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Ash & Pulverized Coal Deposition in Combustors & Gasifiers

Quarterly Report
January 1 - March 31, 1998

By
Goodarz Ahmadi

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For
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Federal Energy Technology Center
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By
Department of Mechanical and
Aeronautical Engineering
Clarkson University

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Submitted to

U.S. Department of Energy

Federal Energy Technology Center

Pittsburgh, PA

Attention:

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Technical Project Officers

Dr. Eric T. Bell

Program Administrator

ASH & PULVERIZED COAL DEPOSITION
IN COMBUSTORS & GASIFIERS

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Project Period: September 1, 1994 to August 31, 1998

Contract Recipient: Clarkson University

Project Principal Investigator: Goodarz Ahmadi

DOE Project Officers: Dr. Norman Holcombe and Dr. Rodney A. Geisbrecht

DOE Program Administrator: Dr. Eric T. Bell

SUMMARY

Further progress in achieving the objectives of the project was made in the period of January I to March 31, 1998. The direct numerical simulation of particle removal process in turbulent gas flows was completed. Variations of particle trajectories are studied. It is shown that the near wall vortices profoundly affect the particle removal process in turbulent boundary layer flows.

Experimental data for transport and deposition of fibrous particles in the aerosol wind tunnel was obtained. The measured deposition velocity for irregular fibrous particles is compared with the empirical correlation and the available data for glass fibers and discussed.

Additional progress on the sublayer model for evaluating the particle deposition and resuspension in turbulent flows was made.

OBJECTIVE AND SIGNIFICANCE

In this section the objective of the project and its significance to the fossil energy program are outlined.

Objectives

The general goal of this project is to provide a fundamental understanding of deposition processes of flyash and pulverized coal particles in coal combustors and coal gasifiers. The specific objectives are:

i) To provide a fundamental understanding of deposition mechanisms for coal and ash particles via digital simulations of turbulent flow conditions in a coal combustor and/or gasifier and the Lagrangian particle trajectory analysis.

ii) To develop a semi-analytical model for wall deposition rate of coal and flyash particles in complex flow and thermal conditions of coal combustors and gasifiers.

iii) To assess the relative significance of turbulent dispersion, Brownian diffusion, thermophoretic, electrostatic and surface forces, as well as particle collision and agglomeration under different conditions.

iv) To assess the significant effects of nonsphericity of coal and ash particles on their transport and wall deposition processes.

v) To provide a detail understanding of wall deposition mechanisms for relatively compact, as well as elongated flyash and pulverized coal particles via a direct numerical simulation of near-wall turbulent flows.

vi) To experimentally verify the validity of the simulation and analytical results for deposition rates of flyash and pulverized coal particles in the size range of 2 to 100 μm in the upgraded MAE Aerosol Wind Tunnel.

Significance to Fossil Energy Program

Transport and deposition of particles play a critical role in operation, efficiency, safety and maintenance of coal combustors and gasifiers. Turbulent mixing of pulverized coal significantly affects the efficiency of combustion, pyrolysis and gasification processes. Deposition of flyash and other particles on the wall leads to the formation of coal slag. Corrosion by coal slag is a serious problem in coal-gasification and combustion systems. Presence of particulate contaminant in the combustion product is also a major source of air pollution in coal energy systems.

No completely satisfactory model describing the motion of a coal or ash particle in the highly transient turbulent flow and thermal conditions in coal combustors and gasifiers exists. More importantly, the controlling mechanisms for deposition of particles on surfaces in a turbulent stream with strong temperature gradients are not fully understood. Without such an adequate understanding, providing mitigation measures against slag formation and/or improving the efficiency of coal combustors are not possible.

The general goal of this research is to provide a fundamental understanding of transport and deposition mechanisms of ash and pulverized coal particles in complex turbulent flow conditions in a coal-fired combustor or in a coal gasifier. The other main objective is to develop an accurate computational model for simulating motions of ash, pulverized coal, and soot particles in complex geometries of coal (gas turbine) combustors and gasifiers. Availability of these tool and knowledge base will be indispensable for developing an environmentally acceptable coal energy system.

PROGRESS REPORT

This section outlines the progress made in the period of January I to March 31, 1998 in accomplishing the tasks of the project. We have made considerable progress in modeling the particle transport, deposition and resuspension processes in turbulent gas flows, and the experimental study of deposition of nonspherical particles. This quarterly report describes our new findings for particle removal and particle transport and deposition in turbulent recirculating flow fields. In addition, the progress made in direct digital simulation of particle removal in duct flows is described.

