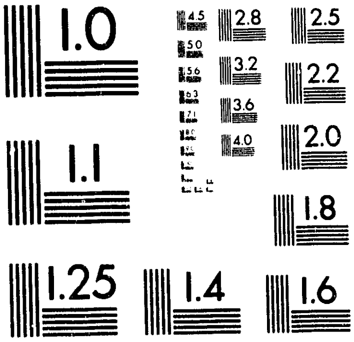
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DOE/PC/91297-7

Quarterly Technical Progress Report

(March 1, 1993 to May 31, 1993)

A COMPUTATIONAL MODEL FOR COAL TRANSPORT AND COMBUSTION

Grant Number: DE-FG22-91PC91297

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Submitted to

U.S. Department of Energy

Pittsburgh Energy Technology Center

Attention:

Dr. Mehrdad Massoudi

Project Officer

A COMPUTATIONAL MODEL FOR
COAL TRANSPORT AND COMBUSTION

Grant Number: DE-FG22-91PC91297

Project Period: September 1, 1991 to August 31, 1994

Contract Recipient: Clarkson University

Project Principal Investigator: Goodarz Ahmadi

DOE Project Officer: Dr. Mehrdad Massoudi

SUMMARY

In the period of March 1, 1993 to May 31, 1993, further progress was made in the experimental study of mono-layer simple shear flow device. Preliminary data concerning the shearing of 12 mm multi-color glass particles are obtained. The experimental data for the mean velocity and the solid volume fraction show the expected variations.

The thermodynamically consistent, rate dependent model for turbulent two-phase flows analysis was used and the phasic fluctuation energy production rates are evaluated. Further progress on the application of the kinetic model for rapid flows of granular materials including the frictional energy losses were made. The velocity and the solid volume fraction profiles for granular flows down a vertical channel were obtained.

The computational model was used and the rapid granular flows around a rectangular block in a channel were analyzed. It is shown that the model is capable of predicting the features of the flow under transient and nonuniform conditions.

PROGRESS REPORT

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 nonreacting turbulent flows of dense or dilute multiphase coal mixtures will be provided.

HIGHLIGHT OF THE EARLIER ACCOMPLISHMENTS

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.

The computational model for rapid granular and two-phase flows in complex geometries was further 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 simulation results of Campbell and Brennen, and good agreements were observed. Progress has been made in developing an appropriate computational model for analyzing turbulent two-phase flows with various loadings.

An experimental setup for generating simple shear flows of a mono-granular layer was constructed. Sample results for shearing of 12 mm multi-color glass particles was obtained.

EXPERIMENTAL STUDY

The main objective of the experimental effort is to provide a fundamental understanding of the mechanisms that control the features of granular particulate flows. The other main goal is to provide reliable data for velocity, concentration and fluctuation energy profiles for a simple shear flow of granular materials in order to verify the foundation of the thermodynamical formulation and computational predictions.

