ABSTRACT

The project is a part of a large cooperative program "Fluidized Bed Combustion Metal Wastage Cooperative R&D Venture," sponsored by USDOE/METC, Argonne National Laboratory, Electric Power Institute, CRSC, ASEA Babcock, Foster Wheeler Development Corporation, Combustion Engineering, and Tennessee Valley Authority. UIUC's participation is through a grant from CRSC. The primary objective of the research is to determine the instantaneous velocity distribution of particles hitting immersed objects in a gas fluidized bed and their impacting frequencies. This information is being used by ANL engineers in the study of the physical mechanism and the development of correlations for tube erosion. The local, ensemble-averaged, particle velocities in the bed have also been made available to them for use in their computer modeling effort for bed hydrodynamics.

Measurements of particle velocities were conducted in a 3.81 cm by 40 cm two-dimensional bed with immersed obstacles simulating two rows of a tube bank. It consists of identical cylindrical rods, 5.08 cm in diameter, extended through the entire width of the bed. The rods are in staggered arrangement with horizontal spacing of 15.2 cm and vertical spacing of 7.62 cm. Bed particles are soda lime glass beads having a material density of 2490 kg/m³ and a mean diameter in the range of 425 to 500 μm. The static bed height was 40.6 cm and the measured minimum fluidization velocity was 20.4 cm/s. The void fraction at minimum fluidization based on expanded bed height was 0.404 and the superficial air velocity used in the experiment was 39.0 cm/s. The position coordinate of a radioactive tracer mixed with the bed particles was tracked at 5 ms intervals in the Computer Aided Particle Tracking Facility (CAPTF) for a total of 40 hours. The local ensemble-averaged particle velocities throughout the bed and the local velocity distribution functions of particles hitting various portions of several selected rods in the simulated tube bank have been obtained. Samples of both directional distribution functions and speed distribution functions for particles hitting the surfaces in a number of specified directions are presented.
EXECUTIVE SUMMARY

This project is a part of a larger cooperative program "Fluidized Bed Combustion Metal Wastage Cooperative R&D Venture," sponsored by USDOE/METC, Argonne National Laboratory, Electric Power Research Institute, CRSC, ASEA Babcock, Foster Wheeler Development Corporation, Combustion Engineering, and Tennessee Valley Authority. UIUC's participation is through a grant from CRSC. The primary objective of the research is to determine the instantaneous velocity distribution of particles hitting immersed objects in a gas fluidized bed and their impacting frequencies. This information will be used by ANL engineers in the study of the physical mechanism and the development of correlations for tube erosion. The local, ensemble-averaged, particle velocities in the bed have also been made available to ANL for use in their computer modeling effort for bed hydrodynamics.

Measurements were made for particle velocities in a 3.81 cm by 40 cm two-dimensional air fluidized bed with immersed obstacles simulating two rows of a tube bank. All major dimensions and operating conditions of the bed were specified by ANL. The tube bank consists of identical cylindrical rods, 5.08 cm in diameter and of a length extending through the entire width of the bed. The rods are in staggered arrangement with horizontal and vertical spacings of 15.2 cm and 7.62 cm, respectively. The center plane of the lower row is at distance of 22.9 cm from the air distributor designed to provide uniform fluidization. Bed particles are soda lime glass beads having a material density of 2490 kg/m³ and a mean diameter in the range of 425 to 500 μm. The static bed height was 40.6 cm and the minimum fluidization velocity \( U_{mf} \) determined from the usual pressure drop behavior was 20.4 cm/s. The mean expanded bed height at minimum fluidization was 41.9 cm, and the corresponding void fraction was 0.404. The superficial air velocity used in the experiment was 39.0 cm/s and its relative humidity was kept in the range 33 to 39 percent. The tracer's instantaneous position was tracked in the UIUC's Computer-Aid Particle Tracking Facility (CAPTF) at 5 ms intervals for a total of 40 hours.

