran and ANSYS models. Specifically, the grid has been modified to include a 0.25mm forward facing step across the combustor-extender joint on the east wall. Although this deformation is somewhat larger than that predicted by the FEA models, we feel this deformation is within the uncertainties of the model prediction. The other, more subtle, deformation effects (e.g., across the isolator-combustor joint) are excluded. A modified grid (i.e., with the 0.25mm forward facing step) is used to recompute the flowfield for a subset of the cases involving different equivalence ratios (\(\phi\)), presented in Ref [11]. Specifically, the three clean-air (i.e., non-vitiated) cases involving \(\phi = 0.262, 0.342, \) and 0.451, respectively. The grid used in the previous study was modified to include the step, without increasing the total number of grid cells. All Wind-US model settings are retained from the previous study. Figure 6.1 illustrates the normalized static pressure development along the flowpath, at \(\phi = 0.262\), both with and without a 0.25mm forward-facing step deformation. The numerical and experimental pressure profiles are taken along the center of the west wall (i.e., injector side). The results for the model with the step deformation shows much improved agreement for the pressure profile in the vicinity of the combustor-extender joint (\(x/H = 25\)). The \(x/H\) parameter is the axial distance from the injector ramp base wall (\(x\)), divided by the injector ramp base wall height (\(H\)).

Figure 6.2 demonstrates the effect of the forward-facing step on the pressure field along the engine symmetry plane. Flow is from left to right and approaches the step at slightly above sonic (\(Mach \sim 1.1\)). The step of 0.25mm is roughly 1 percent of the distance across the flowpath shown here. The step creates a compression (weak shock wave) which affects a significant portion of the
Figure 6.1: Effect of Deformation on Axial Pressure Profile Predicted by Wind-US ($\phi = 0.262$)
flow along the east (lower) wall. Due to the blockage created along the lower wall, the flow expansion along the west (upper) wall is intensified.

Figures 6.3 and 6.4 illustrate the normalized static pressure development along the flowpath, at $\phi=0.342$ and $\phi=0.454$, both with and without a 0.25 mm forward-facing step deformation. Again, the numerical and experimental pressure profiles are taken along the center of the west wall (i.e., injector side). The results for the model with the step deformation show perhaps slightly better agreement for the pressure profile in the vicinity of the combustor-extender joint ($x/H = 25$) for both equivalence ratios. These results suggest that the effect of the forward-facing step is much more subtle for the higher cases than for the $\phi=0.262$ case. This trend may be related to the engine mode, which has been established as ramjet mode for $\phi=0.342$ and $\phi=0.454$, and scramjet mode at $\phi=0.262$. The flow speed approaching the step is lower Mach number, approximately sonic at $\phi=0.342$, and high subsonic at $\phi=0.454$. We speculate that the subsonic flow reaching the step is likely to cause a weaker compression wave, and related expansion along the west wall.
Figure 6.3: Effect of Deformation on Axial Pressure Profile Predicted by Wind-US ($\phi = 0.342$)
Figure 6.4: Effect of Deformation on Axial Pressure Profile Predicted by Wind-US ($\phi = 0.454$)
Chapter 7

Conclusion

Thermal deformation effects are shown to be likely responsible for the discrepancy between Wind-US numerical simulation and experiment in the vicinity of the combustor-extender joint. A small forward-facing step is predicted to occur due to dissimilar materials operating at different temperatures. To improve simulation fidelity, a more extensive set of thermocouple data would be desirable.
Bibliography