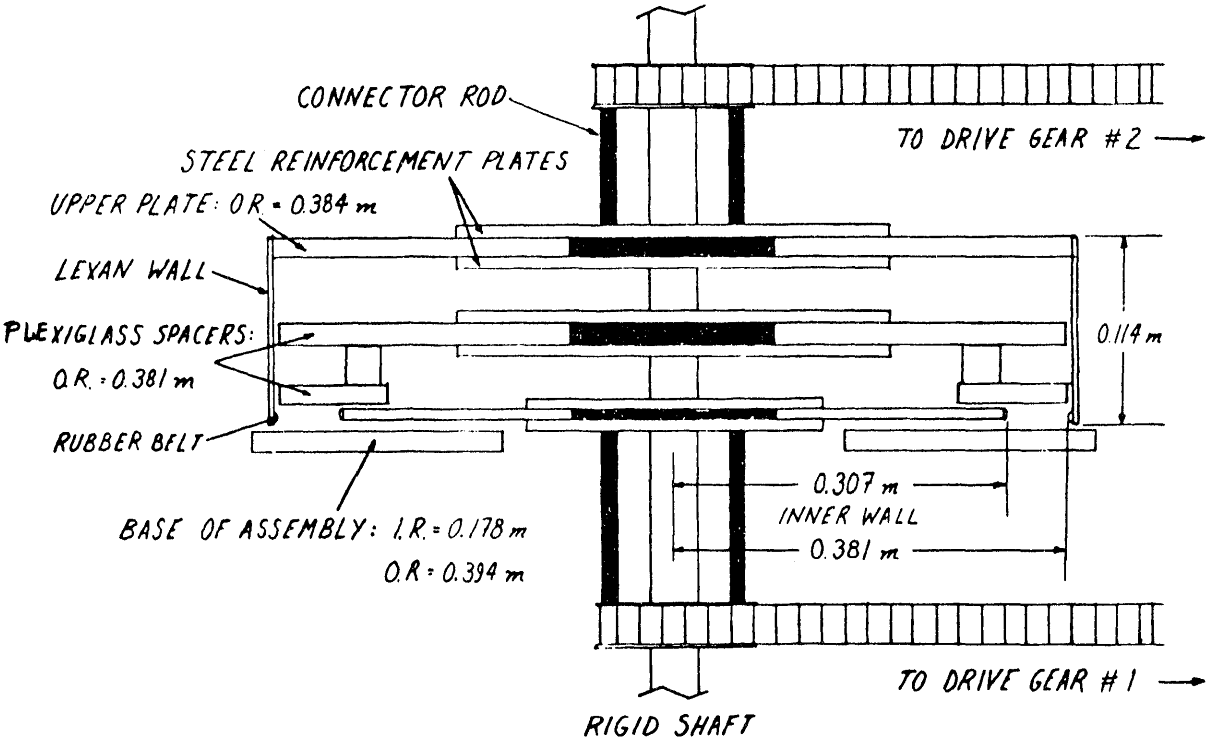

Figure 1. The schematic of the simple shear flow device.

Granular Shear Flow Device

The mono-granular simple shear flow setup with multi-colored spherical glass balls which are 12 mm in diameter were used for the experimental study. The gap size was adjusted and the shear flow device was reassembled. Figures 1 and 2 show the schematic of the device and the shearing cell. Some new runs with colored glass balls using different solid volume fractions and various shear rates were performed. The position of the balls in consecutive frames. taken 1/30th of a second apart from the test run at a shear rate of 62.83 1/sec were measured. Using this technique, the velocity vector of each particle can be calculated. The shearing region was divided into 10-15 equivalent horizontal segments. Averaging procedures are used to provide the experimental velocity profile.

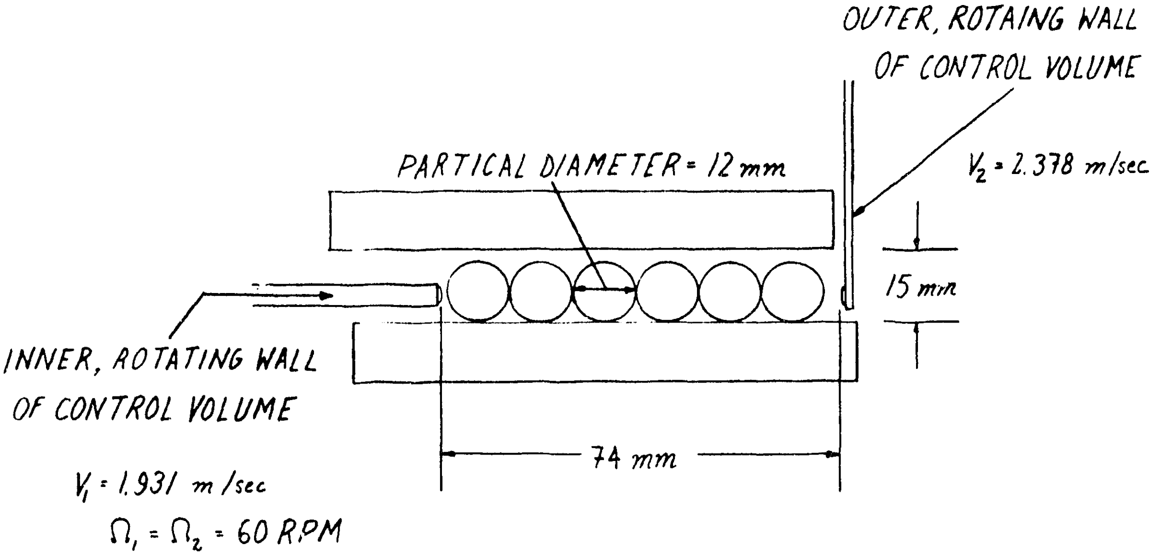

Figure 2. The schematic of the shearing region of the simple shear flow device.

