Chapter One: Motivation and Introduction

Recent interest in high speed flight has created a need for improvements in injection and mixing in supersonic flows. One primary application is the injection and mixing of fuel in scramjet combustors, but there are a number of others. Among the other applications are thrust vectoring and controls (for example, on missiles), thermal protection and cooling (for example, of infra-red seeker domes), boundary layer control, noise reduction, skin friction reduction, and ejector optimization. Though research in supersonic injection and mixing has been underway for some time, the fields are active ones and ones in which much work is needed to satisfy vehicle development requirements. One particular application requiring improvements to current technology is supersonic combustors, for which there is an established need for mixing enhancement.[1]

Traditionally most data on injection and mixing in supersonic flows has come from wind tunnel tests, and such tests continue to be important today. Various injector models are painstakingly constructed and mounted in supersonic wind tunnels, and data is collected using whatever measurement system is both available and suited to the circumstances. Planar visualization data can come from traditional refractive and interferometric techniques as well as from modern laser-based imaging techniques. Probe and surface measurements are also useful, though the need for improvement of such technology exists, particularly in the areas of spatial resolution and survivability in extreme environments. Moreover, as problems of scheduling and expense are nontrivial in most every aerospace research facility, all measurements must be obtained at a minimal cost and in a minimal amount of time.[2]

It is apparent, therefore, that there is a need to reduce the time and expense involved in testing candidate injectors for mixing in supersonic flows, as there is a similar need in most other areas of aerodynamics[2]. While there are a number of relatively new measurement techniques, such as laser-based quantitative flow visualization techniques, that seem to offer help in this area[2], a great number of researchers are looking to computational fluid dynamics (CFD) for help. With the rapid evolution of faster, larger, and less expensive computers, there is hope that numerical simulations can be used in a synergistic way to support and expand upon wind-tunnel testing, reducing costs and development times for aerodynamic systems. This hope is not without basis, especially for test programs in which a thorough, spatially well-resolved, three-dimensional understanding of all flow variables is more important than precise numerical values of a given variable at a few points.[3]

Despite recent advances in CFD and with due respect for the optimism of its more enthusiastic proponents, computational fluid dynamics is a new and developing field, and many issues remain unresolved, especially in complex, highly viscous, multi-species, turbulent flows[3]. Among the issues identified as problematic are boundary conditions and grid distortion[3] and grid density[1, 3].

One of the more serious difficulties with CFD in its present state is turbulence modeling[3]. There are several levels of advanced approaches to the turbulence problem, all of which promise improvement at some level at some time[4,5]. Among the more widely known of the advanced approaches are more complex, "realistic" turbulence models, such as the Reynolds stress models[3, 4], and solution techniques such as Large Eddy Simulation[3, 5] and Direct Numerical Simulation[5], which seek to avoid turbulence modeling, either to as great an extent as possible or altogether, by use of increased grid resolution and advanced solution techniques. While these techniques show promise and one or all of them will probably be important to CFD in the future, they are at this time too expensive and too slow to serve the design needs of researchers in supersonic mixing[5].

Despite new approaches to turbulence modeling such as those discussed above, conventional eddy viscosity turbulence models are the ones most routinely applied in industrial applications[3]. Algebraic models such as Baldwin-Lomax and two-equation models such as

$\kappa-\varepsilon$ and $\kappa-\omega$ are perhaps the most popular forms. An enormous number of variations of each model exist, as researchers apply corrections intended to improve the performance of the standard models[6]. One class of variations are those derived from renormalized group theory (RNG), which applies complex wavespace mathematics to the equations of motion in order to derive from first principles modified versions of conventional turbulence models such as algebraic and two-equation models[7]. Such models, while little different from the *ad hoc* models they are intended to replace, have the distinct advantage of increased mathematical rigor. Their practical advantage, however, is for the most part yet to be proven.

Purpose and Objectives

The purpose of the current investigation is to conduct a systematic study of the performance of one common turbulence model and some of its newer variations in the computation of supersonic injection and mixing and to compare those computations to experiment, thereby to determine the usefulness of computational fluid dynamics in its present state and with that turbulence model for design studies of this type. The investigation involves two injector models chosen to be representative of widely investigated injector types, one flush-mounted injector and one "ramp"-type injector. The turbulence model chosen for the study is the $\kappa-\varepsilon$ model, with its variations derived from renormalized group theory. In keeping with the investigation of the current state of the art of CFD, a commercially available code, GASP™ Version 2.2 (produced by AeroSoft Incorporated) was used for all calculations. The canonical $\kappa-\varepsilon$ turbulence model was implemented as coded by the writers of GASP, and the renormalized-group-based turbulence models were coded and added by the author.

The objectives of the investigation are:

1) To provide reliable computational solutions for the flush-mounted and ramp injector flowfields using the $\kappa-\varepsilon$ turbulence

model. These solutions are intended to parallel the results of experimental investigations, with which they are to be compared.

2) To use those solutions to investigate detailed features of the injector-array flowfield not subject to experimental investigation.

3) To code a $\kappa-\varepsilon$ turbulence model derived from renormalized group theory and to modify it to suit the current investigation.

4) To expand the computational program described in the first objective (above) to include calculations using the renormalized-group turbulence models.

5) To compare the performance of the various turbulence models on the basis of accuracy (agreement with experiment) and efficiency for computations similar to the ones studied.

6) To gain insight and understanding about the issues, problems, and expectations of the computational fluid dynamics studies of supersonic injection and mixing.

Outline

This dissertation is organized in the following manner: Chapter Two reviews the published literature concerning supersonic injection and mixing and introduces the injectors to be studied in this investigation. Chapter Three reviews turbulence modeling and explains the conventional and RNG $\kappa-\varepsilon$ models employed in this investigation. Chapter Four provides details of the numerical simulations themselves. Chapter Five examines the issues of convergence and grid convergence of the numerical solutions. Chapter Six compares the solutions generated by the different turbulence models to the other solutions and to experiment. Chapter Seven provides a detailed analysis of the performance of the nine-hole array injector, and Chapter Eight consists of results and conclusions.