COMPUTATIONAL MODELING

In the earlier reports, we have described the simulation of the gas flow velocity field in complex passages with the use of the STARPIC-RATE computer code that makes use of an advanced anisotropic turbulence model. The particle equation of motion which includes the Stokes drag, the turbulence dispersion effects, the lift force, as well as, the Brownian effects was also used in the simulation. The instantaneous turbulence fluctuations are simulated as an anisotropic continuous Gaussian random vector process. The computational model has been tested earlier for several cases and its accuracy was verified. Studies concerning dispersion and deposition from a point source of particles in a turbulent air flow and deposition from uniform concentration in a circular cylindrical duct and in recirculating flow region were studied before. The details of flow in a duct using a direct numerical simulation procedure and the corresponding particle resuspension are being studied. A summary of the progress made is presented in this section.

Direct Numerical Simulation of Particle Resuspension

To provide a fundamental understanding of particle resuspension process in turbulent flows, a direct numerical simulation of Navier-Stokes equation was performed. The Navier-

Stokes equation is solved directly using a pseudo-spectral computational scheme. The computational grid and the numerical procedure used was outlined in the earlier reports. The velocity vector fields at different times and different planes and the equation governing the motion of particles were presented in the earlier reports. The iso-vorticity contours and the structure of near wall flow were discussed in the last quarterly report. A series of computer simulations for particles that were initially distributed (with a statistically uniform distribution) on the xy-plane at a distance of Y_o = 1 wall unit from the upper wall were performed. It was shown that the locations of ejected particles (that reach different levels) form lines with spacings of about 100 to 150 wall units. These variations appeared to be consistent with the available flow visualization results for the streaky structures in the viscous sublayer. It was also observed that these lines shifted to new locations for time duration of 200 to 400 wall units. It was conjectured that the shifting of lines is due to the break-up (or lifting) of vortices and formation of new ones at other locations as time progresses. Those results suggested that the near wall streamwise structure (coherent vortices) plays a dominant role in the particle entrainment process.

Sample trajectories corresponding to the particles which form a line near z^+=270 are shown in Figs. 17-20. These figures show that the original locations of particles are $270 < Z^+ < 290$ and $200 < x^+ < 400$. The patterns of particle motions observed in these figures correspond to the action of two counter rotating streamwise vortices, and is consistent with the velocity fields shown in the earlier reports. Variations of the slope of particle trajectories in the xy-plane observed in figure 3 are similar to those found in figure 3 in the last quarterly report. The particle trajectory statistics (with appropriate shift in the z-direction) in the yz-plane are shown in figure 4. It is observed that the trajectory statistics are roughly symmetric. The standard deviation is also about 3 wall units and the deviations of sample maximum or minimum from the mean is less than 7 wall units. These statistical results imply that these particles are entrained by the upflow motion generated by a pair of counter rotating vortices. These counter rotating vortices are also clearly observed from the averaged vorticity plot shown in figures 2 and 3 of the quarterly report of September 1997.

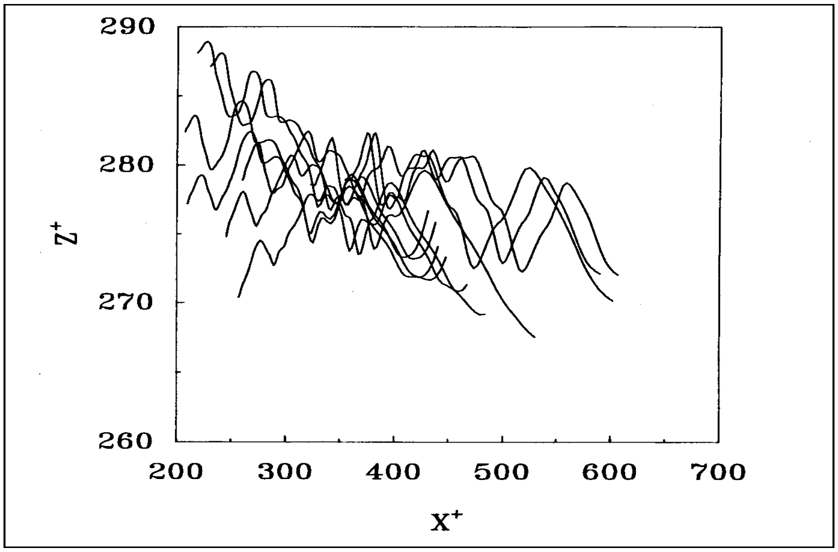

Figure 1. Particle trajectories in the xz-plane corresponding to the particle lineup near z^+=270

