Phase II Project Summary

Firm: CFD Research Corporation
Contract Number: NNM07AA85C
Project Title: Advanced Non-Gray Radiation Module in the LOCI Framework for Combustion CFD

Identification and Significance of Innovation:
NASA Marshall Space Flight Center (Huntsville, AL) will be the lead center for designing launch pads for Ares-I and Ares-V rocket crew launch vehicle systems, as part of Project Constellation space exploration initiative. Prior experiences have demonstrated that it is necessary to maintain the components of the solid rocket motor (SRM), the launch vehicle and the launch pad within acceptable temperature ranges before and during launch. In this context, radiative heat transfer from particulates present in high concentrations in an Ares SRM plume can be a significant part of the total heat transfer to the launch pad and the base of the first stage. Radiation modeling is also needed to accurately predict gas temperatures and heat loading on the combustor walls when using fuels such as methane, under the proposed in-situ resource utilization (ISRU) on Martian surface. As such, neglecting radiation in the above situations can lead to serious inaccuracies in heat flux predictions and thereby, to design flaws. The Loci framework and the combustion modeling code CHEM, developed at Mississippi State University (MSU) with NASA support, are both in use at NASA to simulate reacting flows in rockets motors. However, the Loci framework currently does not have any radiation modeling capabilities. In this STTR project, CFDRC and MSU have teamed to develop an innovative, robust and computationally efficient radiation module in Loci for modeling both gray and nongray gas radiation, providing NASA with state-of-the-art radiation simulation capabilities. The focus in Phase I was to demonstrate feasibility by developing a radiation module in Loci using proven and widely accepted models. Phase II involved developing innovative and accurate models for gaseous and particulate radiation. As a result of this Phase II STTR project, NASA and the OEMs will have an innovative, comprehensive, well- verified and -validated radiation modeling tool in Loci-CHEM.

Technical Objectives and Work Plan:
Radiative heat fluxes are important in combustor/rocket systems and launch pads to be designed by NASA/MSFC under Project Constellation. In this STTR project, CFDRC and its partner Mississippi State University have developed an innovative, comprehensive, high fidelity radiation module in the Loci CFD framework that will enable NASA to obtain accurate physical insight into radiation issues. In Phase I, we successfully demonstrated the feasibility of developing an accurate, highly scalable (in terms of parallel computing) radiation module in Loci-CHEM. This well-validated module contains gray gas model, as well as simplified nongray and particulate radiation capabilities, and has been successfully applied to a nominal SRM demonstration case. The Phase II effort consisted of: 1) Implementing more accurate, robust nongray and particle radiation models, 2) Increasing tool-fidelity by developing innovative methodologies to minimize modeling uncertainties, 3) Formally verifying the module using the Method of Manufactured Solutions (MMS), and, 4) Validating the module and applying it to cases of direct relevance to NASA. As a result of this STTR project, NASA will have a comprehensive suite of radiation modeling capabilities that will help design safer and more efficient rocket-propelled vehicles of the future.

Technical Accomplishments:
In this STTR project, an efficient and well-validated computational module to predict nongray gaseous and particulate radiative heat transfer was implemented in Loci-CHEM. The relative accuracy of a number of wide band, narrow band and weighted-sum-of-gray-gases radiative property models was investigated in predicting radiative transfer through both homogeneous and inhomogeneous nongray gaseous media. The detailed Mie's theory was implemented and verified for calculating particulate radiative properties such as the absorption and scattering coefficients, as well as the isotropic and anisotropic scattering phase functions. The Control-Angle Discrete Ordinates Method (CA-DOM) RTE solution algorithm was verified using the Method of Manufactured Solutions (MMS). A highly efficient line Gauss-Siedel method-based linear system solver algorithm was implemented. The new algorithm was demonstrated to be significantly faster than the PETSc solver with a speedup in excess of an order of magnitude. The non-gray gaseous and particle radiative property models were validated against benchmark data. The coupled

Loci-CHEM-radiation code was applied to a demonstration case of relevance to NASA. As a result of this Phase II STTR project, NASA will have an innovative, robust, scalable, comprehensive, well validated and verified nongray gaseous and particle radiation modeling capability.

NASA Application(s):
As part of Project Constellation, NASA/MSFC is embarking upon the design of launch pads for the Ares rockets, in which radiative heat fluxes from the solid rocket booster (SRB) plume to the launch pad must be considered. For Ares-V, in particular, challenges exist in simultaneously predicting the multiple plume environments, including gas-generator dumps, RSRM-V plume and overall heat transfer to the base of the first stage. Heat loading on combustor walls due to gaseous radiation can also be important with hydrocarbon fuels, such as the methane-oxygen combustion in the proposed in-situ resource utilization (ISRU) on the Martian surface. The LOCI radiation module will enable NASA and government contractors to better design and analyze rocket engine combustion systems, including the new cryogenic rocket engines needed for In-Space Propulsion.

Non-NASA Commercial Application(s):
The LOCI-Chem radiation module will have a wide appeal to rocket engine manufacturers and universities developing rocket engine technology (e.g. Purdue, Penn State, UAH, etc.) under the CUIP Program. The LOCI suite of codes (e.g. LOCI-Chem, LOCI-Stream, etc.) has become an important design/analysis tool at NASA, and NASA's primes are beginning to show interest and use the LOCI codes, such as ATK, Pratt & Whitney, and Aerojet. As an example, a support letter is included from ATK, showing their intent of assessing the LOCI-Chem radiation module. In addition to the LOCI-Chem radiation module, a stand-alone radiation module will be developed for commercialization in other CFD codes. Pratt & Whitney Rocketdyne has expressed interest in implementing the radiation module into their in-house CFD code, and purchasing the module following successful demonstration (support letter included). Another source of revenue will come from implementing the radiation module into CFDRC's DREAM code, a next generation combustion LES code for gas turbine combustor/augmentor analysis. A number of gas turbine OEMs are interested in the DREAM code, and will purchase it following successful demonstration in an AFRL-sponsored SBIR.

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