Figure 3 shows sample for axial and lateral velocity profiles. It is observed that the significant amount of slip exist. The slip is much larger at the inner wall when compared with that of the outer wall. It appears that the centrifugal force is important for this rotating Couette flow geometry. At the inner wall, the centrifugal force moves the particle away from the wall, reduces the normal force and, as a result, the slip velocity increases. At the outer wall, however, the particles are pushed toward the wall by the centrifugal force and the slip velocity decreases.

Figure 3 also shows that the axial velocity is roughly linear in the central part of the shearing region. The lateral velocity is nonzero and generally positive, except for the region very near the inner wall.

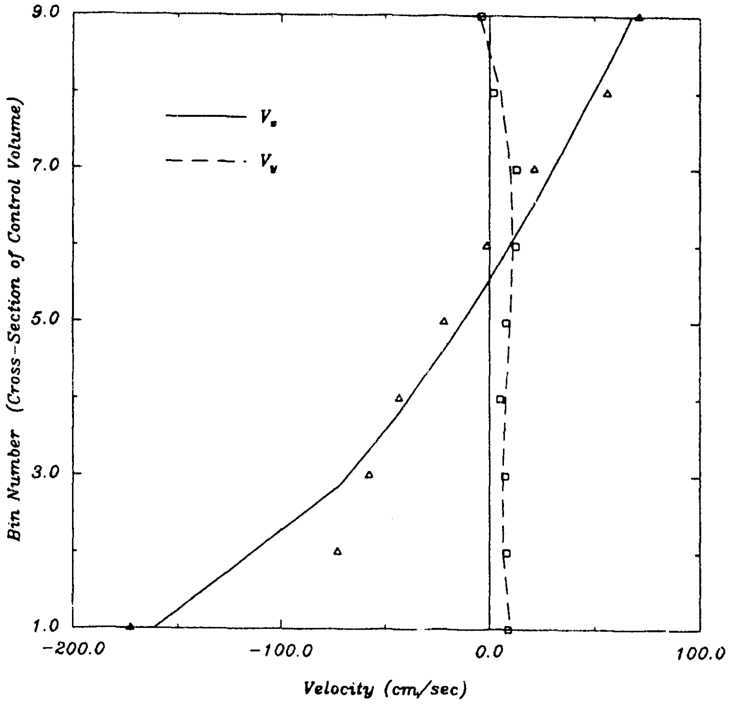

Figure 3. Experimental data for the axial and lateral velocity profiles.

A THERMODYNAMICALLY CONSISTENT RATE-DEPENDENT MODEL FOR TURBULENT TWO-PHASE FLOWS

In the earlier reports, a thermodynamically consistent theory for dense two-phase flow was developed. The new model includes the transport equations for the phasic fluctuation kinetic energies. Anisotropic and rate-dependent expressions for the phasic stress tensors were derived. For dense solid-liquid mixtures, the material parameters of the model were evaluated from the limiting conditions. The special case of simple shear flows of glass beads-water mixtures were studied. The coefficient of restitution for glass bead collision in water was experimentally measured.