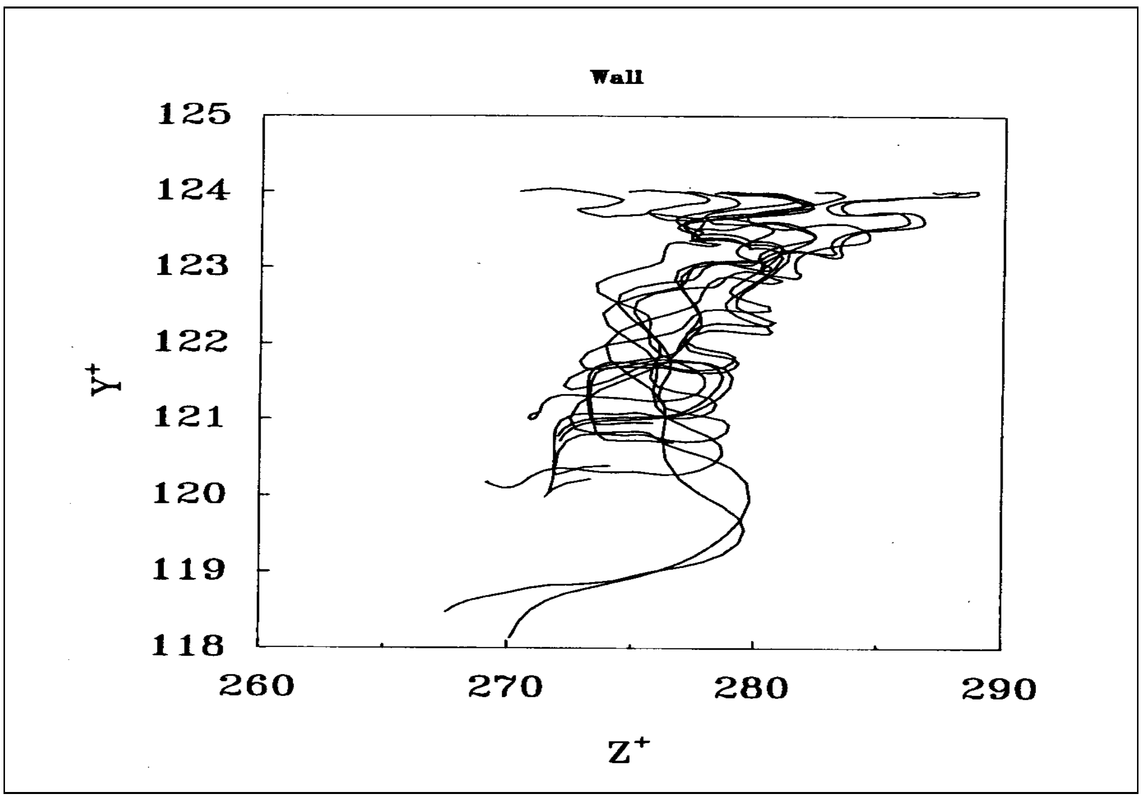

Figure 2. Particle trajectories in the yz-plane corresponding to the particle lineup near z^+=270.