As a result of the improved calibration arrangement, a 2- to 3-fold reduction in the uncertainty of the tracer's position coordinates was achieved. Results include (1) ensemble-averaged solids velocity field with a clarity unattainable in earlier experiments, particularly at the surface of immersed rods, (2) circumferential distribution of particle hitting frequencies at the rod surface, (3) directional distribution functions of particles hitting selected surfaces of several rods in the tube bank, and (4) velocity distribution functions of particles hitting these surfaces in a number of selected directions. Samples are shown in the attached figures. Recent studies at ANL show that metal erosion due to impacting particles depends on the impingement angle in relation to the surface orientation as well as their impinging speeds. Hence, the information embodied in the directional and velocity distribution functions for particles hitting the rod surfaces is expected to be valuable in the search for a better understanding of the physical mechanisms of tube erosion in gas fluidized beds.
Figure 3 Ensemble-Averaged Particle Velocity Field in Two-Dimensional Air Fluidized Bed with Simulated Tube Bank. 425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_o = 39.0$ cm/s

(a) speeds > 20 cm/s appear as a dot,  (b) speeds > 10 cm/s appear as a dot

Figure 4 Circumferential Distribution of Particle Hitting Frequency Per Unit Area (cm$^{-2}$·s$^{-1}$) of Rods 1, 3 and 4 of Simulated Tube Bank

425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_o = 39.0$ cm/s

- Particles from all directions and of all speeds
- Particles from all directions but only of speeds >$U_c$, ($U_c/U_{mf} = 0.8$)
Figure 6  Directional Distribution Function of Particles Hitting Surfaces 4, 5, and 6 of Rod 1 of Simulated Tube Bank
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s

Figure 9a  Velocity Distribution Function of Particles Hitting Surface 4 of Rod 1 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
1. OBJECTIVES

The overall objective of the cooperative program is to assess the causes of and possible solutions for metal wastage in fluidized bed combustors. One such cause is related to the solids velocities in the bed. This project seeks to determine, through experimentation, the velocity distribution functions of particles impacting on immersed obstacles and their impacting frequencies. Such detailed information is needed because of the highly nonlinear relation between erosion rate and the particles' impingement speed and direction. The ensemble-averaged solids velocities, evaluated from their almost instantaneous motion, are being used by engineers of Argonne National Laboratory in their computer modeling effort for bed hydrodynamics.

2. INTRODUCTION AND BACKGROUND

Fluidized bed combustion of coal offers many advantages over conventional pulverized coal boiler with regard to fuel flexibility and environmental acceptability. Among the several remaining technical problems that need immediate solution is metal wastage. The importance of the subject was underscored in a 1987 workshop "Wastage of In-Bed Surface in Fluidized-Bed Combustors", organized by EPRI and held in Chicago, November 2 to November 6.

Wastage of components inside a fluidized bed entails both mechanical and chemical processes. Corrosion is the result of one or more chemical reactions. Abrasion and/or erosion are basically mechanical in origin. Often times, these processes occur simultaneously. In the literature, abrasion refers to material removal by the invasion of foreign particles which remain in contact for a significant length of time. The rubbing of sandpaper on a surface is a rudimentary example. Erosion, on the other hand, is a process of material removal from a substrate produced by the impact of particles moving freely before and after impact. In a fluidized bed, wear caused by fast moving particles in the splash zone and in the bubble wake belong to this category. Wear of injection nozzles is also mainly erosion. Stringer and Wright* presented an excellent discussion on the subject. At high temperatures, corrosion will also take place and possibly dominate; however only erosion is our concern at the present time.

Erosion of immersed tubes in a fluidized bed is a highly localized phenomenon. At a given temperature and for a given tube and particle material, the erosion rate is dependent upon the impact velocity and impact frequency of the particles. At a given location in the bed, the solids velocities are random in nature even under a fixed operating condition. Since erosion is known to be a non-linear function of impingement direction and speed, it is expected than mean velocity alone is inadequate in characterizing erosion. Hence, it is natural to seek a

more complete statistical description as embodied in the velocity distribution function.

This project is a part of a larger cooperative program "Fluidized Bed Combustion Metal Wastage Cooperation R&D Venture," sponsored by USDOE/NETC, Argonne National Laboratory, Electric Power Research Institute, CRSC, ASEA Babcock, Foster Wheeler Development Corporation, Combustion Engineering, and Tennessee Valley Authority. UIUC's participation is through a grant from CRSC.

