RADIATION-TURBULENCE INTERACTIONS IN PULVERIZED-COAL FLAMES

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Preface

This is the sixth quarter Technical Report for of the project titled "Radiation-Turbulence Interactions in Pulverized-Coal Flames", which is funded by the Department of Energy, Pittsburgh Energy Technology Center (Grant #DE-FG22-93PC93210). The report covers the period from March 15, 1995 to June 15, 1995.

Two research associates, two Ph.D. students, and one M.S. student are involved in this project. Additional support for these researchers and the students has been received from a DOE Grant #DE-FG22-92PC533 (PI: M. P. Mengüç), from a NSF-EPSCoR Grant (PI: J.M. McDonough), and from the Department of Mechanical Engineering at UK.

Dr. Sivakumar Manickavasagam, a Research Associate, is primarily responsible for combining the fluid mechanics and radiative transfer computer codes. He is also in charge of developing a new algorithm to account for the soot agglomerate structure and char fragmentation. He and Dr. Sarbajit Ghosal, also a Research Associate, are responsible in designing the experimental system for future measurements.

Mr. Sudip Mukerji, a Ph.D. student, is developing the computer codes for simulation of turbulence using the additive turbulent decomposition (ATD) technique in two and three dimensional geometries. Mr. Derong Wang, another Ph.D. student is primarily supported by a NSF/EPSCoR project. He is modeling the interaction of radiation beam with small scale ATD technique.

Mr. Ramaswamy Govindan is a M.S. student. He has worked on a model to couple radiation turbulence interactions in our flames. In addition to that, he is developing a new optical system to identify particle properties from their polarized scattering characteristics. He is supported mainly by the DOE Grant #DE-FG22-92PC533 and the Department of Mechanical Engineering.

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Contents

1	EXPERIMENTAL STUDIES	1
2	NUMERICAL SIMULATIONS	1

1 EXPERIMENTAL STUDIES

The experimental system has been completed and we have started collecting the preliminary data. The experiments are conducted to obtain data on angularly scattered light intensity as a function of time (referred to as time series). This variation in recorded intensity is related to transience of the scattering particles (soot, char) in the control volume. A comprehensive computational model on radiation-turbulence interaction will be used to explain the data.

The time series are obtained by making single-shot measurements at the rate of thirty data points per second (i.e., at laser pulse frequency). The experiments were carried out using ethylene flame. Additional experiments were performed by feeding coal particles into the ethylene flame. Measurements were taken at 45° at several different flame heights. The data were analyzed and power spectra density and delay maps were plotted.

Figure 1 depicts these two plots at one location in the flame. Figure 2 shows the same for a theoretical chaotic map. The experimental data suggest that the flow is definitely turbulent. The similarity between these two figures is indication of the chaotic behavior of the turbulent combustion.

Currently the data are being interpreted for more careful conduction of future experiments.

2 NUMERICAL SIMULATIONS

The governing partial differential equations (the Navier-Stokes equations) have been transformed into ordinary differential equations (ODEs) based on the Fourier-Galerkin spectral technique described in previous reports. Additive turbulent decomposition (ATD) procedure is being used to solve these equations. At present only the three small-scale momentum equations are being solved to speed up the code debugging process. The energy equation and the compressible continuity equation have been coded but are not being solved at present. Over the past several months extensive debugging and evaluation of the computer code has been carried out. This has involved some rewriting and other enhancements to the code.

As has been mentioned before, ATD is a highly parallelizable algorithm. This aspect of ATD is being exploited from the very beginning. Parallelizability is important to fully utilize the opportunities offered by massively parallel processors (MPPs) which present the only hope of solving realistic turbulent flow problems in the near future. Many different levels of parallelization are possible in ATD and at present only a coarse-grained parallelization of the ODE right-hand side solves is being implemented.

The present small-scale code has been parallelized successfully under both distributed

memory and shared memory paradigms. Parallelization speedups obtained on a 8-processor distributed memory Convex-HP MetaSystem using PVM for message passing are shown in Figure 3. Figure 4 shows speedups obtained on a 24-processor shared memory Convex-HP Exemplar. The results indicate that the speedups achieved with multiple processors scale essentially linearly with the number of processors. This implies that with the availability of true MPPs the ATD algorithm can perform full three-dimensional turbulence simulations in physically realistic situations.

At present only the small-scale equations are being solved with parameterized inputs from the large-scale. The particular flow problem under consideration for testing the code is a three-dimensional turbulent jet. The flow is incompressible and the fluid has constant properties close to those of air: $\rho = 1.0 \text{ kg/m}^3$ and $\mu = 1 \times 10^{-6} \text{ Ns/m}^2$. The jet diameter of 10 mm. is the reference length and the total axial length of the domain is 760 mm.. The jet velocity at the inlet is 5.0 m/s giving an inlet $Re = 5 \times 10^4$. The large-scale solution is obtained from a finite volume commercial CFD code on a $13 \times 14 \times 81$ grid.

Figure 5 shows the large-scale solution and the location of the small-scale subdomain. The subdomain has a small radial offset and its axial position is halfway between the inlet and outlet. This gives a non-dimensional axial location of 38 which is well beyond the potential flow core and in the region of fully developed turbulence. Adequate resolution on the small-scale was obtained by $N = (7, 7, 7)$ Fourier modes. The choice of the small-scale time step was dictated by the stiffness of the problem and the explicit nature of the solution method; it was set to 2×10^{-6} sec. to maintain stability.

Small-scale turbulence solutions were obtained by allowing the code to perform time integrations for longer times corresponding, approximately, to the large-scale time scale. Figure 6 shows the time series of a small-scale velocity component at a location in the center of the small-scale subdomain. The time series shows strong residual periodicity with a time scale of about 2 ms.. This is probably to be expected in a region where the jet profile is self-similar. Moreover, these fluctuations are truly small-scale having magnitudes of order 10^{-4} compared with $\mathcal{O}(1)$ for the large-scale velocity.

For the present test problem with parametrized large-scale inputs the code appears to perform well. These parametric studies are continuing to test the code over a wide range of Reynolds numbers and different flow situations.

Figure 1: Experimental data: (a) Power spectra density vs. frequency, and (b) the Delay Map.

Figure 2: Theoretical Chaotic Map: (a) Power spectra density vs. frequency, and (b) the Delay Map.

Figure 3: Parallelization speedup on Convex-HP Metasystem

Figure 4: Parallelization speedup on Convex-HP Exemplar

Figure 5: Large-scale flowfield and location of small-scale domain

Figure 6: Time series of small-scale velocity