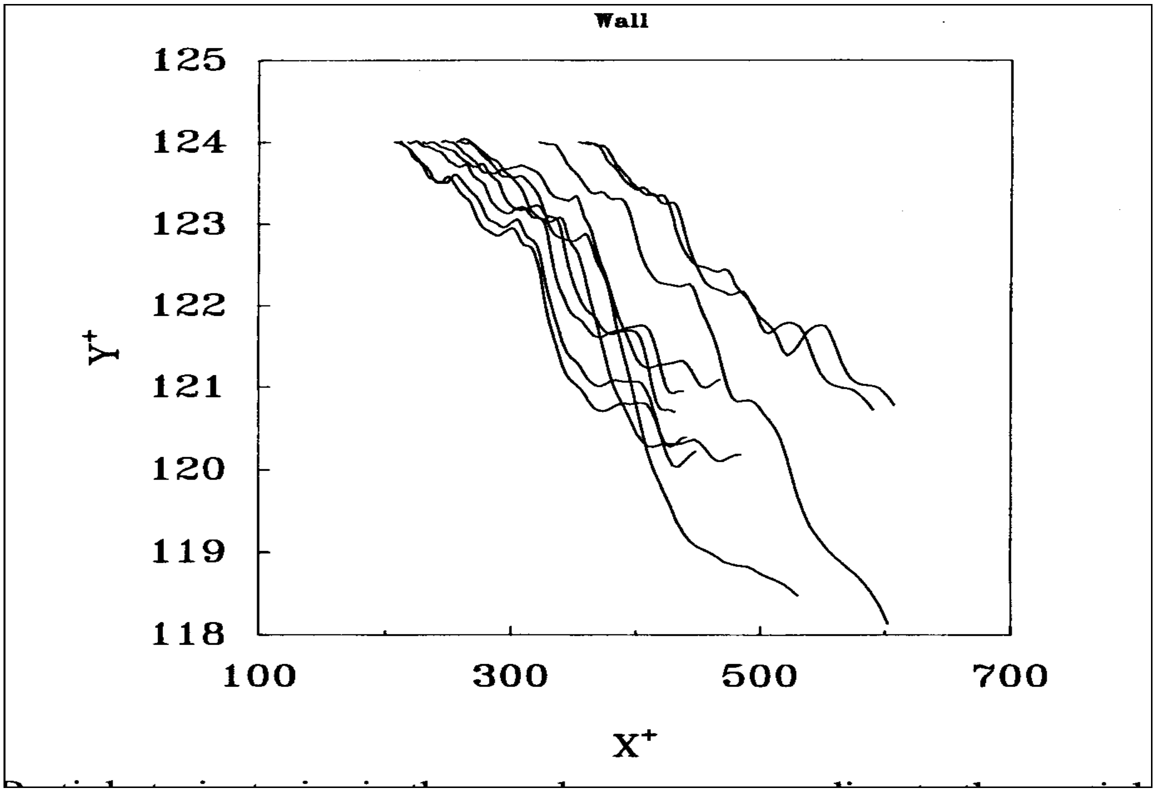

Figure 3. Particle trajectories in the xy-plane corresponding to the particle lineup near z^+=270.

The trajectory statistics of all particles which reach to the distance of 4 wall units away from the upper wall are shown in figure 5. Here also the trajectories are translated to a common z-coordinate at the last time step. This figure shows that the standard deviation is about 15 wall units and the deviation of the sample absolute maximum and minimum from the mean is less than 50 wall units. The symmetry of trajectory statistics in figure 5 implies that the total number of clockwise and counter clockwise single streamwise vortices are roughly equal. This conclusion is also supported visually by the iso-vorticity plots shown in figures 2 and 3 of the quarterly report of September 1997. Note also that the distance of 2σ = 30 wall units is comparable to the commonly assumed radius of 25 wall units for the near wall vortices.