The project has just completed its second year of research which ended on August 31, 1989. The first year contract called for the design and fabrication of a special two-dimensional bed, 3.81 cm x 40 cm in cross section and provided with a central air jet. Local velocity distribution functions of solids impinging on a rectangular obstacle were obtained. Measurements were made in the Computer-Aided Particle Tracking Facility (CPTF) at the University of Illinois, Urbana-Champaign. The selection of the special two-dimensional bed was to provide experimental data of the ensemble-averaged solids velocities needed for the validation of ANL's computer modeling effort for bed dynamics. All contractual obligations for the first year were fully met.

The determination of the velocity distribution functions of particles hitting immersed obstacles of different configurations and their hitting frequencies continued throughout the second year. All experiments were conducted in the two-dimensional bed, but modified for uniform fluidization at the request of Argonne National Laboratory. The central jet was dismantled and a new air distribution system was incorporated. To achieve improved resolution of the position data of the radioactive tracer, the scintillation 'detectors that monitor the tracer's instantaneous location were rearranged to better accommodate two-dimensional geometry. The instantaneous particle velocity data were acquired at 5 ms intervals instead of the 30 ms intervals used in the first year. In addition, the calibration setup was greatly improved. As a result, the uncertainties in the measured velocity data are significantly reduced.

3. EXPERIMENTAL FACILITIES AND PROCEDURES

3.1 Two-Dimensional Atmospheric Fluidized Bed

Figure 1 is an abbreviated assembly drawing of the modified the two-dimensional bed showing the key dimensions, inlet of the fluidization air, and the air plenum. The air distributor is of box design, packed with 3 mm diameter polyester beads sandwiched between two plexiglass distributor plates, 3.81 cm x 40 cm and 0.635 cm (0.25 in.) thick. Both plates are provided with holes, 0.14 cm (0.0055 in.) diameter, 0.873 cm (11/32 in.) center-to-center spacing in a staggered arrangement. The design of the air distribution system is to provide a uniform fluidization. The top surface of the upper plate is covered with an 80 mesh stainless steel wire gauze which constitutes the bottom of the bed. The top of the bed is open to atmosphere.
Figure 1 Assembly Drawing of a Two-Dimensional Air Fluidized Bed
The simulated tube bank consists of two rows of staggered 5.08 cm (2 in.) round rods mounted normal to the 40 cm (15 3/4 in.) surface and across the entire width of 3.81 cm (1.5 in.) of the bed. All rods of the tube bank can be individually removed from the bed. Obstacles in the form of a single round cylinder, 12.7 cm (5 in.) in diameter, and a single 12.7 cm square cylinder were also fabricated.

Fluidization air was supplied by a Gardner-Denver compressor rated at 1,000 dfm at 100 psig. Prior to entering the distribution network, it was dehumidified and filtered to remove entrained oil. Additional filters were installed in the supply line leading to the two-dimensional bed. The humidity of the fluidization air was controlled by diverting a portion of the air flow into a humidifier in which air was forced to bubble through a layer of water and then reintroduced into the supply line. The relative humidity of the fluidizing air was measured by a Vaisala humidity sensor placed in the bed and above the bubbling surface. It ranged from 33 to 39 percent. The air flow rate was measured by standard ASME orifices with flange pressure taps and U-tube manometers were used for measuring the pressure difference across the orifice plates.

3.2 UIUC's Computer-Aided Particle Tracking Facility

The particle tracking technique is based on continuous tracking of a radioactive tracer particle which is dynamically identical to the particle species under study. As the tracer particle moves with the other particles in the bed, its gamma radiation is continuously monitored by 16 strategically arranged scintillation detectors mounted at close proximity to the 40 cm surfaces of the bed, eight at the front and eight at the rear in a staggered configuration. Using an automatic triangulation scheme, modified to take full advantage of the redundancy provided by the 16 detectors, the instantaneous location of the tracer is determined. The data for the instantaneous location acquired at 5 ms intervals are time-differentiated numerically to yield instantaneous velocities. In earlier experiments, the position data were acquired at 30 ms intervals. Mean and fluctuating components of the tracer velocity and the distribution of its occurrence probability which is related to the solids density distribution are then calculated. A description of the first generation CAPTF has been documented.*

