Phase I Project Summary

Firm: CFD Research Corporation
Contract Number: NNX12CF18P
Project Title: An Eulerian Transported PDF Method Framework For Scramjet Flowpath Analysis And Design

Identification and Significance of Innovation

Scramjet engines promise to become a next-generation revolutionary technology for aerospace applications. Some of the significant challenges in rapid development of scramjets include complex flow physics; design methods; propulsion air-frame integration; difficulty of producing realistic experimental conditions. The role of Computational Fluid Dynamics (CFD), therefore, is crucial in design and development of the scramjet engines. The proposed innovation includes development of a comprehensive Eulerian Transported PDF (TPDF) methods framework coupled with efficient RANS/LES flow solvers for simulating high-speed turbulent reacting flows and an innovative chemistry acceleration module. In Phase I of this project we developed and demonstrated two Eulerian TPDF methods 1) A Stochastic Eulerian Fields method (SEF) and 2) a Multi-environment Eulerian PDF method (MEPDF). It was found that the Eulerian Transported PDF methods are successful in simulating subsonic and supersonic reacting flows with moderate-to-strong turbulence-chemistry interactions. The Eulerian TPDF methods will significantly improve the accuracy of current combustion simulation codes, while taking advantage of existing CFD-framework including higher-order temporal and spatial discretization schemes, among other things.

Innovations from this Project:

1. Development of an Eulerian TPDF framework for using the SEF and MEPDF approaches for simulating turbulent reacting flows.
2. Development of subsonic and supersonic reacting flow solvers which can utilize the SEF and MEPDF approaches
3. Validation of the solvers in canonical configuration (jet-flames) in both subsonic and supersonic regimes
4. The SEF and MEPDF methods were applied successfully to a Mach 1 hydrogen jet flame in a Mach 2 vitiated air and show better predictions than pure finite-volume simulations.

Technical Objectives and Work Plan

The overall obnective of this work is to develop a comprehensive turbulent combustion modeling framework based on Eulerian TPDF methods. In Phase I the feasibility of the proposed Eulerian TPDF approach for accurately and efficiently modeling turbulence-chemistry interactions has been demonstrated. Specific objectives of Phase I included the following:

1. Develop a basic Eulerian Transported PDF framework for modeling supersonic turbulent combustion.
2. Identify and implement specific extensions to the transported PDF approach for accurately modeling turbulent, high-speed, compressible reacting flows.
3. Analyze and quantify the differences between the SEF and MEPDF versions of the Eulerian PDF methods in the context of high-speed reacting flow.
4. Demonstrate the efficacy of transported PDF methods in modeling supersonic turbulent reacting flows in canonical configurations (jet-flames) and for typical scramjet type applications.

Technical Accomplishments

All technical objectives of Phase I have been accomplished by the SBIR team. The major achievements include

1. A powerful Eulerian transported PDF (ETPDF) methods framework has been developed for simulating subsonic and supersonic turbulent reacting flows. Two main variants of the ETPDF namely, SEF and MEPDF have been implemented into the reacting flow solvers for both subsonic and supersonic reacting flow simulations.
2. Both MEPDF and SEF methods perform well in predicting the MEAN and RMS values, in turbulent reacting flows.
3. The Stochastic Eulerian Field Method, (SEF) method is very computationally expensive, and can take anywhere from 10-20 times more clock-time compared to the pure Finite Volume (FV) simulations. But it was found to be better able to capture the RMS fluctuations in species and temperature values.
4. The MEPDF method can be as little as twice as expensive as a pure FV run, and is still able to capture the mean and RMS values with reasonable accuracy. The MEPDF method, therefore, holds the maximum

promise for applicability to large-scale three-dimensional fine-grid RANS and LES simulations.

5. The Eulerian PDF methods performed very well when applied to a supersonic H2-air jet flame.

Results show a highly successful Phase I effort with significant potential payoff in the Phase II, where the models will be further developed and applied in production environments.

Potential NASA Application(s):

The tools developed in this SBIR project will be directly useful to NASA's Hypersonics Program. The methods developed under this project will have wide ranging applications at NASA. In addition to high-speed combustion devices such as ramjets and scramjets, design of propulsion devices such as solid rocket motors, liquid rocket engines and gas turbine combustors can benefit from these tools. The Eulerian transported PDF methods are an area of active research and have excellent promise to provide accurate and computationally tractable models for complex turbulence-chemistry interactions.

Potential Non-NASA Application(s):

The software tool developed in this project will significantly improve the accuracy and reduce turnaround times for design and analysis cycles for high-speed combustion applications such as supersonic combustion ramjets. It will also be useful for simulating low-speed combustion devices such as gas turbine combustors and augmenters. The technology will facilitate significant advancement in use of CFD analysis in applications including propulsion devices, gas-turbine combustors and other combustion devices. The software will be beneficial to OEMs such as GE, Pratt & Whitney, Williams International, and Rolls Royce in designing various propulsion devices and gas turbine combustor components. It will be a valuable tool for all industries that require CFD simulation of reacting flows in a hardware design process. Modules developed in this project will also be of interest to commercial CFD OEMs for integrating with their own simulation software.