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Quarterly Technical Progress Report

(September 1, 1994 to November 30, 1994)

A COMPUTATIONAL MODEL FOR COAL TRANSPORT AND COMBUSTION

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A COMPUTATIONAL MODEL FOR
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Project Period: September 1, 1991 to March 12, 1995

Contract Recipient: Clarkson University

Project Principal Investigator: Goodarz Ahmadi

DOE Project Officer: Dr. Mehrdad Massoudi

SUMMARY

In the period of September 1, 1994 to November 30, 1994, further progress was made in the analysis of granular materials in ducts and passages with bumpy walls. The analysis of gravity chute flows was completed.

Additional results on flows of gas-solid mixtures in vertical ducts were obtained. The results were compared with the experimental data of Tsuji an co-worker and Miller and Gidaspow and good agreement was obtained. The computational model was used to study two-phase flows in a horizontal duct.

Significant progress was made in the formulation of chemically active two-phase solid-fluid flows. The experimental study of mono-granular layer simple shear flow device was completed. Preparation of the final report was initiated.

PROGRESS REPORT

GENERAL

The research works of the project are successfully completed. Since the final report is being currently preparation, a short quarterly report is submitted.

OBJECTIVES

The objective of this project is to develop an accurate model describing turbulent flows of coal slurries, rapid flows of granular coal-air mixtures, and turbulent coal combustion processes. The other main objective is to develop a computer code incorporating the new model. Experimental verification of the foundation of the model is also included in the study.

SIGNIFICANCE TO FOSSIL ENERGY PROGRAM

A completely satisfactory theory describing the bulk coal transport including the interstitial fluid effects does not exist. This is particularly the case for turbulent flows of dense coal particle-liquid mixtures and chemically active coal combustor flows. Coal slurry and bulk transports, and operation of coal combustors accounts for a substantial portion of the cost of coal energy conversion systems. The major increase in cost arises from the need to over-design these facilities to guarantee reliability. Understanding the flow behavior of relatively dense coal slurries and bulk solids in various geometries including coal combustors, are indispensable to economical design of the needed equipment. This project aims to develop a sound practical model for coal transport and combustion. In addition, a computational predictive capability for analyzing rapid flows of granular coal particles, and reacting and non-reacting turbulent flows of dense or dilute multiphase coal mixtures will be provided.

HIGHLIGHT OF THE EARLIER ACCOMPLISHMENTS

An experimental setup for generating simple shear flows of a mono-granular layer was designed and fabricated. A complete set of Experimental data for mean velocity, fluctuation energy and solid volume fraction for shearing of 12 mm multi-color glass particles were obtained.

Thermodynamically admissible expressions for the phasic stress tensors, heat and fluctuation energy flux vectors for turbulent multiphase flows were derived. The material parameters of the model were evaluated from the limiting conditions of rapid flows of dry spherical granular particles, and single-phase turbulent fluid flow. The case of simple shear flows of glass beads-water mixtures was studied.

A thermodynamically consistent model for rapid flow of granular materials in a rotating frame of reference, along with a transport equation for the granular kinetic stress tensor were developed. The model parameters for the special case of spherical nearly elastic particles were evaluated. The results for the granular stresses and the normal stress differences were compared with the available simulation data and good agreement was observed.

Effects of frictional loss of energy on rapid granular shear flows were studied. The previously developed kinetic based model was used and the mean velocity, the fluctuation kinetic energy and the solid volume fraction profiles were evaluated under a variety of conditions and different friction coefficients.

A computational model for analyzing rapid granular in complex geometries was developed. The discrete element scheme was used and the granular flow down a chute was analyzed. The results were compared with the experimental data model prediction of Savage, and the existing simulation results, and good agreements were observed. The model was used to analyze granular flows in a duct with an obstructing block.

A computational model for analyzing turbulent two-phase flows with various loadings was developed. The special case of gas-solid flows in a vertical duct was analyzed and the model predictions were favorable compared with the available experimental data. Extension of the computational model to horizontal duct is also considered.

COMPUTATIONAL MODEL DEVELOPMENT

The goal of this phase of the study is to develop an appropriate computational scheme for solving granular and two-phase flows.

Granular Flows with Bumpy Boundary

The boundary condition is known to significantly affect flow and transport of granular materials. Here the effect of bumpy walls with roughnesses comparable to the size of the particle is studied. The kinetic model of granular materials including frictional losses is also used in the analysis. The presence of bumpy boundary conditions leads to a strongly coupled system of governing equations which has to be solved numerically even for the simple case of a Couette flow. As noted in the earlier report, a special discretization scheme for evaluating the granular flow field was developed. The computational model was used and the mean velocity, the fluctuation kinetic energy and the solid volume fraction profiles for granular flows between two parallel walls were evaluated. The results for different values of friction coefficients were presented in the previous report and were compared favorably with the molecular dynamics (MD) simulations of Savage and Dai (1992) for frictionless particles.