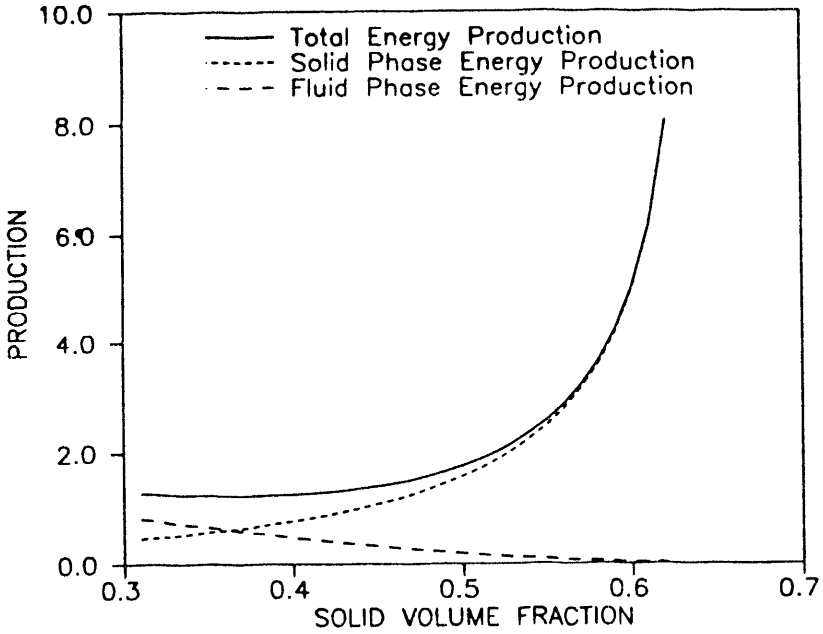

Figure 4. Variations of nondimensional phasic fluctuation energy productions with solid volume fraction for 1.1 mm glass beads in water.

Figure 4 shows variations of nondimensional phasic fluctuation energy productions with solid volume fraction for 1.1 mm glass beads in water. It is observed that the nondimensional particulate fluctuation energy production increases rapidly with an increase in solid volume fraction. The fluid fluctuation energy production, however, decreases as ν increases. For the present condition, the phasic fluctuation energy become equal for ν being about 0.35. This figure shows that for large solid volume fractions, the fluctuation energy is mainly produced by the particulate phase and the contribution of the fluid phase is negligible as ν approaches the limiting solid volume fraction of about 0.64. The production rate of the fluctuation energy also becomes extremely large close to the maximum packing conditions. Experimental confirmation of these results is not possible due to the lack of data for the phasic fluctuation energy production.

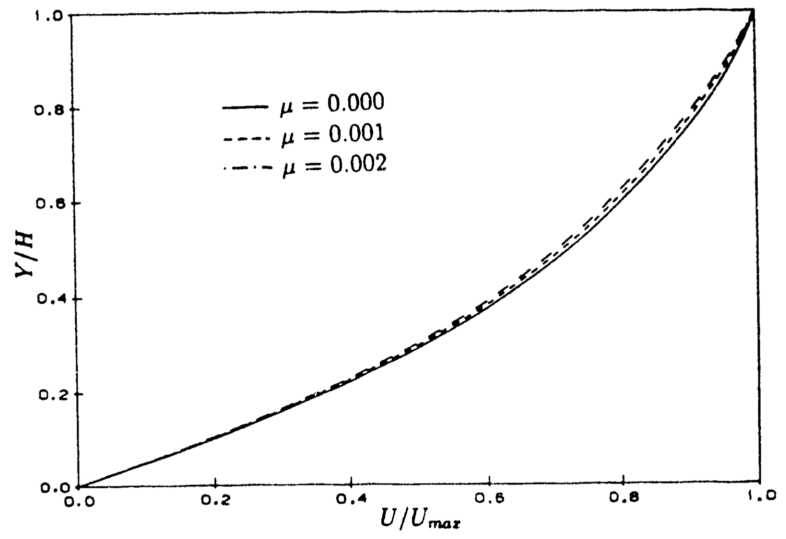

Figure 5. Mean velocity profiles for granular flows done a vertical channel for different values of friction coefficient.

ANALYSIS OF RAPID GRANULAR FLOWS INCLUDING FRICTIONAL LOSSES

The previously developed kinetic model for particulate flows, including frictional energy losses, was used to analyze the rapid granular gravity flows down a vertical channel. The equations of motion were solved using a fourth-order Runge-Kutta numerical scheme. The corresponding mean velocity and solid volume fraction profiles are shown in figures 5 and 6. It is observed that the velocity profiles are roughly paraboidal, and change slightly with an increase in the friction coefficient. Figure 6 shows that the solid volume fraction has a rather low value in the shearing region near the wall, and increases to its peak value near the centerline.

