Chapter Eight: Summary and Conclusions

A computational study investigated the performance of three different $K-\varepsilon$ turbulence models, the Chien variant of the canonical $K-\varepsilon$ and two new models derived from renormalized group theory. The turbulence models were tested on boundary layer flow over a supersonic flat plate as well as on the more complex flows of two candidate injectors for supersonic injection and mixing. The objectives were to code the new $K-\varepsilon$ models, to test these models in comparison with the standard $K-\varepsilon$ against experimental data and theoretical correlations, to use both the traditional and RNG $K-\varepsilon$ models to provide reliable computational solutions for the injector flowfields, and to use those solutions to gain insight and understanding into the design and performance of one of the candidate injectors, the novel nine-hole injector array. This array injected sonic helium into air at Mach 3.0. The second candidate injector was an unswept ramp, which injected a mixture of helium and air at Mach 2.669 into air at Mach 4.5.

Calculations for this series of investigations were performed using GASP™ version 2.2, and the new turbulence models were coded for insertion into the turbulence routines for this commercial code. Though parabolic (space-marching) solution was possible in some portions of the flowfields, most computations were performed with global iteration. Mesh sequencing was used as a technique for convergence acceleration and for the investigation of grid independence. Two-level mesh sequencing was employed for the two-dimensional flat-plate test case, with three-level mesh sequencing for the more complicated injector calculations. The finest mesh for the flat plate case had 40,000 computational cells. For the injector array the finest mesh had 926,080 cells, and the finest mesh of the ramp injector had 6,018,048 cells. In all cases the y^+ at the center of the first cells adjacent to walls was on the order of 1.0 or lower.

The data from the flat-plate calculation was compared with Van Driest empirical correlations for supersonic boundary layers. The injector array helium mass-fraction data was compared to data from a comparable experiment. For the ramp injector helium mass fraction, stagnation temperature, and total pressure recovery were all compared to experiment.

The following conclusions can be drawn from the investigation:

1. Grid convergence was proven for the two-dimensional flat-plate boundary-layer calculation. For this case the "fast" RNG $K-\varepsilon$ model returned a solution identical to that of the more standard Chien $K-\varepsilon$ model, as was expected. Both solutions compared well with Van Driest correlations.
2. Despite attempts to adequately resolve the many small-scale details of the injector flowfields, grid convergence was not proven in either three-dimensional case. This is not an unexpected result, given the complexity of the flowfields, the computational costs involved in resolving such complexity, and the finite resources available for this study. Furthermore, rigorous proof of grid convergence of the finest meshes would require comparisons with solutions generated with still finer meshes, which were not available in this study. The comparison with solutions generated with coarser meshes provided only an approximate answer to the question of grid convergence, and should not be viewed as providing absolute proof of a lack of grid convergence.
3. In both the nine-hole injector array and ramp injector calculations, the nearfield solutions appear much closer to grid convergence than do the farfield data. One explanation of this phenomenon is that grids are clustered to provide smaller cells in areas of geometric and aerodynamic complexity as they occur in the nearfield, and that these smaller cells enhance grid convergence. Another explanation is that, in injection and mixing studies such as these, the flowfield in the vicinity of injection is primarily influenced by inviscid effects, which are less sensitive to cell size than are viscous effects. Further downstream grid clustering is relaxed and

viscous effects become more significant, making grid convergence more difficult to achieve.

4. The ramp-injector calculations show stronger tendencies toward grid convergence than do the injector-array calculations, as measured by similarity of peak mass fractions and by overall comparison of helium and pressure contours. This result is consistent with the larger size of the ramp-injector grid, but may be somewhat unexpected given the differences in mesh sequencing. (The fine mesh was four times larger than the medium for the array calculation, but eight times larger for the ramp.) For this reason the ramp-injector calculations were chosen for a more detailed turbulence model comparison.