Granular Gravity Flows

Granular gravity flows over an inclined bumpy chute is an important flow and is often used as a bench mark for test of various theories. The earlier developed kinetic-based model for rapid flows of granular materials which includes the frictional losses of energy during particle-particle and/or particle-wall collisions is used for analyzing granular chute flows. The predicted mean velocity, fluctuation energy, and solid volume fraction profiles are evaluated and the results are compared with existing experimental data. A manuscript is prepared and is submitted to the Journal of Fluid Mechanics for publication.

TWO-PHASE FLOWS

As was noted in the previous report, a computational model for solving dense and dilute two-phase flows was developed. In this section, the computational model predictions for mean gas velocity, mean particle velocity, and phasic turbulence intensities for 0.5 and 1 mm particles are presented and compared with the experimental results of Tsuji et al. (1984) and Miller and Gidaspow (1992). In addition, the variations of phasic shear and normal stresses, as well as the phasic fluctuation energy production and dissipation are also evaluated. A manuscript is prepared and is submitted to the International Journal of Multiphase flows for publication.

The computational model was also applied to two-phase flows in a horizontal duct and the model predictions was compared with data of Tsuji et al. The results shows interesting features of the solid-gas flows in horizontal channel.

EXPERIMENTAL STUDY

As was reported in the earlier report, a mono-granular simple shear flow setup was constructed and was used for the experimental study. A collection of multi-colored spherical glass balls which are 12 mm in diameter were used as granular particles. A video camera is used to record the motions of particles. For different shear rates, the position of the balls in consecutive frames taken 1/30th of a second apart were measured. Using this technique, the velocity vector of each particle was calculated. Averaging procedures are used to provide the experimental velocity and concentration profiles. The experimental data for the mean velocity, RMS fluctuating velocities and the slip velocity variation are obtained. Preparation of the report for the experimental study is initiated.

CHEMICALLY ACTIVE TWO-PHASE FLOWS

Considerable progress is made in the formulation of a thermodynamically consistent model for chemically active two-phase flows. The equations governing the phasic conservation mass and energy, as well as the balance of momentum and fluctuation energy are derived. The appropriate form of the mean entropy inequality is obtained and is used for formulating thermodynamically consistent constitutive equations for chemically active multi-phase mixtures in a turbulent state of motion.

BIBLIOGRAPHY OF PUBLICATIONS EMANATING FROM THIS PROJECT

Journals Publications

G. Ahmadi and S.J. Chowdhury, "A Rate-Dependent Algebraic Stress Model for Turbulence," Applied Math. Modelling 15, 516-524 (1991).

H. Ounis and G. Ahmadi, "Motions of Small Particles in a Turbulent Simple Shear Flow Field Under Microgravity Condition," Physics of Fluids A 3, 2559-2570 (1991).

S. Abu-Zaid and G. Ahmadi, "A Thermodynamically Consistent Stress Transport Model for Rotating Turbulent Flows," Geophys. Astrophys. Fluid Dynamics 61, 109-121 (1991).

G. Ahmadi, "A Thermodynamically Consistent Rate-Dependent Model for Turbulence, Part I - Formulation," Int. J. Non-Linear Mech. 26, 595-607 (1991).

K.A. Elrais, W. Eckerle, G. Ahmadi and A.H. Eraslan, "Simulation of Transient Three-Dimensional Natural Convection and Saturated Pool Boiling, Int. J. Numerical Methods Heat Fluid Flow 2, 139-154 (1992).

S.J. Chowdhury and G. Ahmadi, "A Thermodynamically Consistent Rate-Dependent Model for Turbulence, Part II - Numerical Results," Int. J. Non-Linear Mech. 27, 705-718 (1992).

W.G. Paff and G. Ahmadi, "On Convergence of Karhunen-Loeve Series Expansion for a Brownian Particle," J. Appl. Mech. Trans. ASME 60, 783-784 (1993).

S. Abu-Zaid and G. Ahmadi, "A Stress Transport Model for Granular Flows in a Rotating Frame, Int. J. Engng. Sci. 30, 1483-1495 (1992).

S.J. Chowdhury and G. Ahmadi, "Analysis of A Mixing Layer by a Rate-Dependent Turbulence Model," ASCE, Journal of Engineering Mechanics 119, 1700-1706 (1993).

D. Ma, A.H. Eraslan and G. Ahmadi, "A Computer Code for Analyzing Transient Three-Dimensional Rapid Granular Flows in Complex Geometries, Computer Fluids 22, 25-50 (1993).

S. Abu-Zaid and G. Ahmadi, "Analysis of Rapid Shear Flows of Granular Materials by a Kinetic Model Including Frictional Losses," Powder Technology 77, 7-17 (1993).

S. Abu-Zaid and G. Ahmadi, "A Thermodynamically Consistent Rate-Dependent Model for

Turbulent Two-Phase Flows, Part I - Formulation," MAE Report-281 November (1993). Also submitted to Int. J. Non-linear Mechanics.

S. Abu-Zaid and G. Ahmadi, "A Thermodynamically Consistent Rate-Dependent Model for Turbulent Two-Phase Flows, Part II - Simple Shear Flows," MAE Report-282 November (1993). Also submitted to Int. J. Non-linear Mechanics.