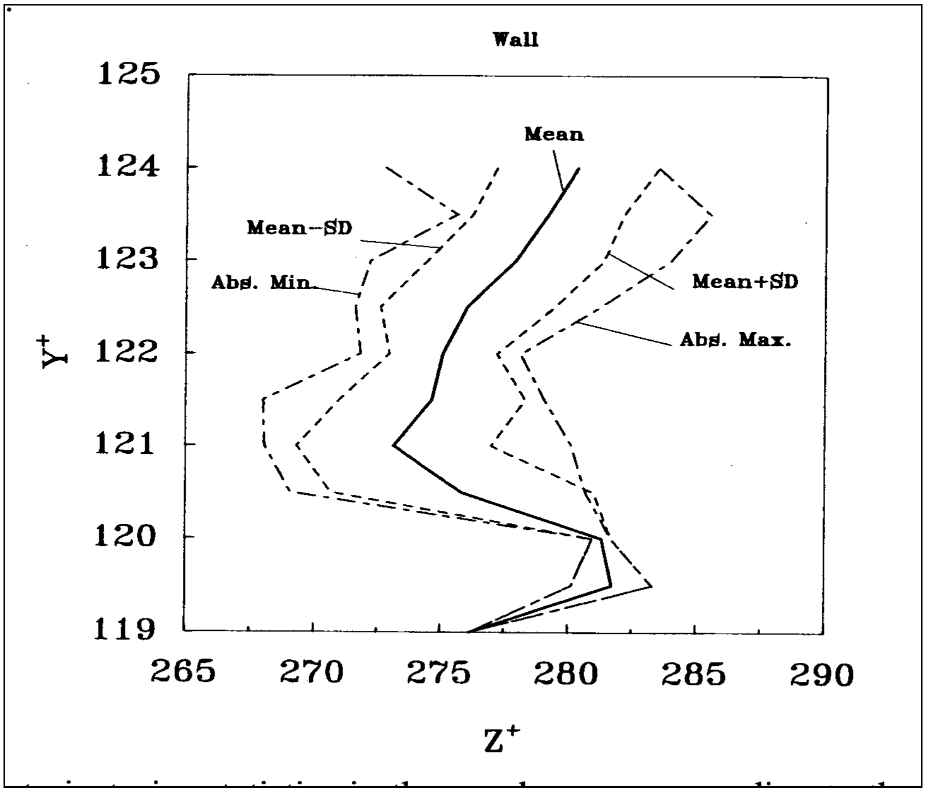

Figure 4. Particle trajectories statistics in the yz-plane corresponding to the particle lineup near $z^+=270$.

In this part of the study, simulation results for particle entrainment in a turbulent channel flow are presented. The flow field is generated by a direct numerical simulation (DNS) of wall bounded flow with the use of a pseudospectral computational model. Ensembles of particle trajectories are evaluated and statistically analyzed. The instantaneous streamwise fluid velocities for detaching the particles from a real surface are evaluated and the trajectories of these particles are determined. Based on the presented results, the following conclusions may be drawn:

1. A roughly periodic streaky structure in the viscous sublayer, with the spacing of about 100 to 150 wall units, exists in the simulated flow field.

2. Single streamwise-oriented vortices are statistically more probable than counter-rotating vortices of equal strength at any instance.

3. When averaged over a time duration of about 200 wall units, the iso-vorticity plots show that averaged counter rotating vortices of roughly equal strength occurs quite frequently.

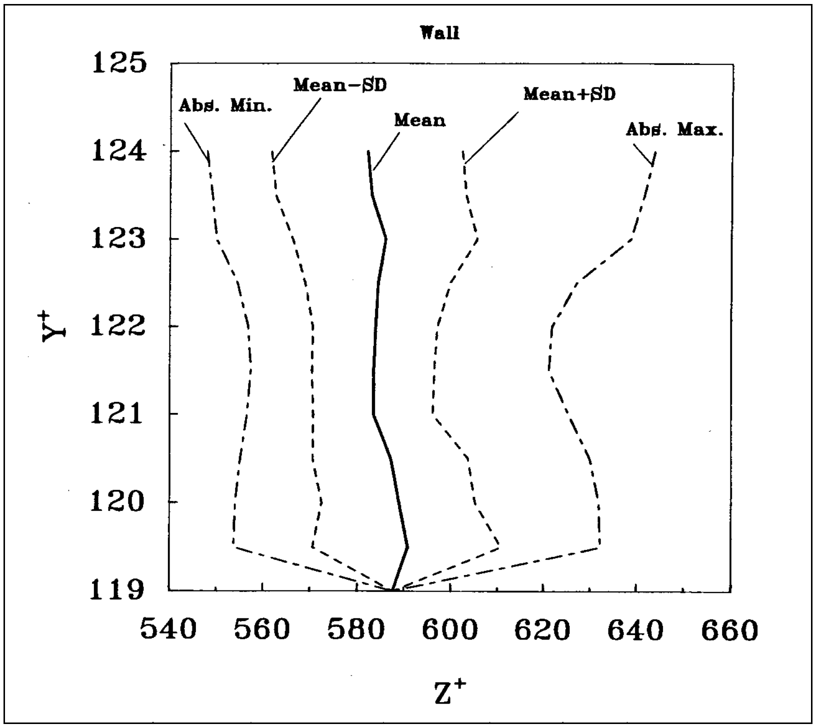

Figure 5. Particle trajectories statistics in the yz-plane for all particles that reach to the distance of 4 wall units.

4. Intersection of entrained particle trajectories with various planes parallel to the wall form narrow bands. The lateral spacing of these lines are about 100 wall units.

5. Trajectory statistics for groups of entrained particles in most cases show asymmetric patterns. These are indicative of the action of a single streamwise vortex.

6. Trajectory statistics of all entrained particles are roughly symmetric. This implies that the total number clockwise and counter clockwise vortices are approximately equal.

7. Particle capture in the relatively high speed streams, which move away from the wall, is the main mechanism for the entrainment.

8. The streaming motions toward or away from the wall form due to the streamwise near wall structures (including elongated vortices and/or ejection/inrush events).