The Radioactive Tracer

The bed particles used in the present study are technical quality soda-lime glass spheres, 425-500 µm, manufactured by Potter Industries. They have a specific gravity of 2.45 to 2.49. The radioactive tracer particle was manufactured from a miniature scandium ingot having a specific gravity of 2.89. The scandium particle was coated with a layer of polyurethane of such thickness that the effective density of coated

scandium particle matches closely with that of the glass spheres. The diameter of the coated scandium particle was approximately 500 μm. The coating also prevents the abrasive loss of radioactive material in the erosive fluidized environment. The coated tracer was irradiated in the University of Missouri Research Factor to obtain activities ranging from 400 to 600 μCi. The irradiation process resulted in scandium-46 isotope which has a half-life of 84 days and decays to stable titanium-46 by emission of gamma rays at 0.889 MeV and 1.112 MeV. Activities at the cited level are needed to reduce the effect of the intrinsic noise by increasing the signal to noise ratio and to allow moderate amplification for better signal conditioning. It also reduces the effects of attenuation and scattering of the gamma rays by the varying concentration distribution of glass particles during the operation of the fluidized bed.

High Speed Data Acquisition and Signal Processing

During the first year, all particle velocity data were acquired at 30 ms intervals which was adequate for the long time ensemble-averaged velocities. Much higher rate was needed for the determination of the velocity distribution function and the impact frequency of particles hitting the surface of immersed obstacles in the bed. The impact frequency is evaluated by counting the number of times the radioactive tracer appears in the sampling cell adjacent to the obstacle and moves toward the surface. The procedure is accurate only if the cell size is sufficiently small. Consider, for instance, a particle transverses at an instantaneous velocity of 50 cm/s. In 30 ms, it will travel a distance of 1.5 cm which is excessively large for a 5.08 cm rod. Hence, a higher sampling rate was necessary and, in this report, all position data of the tracer were obtained at 5 ms intervals, representing a six-fold increase in the sampling rate. In order that research progress is not interrupted, a short-term and a long-term plan have been implemented.

The short-term plan does not involve hardware modification. At the present time, the output signals from the scintillation detectors are processed in parallel using a digital counting circuitry. It consists of an amplifier, a leading edge discriminator, a binary counter, a TTL pulse shaper and an interface to transfer the gamma ray count to an on-line computer. The latter is a DEC PDP 11/34A micro-computer procurred seven years ago. The discrete, instantaneous positions of the tracer are computed from previously established calibration tables and the position data are stored in a magnetic disk, DLI. Since the speed of the computer is limited, the computation requires approximately 30 ms which corresponds to a sampling rate of 33 Hz. To acquire the data at 5 ms intervals which corresponds to a sampling rate of 200 Hz, we resort to the off-line data processing technique for which the computer is used only for recording the gamma ray counts, leaving the calculation of the instantaneous tracer position off-line. The storage capacity of the DLI disk is 5.2 Mbytes. With the on-line mode, it allows us to store the two coordinates (x,z) of the tracer's position vector acquired during approximately 300 min of experimental run. When the system is operated in the off-line mode, the count rate of all 16 detectors has to be stored and subsequently used for the determination of the tracer's position coordinates. For a sampling rate of 200 Hz, the disk can
accommodate only 9.3 min of real time experiments. Furthermore, since the sampling cell is smaller, the number of data points available in each cell in a given time is smaller. Therefore, much longer experimental runs are required. On the other hand, however, when only the impact frequency at the surface of the immersed obstacle is sought, computation of the tracer velocities needs to be performed only for the sampling cell adjacent to the obstacle surface in question.

The software for data acquisition in the off-line mode consists of one main command program and three subprograms--BMPOFF, POLOFF, and POSOFF. The main command program controls the appropriate rate of operation of the subprograms. The acquisition of the gamma ray count rates and their real-time storage in the DLL disk are performed by BMPOFF. The POLOFF subprogram provides 16 sets of the polynomial coefficients that relate the count rate to the distance between the tracer and the NaI crystals of the scintillation detectors. The relation is determined from a prior calibration and the information is stored in another disk, DLO. The POSOFF subprogram calculates the instantaneous position coordinates of the tracer using the count rate data stored in DLL disk and the calibration data stored in DLO disk. The results are also stored in DLO disk. The main program initializes the DLL disk and transfers the instantaneous position data back to DLL.