M. Massoudi and G. Ahmadi, "Rapid Flows of Granular Materials with Density and Fluctuation Energy Gradients," Int. J. Non-linear Mechanics 29, 487-492 (1994).

J. Cao, and G. Ahmadi, "Numerical Simulation of Granular Couette Flows Between Two Rough Parallel Plates," MAE Report-274 July (1993). Also submitted to Particulate Science and Technology, An International Journal.

J. Cao, G. Ahmadi and M. Massoudi, "Gravity Granular Flows Down an Inclined Bumpy Chute with Friction," MAE Report-275 September (1993). Also submitted to Journal of Fluid Mechanics.

J. Cao and G. Ahmadi, "Gas-Particle Two-Phase Turbulent Flow in a Vertical Duct," MAE Report-285 February (1994). Also submitted to International Journal of Multiphase Flows.

Conference Presentations

G. Ahmadi and S. Abu-Zaid, "Overview of Thermodynamical Approach to Modeling Turbulent Flows of Two-Phase Solid-Liquid Mixtures," International Conference on Multiphase Flow '91-Tsukuba, Tsukuba, Japan, September 24-27, 1991.

G. Ahmadi and S. Abu-Zaid, "A Thermodynamically Consistent Model for Turbulent Two-Phase Flows," 28th Annual Technical Meeting of the Society of Engineering Science, Gainsville, FL, November 6-8, 1991.

G. Ahmadi and S. Abu-Zaid, "Analysis of Rapid Shear Flows of Granular Materials by a Stress Transport Model," 28th Annual Technical Meeting of the Society of Engineering Science, Gainsville, FL, November 6-8, 1991.

G. Ahmadi, "Overview of Thermodynamical Modeling of Turbulent Flows of Multiphase Mixtures," Proceedings of the International Conference on Engineering Application of Mechanics, Vol. 3, Sharif University of Technology, Ed. by M.S. Sadeghipour et al., June 9-12, 1992, 386-399.

G. Ahmadi and S. Abu-Zaid, "A Thermodynamically Consistent Stress Transport Model for Rapid Granular Flows," The 23nd Annual Meeting of the Fine Particle Society, Las Vegas, Nevada, July 13-17, 1992.

G. Ahmadi and S. Abu-Zaid, "A Model for Turbulent Two-Phase Flows," MEET'N'93, ASME/ASCE/SES Joint Meeting, University of Virginia, Charlottsville, VA, June 6-9, 1993.

G. Ahmadi, D. Ma, and A. Eraslan "Rapid Granular Flow in Complex Geometry Regions," MEET'N'93, ASME/ASCE/SES Joint Meeting, University of Virginia, Charlottsville, VA, June 6-9, 1993.

G. Ahmadi, "A Computational Model for Coal Transport and Combustion," University Coal Research Contractors" Review Conference, Pittsburgh, PA, June 23-25, 1993.

G. Ahmadi and S. Abu-Zaid, "Turbulent Two-Phase Flow of Dense Mixtures-A Thermodynamically Consistent Model," The 24th Annual Meeting of the Fine Particle Society and First International Conference on Pharmaceutical Sciences and Technology, Chicago, Illinois, August 23-28, 1993.

J. Cao, and G. Ahmadi, "Numerical Simulation of Granular Couette Flows Between Two Rough Parallel Plates," The 24th Annual Meeting of the Fine Particle Society and First International Conference on Pharmaceutical Sciences and Technology, Chicago, Illinois, August 23-28, 1993.

G. Ahmadi, D. Ma, and A. Eraslan "Analysis of Transient Rapid Granular Flows in a Channel with an Obstruction," The 24th Annual Meeting of the Fine Particle Society and First International Conference on Pharmaceutical Sciences and Technology, Chicago, Illinois, August 23-28, 1993.

M. Massoudi and G. Ahmadi, "Rapid Flows of Granular Materials With Density Gradient," The 24th Annual Meeting of the Fine Particle Society, and First International Conference on Pharmaceutical Sciences and Technology Chicago, Illinois, August 23-28, 1993.

J. Cao and G. Ahmadi, "Analysis of Gas-Particle Turbulent Flow in a Vertical Duct," The Second International Conference on Pharmaceutical Science and Technology and The 25nd Annual Meeting of the Fine Particle Society, New Brunswick, NJ, July 25-29, 1994.

J. Cao, G. Ahmadi and M. Massoudi, "Analysis of Gravity Granular Flows Down an Inclined Bumpy Chute with Friction," The Second International Conference on Pharmaceutical Science and Technology and The 25nd Annual Meeting of the Fine Particle Society, New Brunswick, NJ, July 25-29, 1994.

J. Cao, G. Ahmadi and M. Massoudi, "Rapid Granular Flows Down an Inclined Bumpy Chute," 31th Annual Technical Meeting of the Society of Engineering Science, Texas A&M University, College Station, TX , October 10-12, 1994.

J. Cao and G. Ahmadi, "Turbulent Flow of Two-Phase Gas-Particle Mixture in a Vertical Duct," 31th Annual Technical Meeting of the Society of Engineering Science, Texas A&M University, College Station, TX , October 10-12, 1994.