9. The presented simulation results show that the regions with the peaks of the upflow velocity (away from the wall) are concentrated in relatively narrow bands. The vertical fluid velocity in these bands varies widely and includes certain regions in which the velocity is directed toward the wall.

EXPERIMENTAL STUDY

The goal of the experimental study is to provide the much needed data base on deposition rates of (generally nonspherical) coal and flyash particles. The experimentation is being performed in the horizontal aerosol wind tunnel and for glass fiber transport and deposition. The geometry of the wind tunnel and the experimental procedure were described in the earlier reports. In the earlier report, the experimental data for the non-dimensional deposition velocity versus the non-dimensional equivalent particle relaxation time, τ_{eq}^{+} (based on the orientation averaged resistance) were presented. Use of the τ_{eq}^{+}-Scaling clearly shows the significant increase of the deposition velocity with aspect ratio of the fiber. This observation is as expected because the increase in aspect ratio increases the wall capture efficiency by the interception mechanism. The flyash particles are nonspherical and, generally, irregular in shape. To provide an understanding of the transport of this kind of particles, the experimental results for the deposition rates of irregular shaped paper fibers using τ_{eq}^{+}-scaling are described in this section.

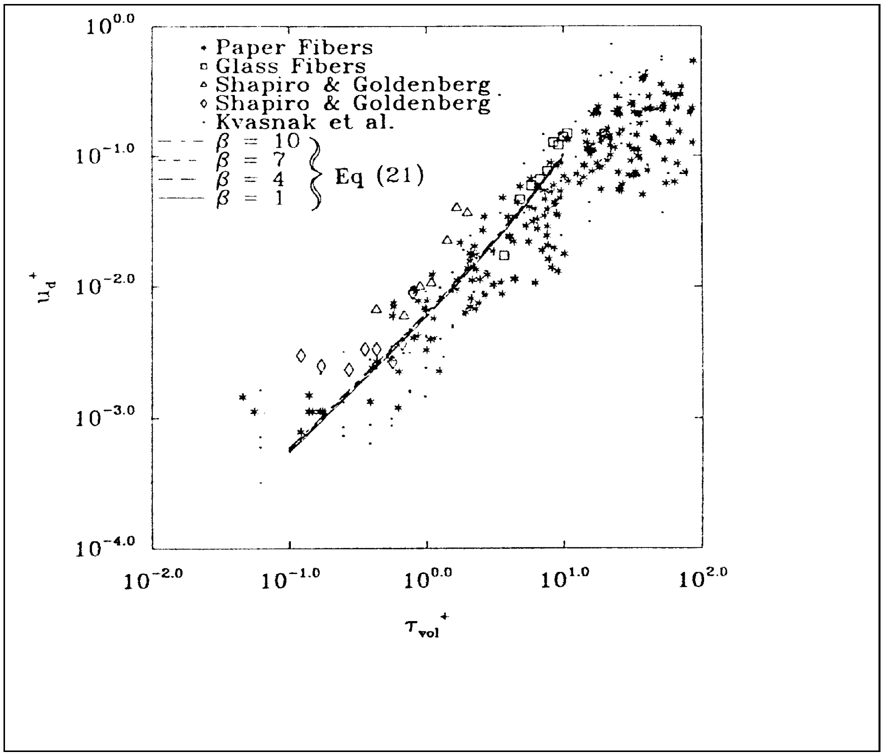

Figure 6. Measured deposition velocity of paper fibers versus equivalent volume relaxation time

Figure 6 shows the non-dimensional deposition velocity of paper fibers versus non-dimensional particle relaxation time. Here τau^{+}_{vol}, the relaxation time based on the diameter of an equivalent volume sphere is used. As noted before, for evaluating the equivalent spherical diameter, a paper fiber was assumed to be an ellipsoid of revolution with diameter and length equal to the shortest and the longest dimensions measured under the microscope. The experimental data for glass fibers and glass spheres along with the experimental data of Shapiro and Goldenberg (1993), and the predictions of the empirical equation are shown in figure 6 for comparison. It is observed that the experimental data for irregular shaped paper fibers are in reasonable agreement with the data for glass fibers and spherical particles. The empirical model predictions also appear to be in good agreement with the experimental data for the paper fibers. This result indicates the importance of gravitational sedimentation, which dominates the deposition rate of large spherical and non-spherical particles, in the horizontal flow configurations.