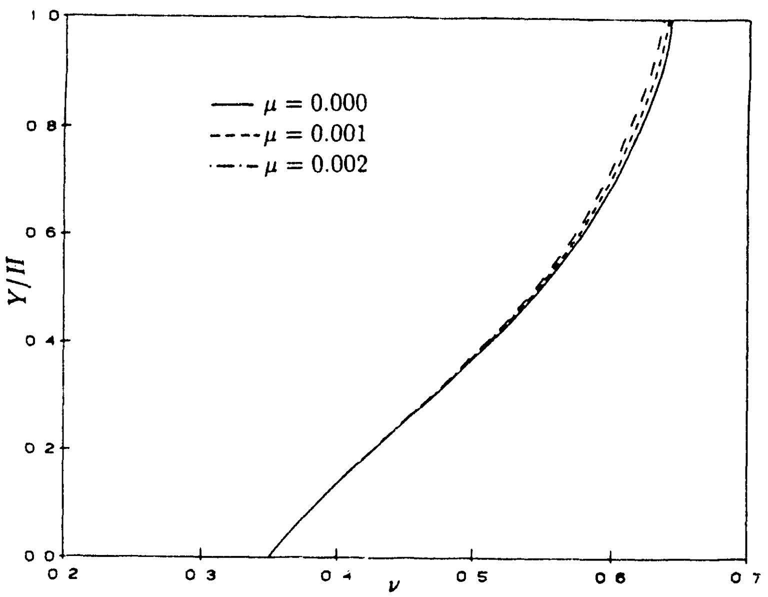

Figure 6. Solid volume fraction profiles for granular flows done a vertical channel for different values of friction coefficient.

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 Around a Block

Further progress was made in application of the computational model for granular flow analysis. The computational model was used and the granular flow around a rectangular cylindrical block in a channel was studied. The flow region was assumed to be 15 m long and 2.4 m wide. The flowing granular layer thickness was taken to be about 0.25 m. A 1.5 m long, 0.8 m wide and 0.25 m high rectangular block was assumed to be located at the center of the channel. The physical properties of spherical polystyrene beads with a specific gravity of 1.03 and the mean diameter of approximately 1.2 mm were used in the calculation.