5. Data from the injector-array calculations indicated that differences between the Chien $K-\varepsilon$, "fast" RNG $K-\varepsilon$, and "mixing" RNG $K-\varepsilon$ solutions were very minor in all meanflow variables. When the ramp data was used to investigate the differences between the Chien and "mixing" RNG $K-\varepsilon$ solutions, meanflow data was likewise similar but larger differences were discovered in turbulence variables in isolated portions of the flowfield. In regions of high eddy viscosity the "mixing" RNG value was frequently two to five percent higher than the Chien equivalent, and occasionally the differences were as large as ten or twenty-five percent. However, even in the locations where the two turbulence models returned significantly different values of eddy viscosity, the differences in meanflow variables, including mass fraction, were almost always insignificantly small. These results, combined with an understanding of the velocity-gradient dependence of RNG $K-\varepsilon$, suggest that the RNG additions to the turbulence equations produce substantial changes in the eddy viscosity field primarily in regions of strong meanflow gradients. The results further suggest that in these regions of strong meanflow gradients inviscid effects are likely to dominate the viscous terms in the meanflow equations, masking most of the details of the turbulence model.

6. Comparison of the injector-array data with helium mass fractions from experiment were not favorable. While the general shape of the helium plume was captured, calculations with all turbulence models vastly overpredicted helium mass fraction throughout the plume, as well as the plume height. The failure to prove grid convergence for this case, particularly in the farfield region where experimental data was taken, provided the best explanation of the poor comparison. However, a number of other explanations were possible, including poor turbulence modeling.

7. Comparison of ramp-injector data with helium mass fraction, total temperature, and total pressure data was rather favorable, given the difficulties involved in data collection and the absence of wind-tunnel side-walls in the computational domain. Prediction of plume penetration, peak helium mass fraction, maximum and minimum total temperature, and total pressure recovery were well within the bounds of experimental error. Comparison with experiment were more favorable at the first measurement station (ten ramp heights downstream of injection) than at the second (twenty ramp heights downstream). While there were some discrepancies, a strong argument has been made that the data collection problems were responsible for many of them, and some others were likely the result of sidewall effects, particularly at the second measurement station.

8. The most significant modeling error identified in the ramp-injector comparison appeared to be a consistent trend toward underdiffusion. Because turbulence effects dominated the laminar viscosity in this flowfield, underdiffusion was most likely the fault either of the turbulence model itself or of the treatment of turbulent diffusion. Solutions returned by the “mixing” RNG $K-\varepsilon$ turbulence model were in better agreement with experiment than those of the Chien $K-\varepsilon$ in most cases, but differences between the two computed solutions were small enough to be negligible.

9. “Fast” RNG $K-\varepsilon$ required approximately 1.5 times as much CPU time per iteration as did Chien $K-\varepsilon$, and “mixing” RNG $K-\varepsilon$ required

1.7 times as much. These values represent a significant expense, though more careful coding might reduce them somewhat. Given the modest impact the RNG additions made on the $K-\varepsilon$ solutions and the large increase in cost, the merit of these turbulence models for calculations of this type remains dubious. A researcher might be better advised to invest the additional CPU time in a more resolved grid for use with Chien $K-\varepsilon$ or some other two-equation turbulence model.

10. Careful evaluation of data from the injector-array calculations provided a great deal of insight into and understanding of the performance of that candidate injector. Such evaluation was meaningful despite incomplete grid resolution and the poor comparison of the calculation with experiment, because the primary data of importance for performance evaluation was taken from the nearfield, where grid convergence was more complete, inviscid effects tended to dominate, and the quality of the computed flow solution was expected to be better. Insights gained from this evaluation include the following:

a) The low pitch angle of the first (most upstream) row of injectors produced a set of three interacting, oblique shocks. The flow disturbance caused by these shocks influenced the entire mixing region downstream. Any design modification should continue to minimize the pitch and yaw angles of the first-row injectors, to reduce flow blockage and minimize the size and strength of the resultant shocks.

b) The oblique shocks associated with the first row of injectors interacted in the spaces between the centerline and outer injectors, producing channels of air at high pressure. Downstream of the first-row injectors, this high-pressure air was driven downward by the shocks and turned into low-pressured wakes of nearly pure helium, which followed each first-row injector. Within the helium-rich outer wakes, the inflowing air met a counterflowing stream of air drawn from the opposite side and was forced to turn upward, though the helium plume itself. The resultant entrainment mechanism was quite advantageous to the mixing process, and should be preserved in any design modification. Possible threats to this entrainment mechanism are an increase in separation of the columns of injectors that could prevent the oblique shocks from interacting and, conversely, a decrease in the separation of the columns, which could strengthen the interaction of the shocks and decrease the flow rate of air between the injectors.