For paper fibers, figures 7 and 8, respectively, shows the variation of non-dimensional deposition velocity versus the non-dimensional equivalent particle relaxation time (based on the orientation averaged resistance) and the relaxation time based on minimum diameter. The experimental data of Shapiro and Goldenberg (1993), along with the prediction of the empirical relation are presented in these figures for comparison. The effect of particle aspect ratio in increasing the deposition rate is more clearly observed from this figure. Figures 7 and 8 also shows good agreement between the experimental data and the empirical model predictions.

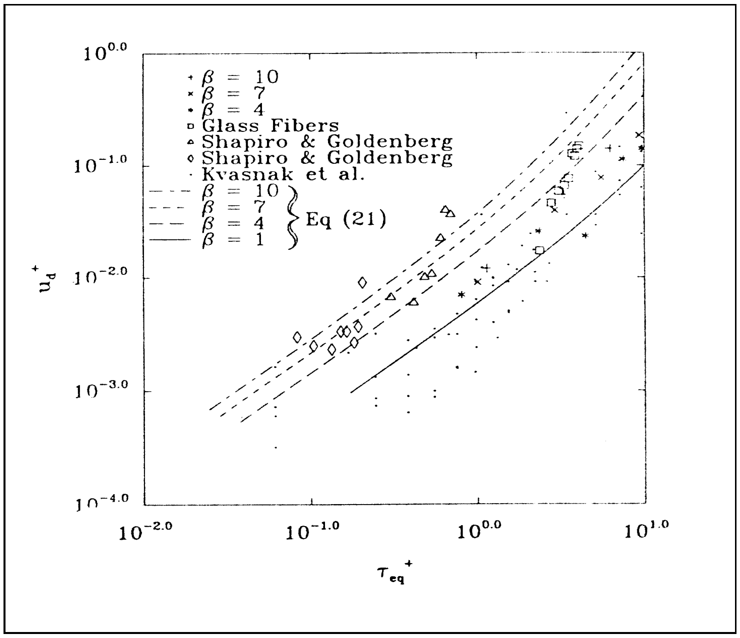

Figure 7. Variations of deposition velocity of paper fibers with equivalent relaxation time for different aspect ratios

Based on the presented experimental data in this and earlier reports the following conclusions concerning fibrous glass and paper particles may be drawn.

- The deposition rate of 5 μm glass fibers shows a substantial increase with length.
- The experimental data for deposition rate of glass fibers are in good agreement with the earlier data and the empirical model prediction.

- Using the equivalent particle relaxation time (based on the orientation averaged resistance), the experimental data show a significant increase with the particle aspect ratio.

- The fiber deposition rate increases rapidly with aspect ratio for a fixed minimum diameter.

- The deposition rates of fibrous irregular shape dust particles follow the same trend of variations as those of glass fibers and equivalent volume spherical particles.

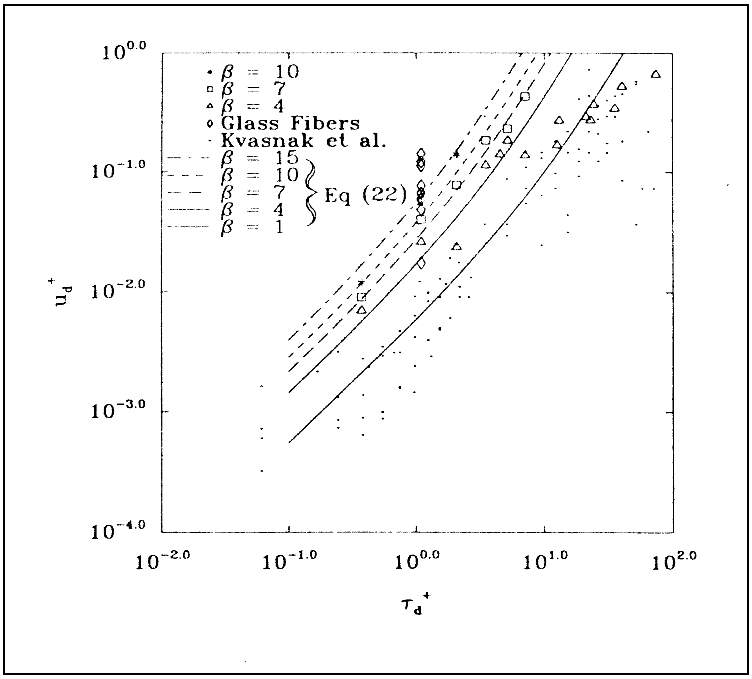

Figure 8. Variation of deposition velocity of paper fibers with relaxation time based on minimum diameter for different aspect ratios

- For a fixed volume, the fiber deposition rate in a horizontal duct increases only slightly with the aspect ratio.