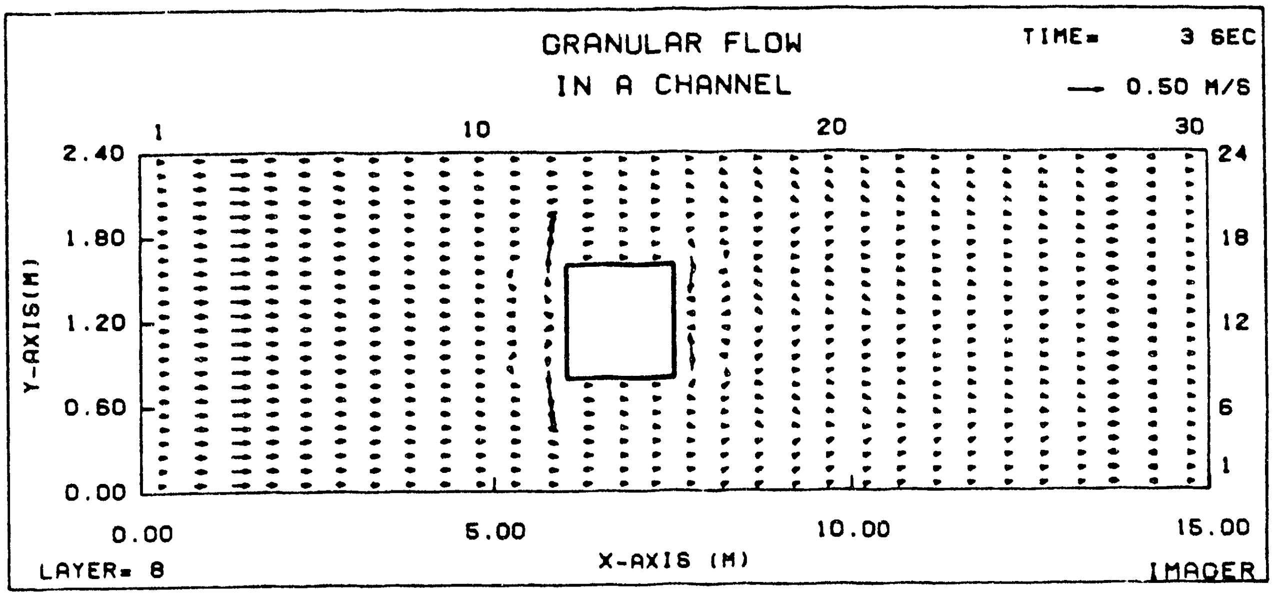

Figure 7. Velocity vector plot at the surface layer in the (x, y) plane at t=3 sec.

In the computer simulation, the flow region was discretized by using a uniform rectangular grid system with 30 elements along the x-direction and 24 elements along the y-direction. The length increments of Δx=0.5 m and Δy=0.1 m were used. The total number of elements in the (x,y) plane was 720, which consists of 104 boundary elements and 616 internal elements. The total depth was divided into eight specified layers along the z-direction with depths of each layer being 0.03 m except for the surface layer which was selected to be 0.04 m. Since each layer had 720 elements (in (x,y) plane), a total of 5760 elements was used to represent the granular flow region.

The computed results shows that the flow around the block involves a rather complicated accelerating and decelerating zones. Furthermore, there is a possibility of settling for granular particles behind the block.

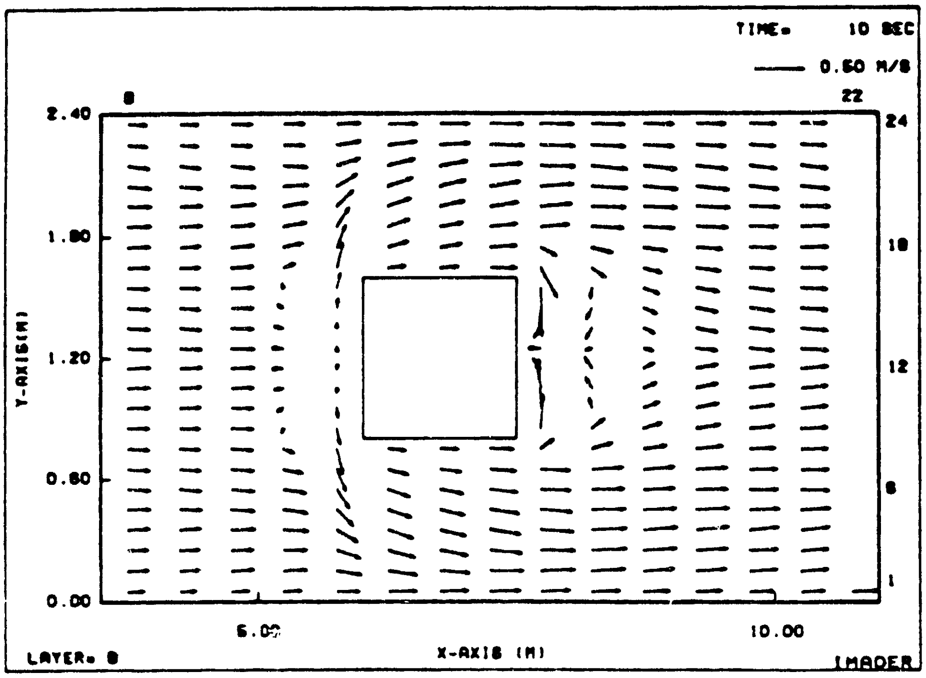

Figure 8. Velocity vector plot at the surface layer in the (x, y) plane at t=10 sec.

The computer simulation results for the velocity conditions are shown in Figures 7-9. Figure 7 shows the velocity vector field in top layer of the (x, y) plane of the flow region at time, t=3 sec. It is observed that the block significantly distorts the flow field. In particular, the granular materials seems to bounce back from the front of the block, and turn toward the centerline of the flow at the section behind the block. At this time, the flow is not fully developed. This is the reason for the plane waves observed in figure 7 near the inlet and outlet of the channel.