c) Flow in the wakes downstream of the first and second rows of injectors was subsonic and at places reversed. These wakes were regions of low static and total pressure, and likely increased drag. Nonetheless, such subsonic regions might be useful for flameholding in combusting applications.

d) Subsonic flow upstream of the second, centerline injector effectively prevented the formation of a second-row shock in the near-wall region, though a shock did form a distance above the wall where the first-row injectant plume encountered the more steeply angled second-row plume. The larger pitch angle of the second-row centerline injector increased the overall penetration rate of the centerline injector column, and was quite useful in this regard. A compromise must exist, therefore, between penetration angle and shock strength, to allow the greatest possible penetration without prohibitively large shock losses.

e) A strong shock did form on the centerward side of the second-row outer injectors, beginning at the wall itself. This strong shock was a consequence of the centerward displacement and yaw of the second-row outer injectors, which removed those injectors from the shelter of the first-row plumes' wakes and increased the frontal area. While this displacement and yaw were included in the injector design to imitate the shape of a swept ramp, there was no conclusive evidence that displacement or yaw was necessary for the formation or preservation of the aerodynamic structures primarily responsible for mixing. The degree of displacement and yaw are therefore first-order design variables for this injector concept, and any attempt at optimization should begin with an investigation of their importance in the development of relevant aerodynamic structures. It is possible that one or both could be minimized without degradation of performance, or that the two might be interchangeable to a degree.

f) The centerward displacement and yaw of the outer injectors of the third row, relative to those of the second-row, resulted in strong shocks forming at their upstream edges. These shocks allowed a strong interaction of all three third-row injectors and a near-total blockage of the air-channels between them. Flow ahead of the injectors near the wall was nearly stagnated across the injector width, from the centerline outward past the outer injectors, and injectant plume surface area (mixing area) was decreased. As with the second-row outer injectors, the displacement and yaw of the third-row outer injectors are first-order design variables and should be minimized at all costs.

g) A further consequence of the centerward displacement and yaw of the third-row outer injectors was the splitting of the third-row centerline plume into two distinct branches, one nearly vertical and the other nearly horizontal. The more vertical branch of the plume, having a lower mass flow rate than would an entire injector plume, lacked the momentum to increase penetration angle of the overall centerline plume beyond that established by the lower-angled, second-row centerline injector. The more horizontal branch became trapped in the boundary layer and mixed only slowing with the freestream air. Neither branch of the split plume accomplished the intended purpose. Once again it is imperative that the centerward displacement and yaw of the outer injectors of the third row be minimized. If minimization of displacement and yaw cannot prevent the plume splitting and flow stagnation problems, one possible solution is the complete removal of the third-row centerline injector. Such a change would reduce blockage without reducing penetration of the centerline plume.

h) Despite pitch angles that were in each row equal to those of the centerline injector, the plumes associated with the outer injectors never achieved penetration comparable to those of the centerline. In part this underpenetration may be the result of the entrainment of the outer-column plumes into the streamwise vortices which position they overlap. Nonetheless, a price was paid for the relatively high pitch angles, in the form of shock losses. There is reason to believe similar behavior of the outer-column plume might be achieved with lower pitched, and therefore more thermodynamically efficient, outer injectors. Such efficiency would be particularly important if centerward displacement and/or yaw of the outer injectors cannot be eliminated.

i) The mass flow rate of each injector relative to the others will affect plume interactions. Mass flow rates of the individual injectors can be controlled by altering total pressure or injector area. Increasing mass flow rate will give a particular injector added influence over the flowfield. Decreasing mass flow rate will have the opposite effect. In particular, mass flow rates might be adjusted to optimize penetration.

j) The nine-hole injector array did indeed produce a pair of strong, counter-rotating, streamwise vortices, which entrained air into the injectant stream and aided mixing exactly as anticipated. The key flow structures in the formation and preservation of these vortices were low-pressure, injectant-rich wakes downstream of the outer injectors of each row, shock-induced high-pressure regions above and centerward of the outer injectant plumes, and lower (though still elevated with respect to the wakes) pressures on the outside of the outer wakes.