- The eddy diffusion-impaction, gravitational sedimentation, and the interception (effective capture radius) mechanisms dominate the deposition of fiber particles larger than I gm in turbulent flows.

SUBLAYER MODEL FOR PARTICLE DEPOSITION

The significance of streamwise coherent vortices in the turbulent shear flows on particle deposition and removal processes was emphasized in the earlier reports. A simplified sublayer flow model for analyzing particle deposition including the effects of rebound form surfaces was described in the earlier reports. The present study is concerned with evaluating the particle deposition rate based on their motions in the near wall vortices. The equations for particle motion in the turbulence near-wall vortices were described in our earlier works. The details of the interactions of particles with the near wall eddies were described in the last quarterly report, were a number of sample trajectories were also presented.

PARTICLE RESUSPENSION IN TURBULENT FLOWS

In the previous reports, a flow structure-based model for particle resuspension from rough surfaces in turbulent streams were developed. The effect of surface roughness was included in the analysis. It was assumed that the real area of contact is determined by elastic deformation of asperities and the effect of topographic properties of surfaces were included. The JKR adhesion model was used to analyze the behavior of individual asperities. The theories of rolling and sliding detachment were used and the flow induced resuspension was studied. The effects of the near wall coherent eddies, and turbulence burst/inrush motion were included in the model development. The critical shear velocities needed to detach different size particles from rough surfaces under various conditions were evaluated and discussed. The model predictions were compared with the available experimental data and good agreement was obtained. The results indicated that particle removal from rough surfaces could be achieved by both rolling and sliding mechanism. Spherical particles, however, are more easily dislodged by the rolling motion in comparison with the sliding mechanism.

PARTICLE TRANSPORT AND DEPOSITION IN RECIRCULATING FLOWS

The mean flow and turbulence intensity fields in a recirculating flow in a two-dimensional duct in addition to particle dispersion and deposition . patterns were described in earlier quarterly reports. The effect of gravity and its direction was also studied. For small particles, it was shown that the recirculating flow pattern and turbulence dominates the particle deposition rate and the effect of gravity is not as significant.

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W. Kvasnak and G. Ahmadi, “Dispersion of Deforming Fuel Droplets in a Spray - A Computational Modeling Approach,” Sixteenth Annual Conference of the American Association for Aerosol Research, AAAR ’97, Denver, CO, October 13-17, 1997.

D.H. Smith, V. Powell and G. Ahmadi, “Behavior of the Filtration System in an Integrated Gasification and Cleanup Facility - II: Incomplete Filter Cleaning,” Sixteenth Annual Conference of the American Association for Aerosol Research, AAAR ’97, Denver, CO, October 13-17, 1997.

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Seminar and Lecture Presentations

"Particle - Turbulence Interactions - Part I, Dilute Flows," Morgantown Energy Technology Center, U.S. Department of Energy, Morgantown, WV (September 13, 1995).

"Particle - Turbulence Interactions - Part II, Dense Flows," Morgantown Energy Technology Center, U.S. Department of Energy, Morgantown, WV (September 20, 1995).

"Modeling of Granular and Dense Two-Phase Flows," Department of Mechanical Engineering, University of Pittsburgh, Pittsburgh, PA (October 26, 1995).

"Particles Transport and Deposition in Turbulent Flows," Department of Mechanical Engineering, West Virginia University, Morgantown, WV (November 29, 1995).

"Recent Advances in Computational Modeling of Particle Transport, Deposition and Resuspension," Center for Applied Energy Research, University of Kentucky, Lexington, KY (December 18, 1995).

"Computational Modeling of Particles Transport, Deposition and Resuspension in Industrial Systems," MEMC, St Louis, MO, (June 27, 1997).

"Some Ideas for Computational Modeling of Dilute and Dense Turbulent Two-Phase Flows," FLUENT, Lebanon, NH, (July 17, 1997).

"On Computational Modeling of Particles Transport and Deposition in Hot-Gas Filter Vessels," Federal Energy Technology Center, Morgantown, WV (August 6, 1997).

"Recent Advances in Particle Transport, Deposition and Removal," ASYST Technologies Inc., Fremont, CA (October 13, 1997).