At time t=10 sec the flow is still developing. A close up of the velocity pattern for the surface layer in the (x, y) plane (element 8 to 22) is shown in figure 8. This figure shows that a source of granular materials seems to appear at the center line in front of the block which interacts with the incoming uniform velocity field. A reverse flow region forms in front of the block which penetrates the upstream flow field up to about one meter. On both sides of the block, the flow accelerates and a separation bubble is formed behind the block. At the center line behind the block a sink flow seems to appear. Further downstream, the wake region can be seen.

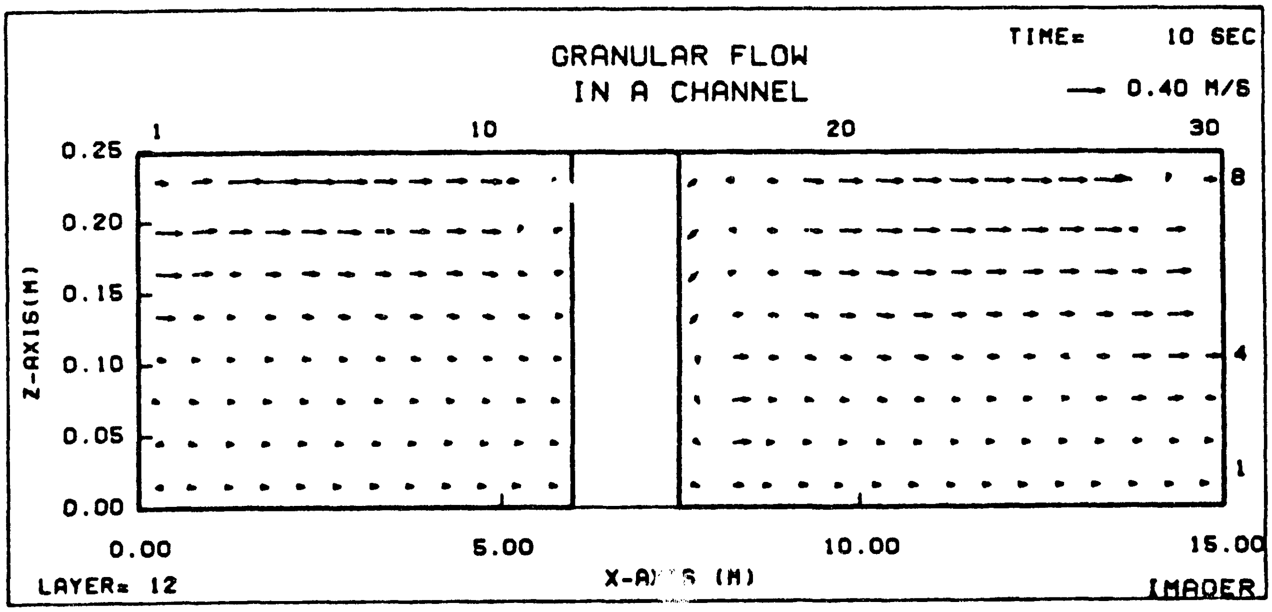

Figure 9. Velocity vector plot at the (x, z) plane of symmetry at t=10 sec.

Figure 9 provides the (x, z) section view at the plane of symmetry of the flow region at time t=10sec. It appears that the granular particles move upward in front of the block, while they move downward behind the block. This explains the formation of source and sink type flows in front and behind the block noticed at the surface layer in figures 7 and 8.

Numerical results for the velocity fields in the channel cross sections indicate that at the section in front of the block, two counter rotating vortices are formed and particles are moving outward from the centerline. In the section behind the block, the flow pattern is quite opposite and the particles near the centerline move downward. These observations indicate that the granular flows around the block are truly three dimensional and quite complex. Thus, a two dimensional computation model is not capable of capturing the main features of such flows.

Two-Phase Flow

Formulation of appropriate equations for motion of dense two-phase mixtures, and some features of the computational scheme of solution were described in the earlier report. In the last few months effort to include the effects of fluid turbulence particles fluctuation energy and collisional effects into the computational model was continued. Particles are assumed to be spherical with different diameters. The suitability of different boundary conditions for the fluid phase and particulate phase are also studied.

ARTICLES AND PRESENTATIONS

Journals Publications

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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.

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