The software for data reduction consists of two FORTRAN programs--MEANOF and DSTROF. The MEANOF program calculates the ensemble-averaged particle velocities and the DSTROF program evaluates the velocity distribution function and impact frequency. The computed data are then transferred to CONVEX C220 minisupercomputer with an integrated vector processor and large memory through telephone line with a 2400SA modem manufactured by Practical Peripherals. The operating system is CONVEX UNIX and the plotting routine used was developed by National Center for Atmospheric Research (NCAR). The data for velocity distribution function and impact frequency are stored in CONVEX C220 and subsequently transferred to Macintosh II PC for plotting, using the KERMIT software.

The long-term plan for improving the data acquisition and processing capability, both in speed and in quality, involves updating the hardware as well as software modification. The existing Bicron Model 2M2/2 NaI scintillation detectors have become aged in use, giving an output of approximately 5 mV. This low output necessitates the use of variable gain amplifiers in order to increase the pulse height to a level above the 30 mV threshold of the discriminators. The use of the amplifier reduces the signal-to-noise ratio. The new NaI detectors can be operated at a high applied voltage, resulting in a greater output signal. Using an allowable voltage of 1400 v, the pulse height exceeds 65 mV. This improvement is significant in that it eliminates the use of intermediate amplifiers with the concomitant increase in signal-to-noise ratio. Furthermore, the enhanced detector output allows the incorporation of a pulse splitting scheme that almost eliminates or greatly reduces the decay time of the current pulses and thus significantly increases the speed of data acquisition. Details of the pulse splitting scheme, signal conditioning and discriminating, pulse counting, and com-
puter interface have been reported previously* and thus will not be re-
peated. It should be noted that the major portion of the cost involved
in the development and implementation of the long-term plan is not borne
by the project. The plan, when operational, would make it possible for
us to return to on-line processing of the tracer's position data with
increased speed and accuracy.

3.3 Operating Conditions

Under the terms of the contract, the operating conditions of the two-
dimensional bed, as specified by the Argonne National Laboratory, were
as follows:

- Bed particles - technical quality soda-lime spheres, (Potter
  Industries P-0230), density: 2490 kg/m³, diameters after
  sieving: 425 to 500 µm.

- Immersed Obstacles
  
  (a) Single square cylinder, 12.7 cm x 12.7 cm, with its center
  located 29 cm above the air distributor plate and two of
  its flat surfaces parallel to the air distributor plate.
  The static bed height is 48 cm.

  (b) Simulated tube bank consisting of two rows of round
  cylinders, 5.08 cm in diameter, in staggered arrangement
  with horizontal spacing of 15.2 cm and vertical spacing of
  7.6 cm. The center plane of the bottom row is located at
  a distance of 22.9 cm from the air distributor plate. The
  static bed height is 40.6 cm.

  (c) Single round cylinder, 12.7 cm in diameter, with its
  center located 29 cm above the air distributor plate. The
  static bed height is 48 cm.

3.4 Improved Calibration Set-Up

The count rate of the γ-ray emitted by the radioactive tracer and sensed
by the NaI crystal of the scintillation detector depends, for a fixed
strength of the radioactivity, on the distance between the tracer and
the crystal. The distance versus detector count rate relation was
determined by in-situ calibration. The procedure consists of attaching
the tracer to the conical tip of a 12.7 mm (0.5 in.) steel rod held
rigidly in a positioning device located above the bubbling surface of
the two-dimensional bed. The calibration rod was thus a simple cantil-
lever. When the cantilever's length is large which occurs at locations
farther away from the bubbling surface, its tip exhibits small movement
under the action of fluctuating pressure and solids motion, thus con-
tributing error to the calibration data. This shortcoming was to a
great extent remedied by providing additional support. The rod has, in
essence, been converted from a cantilever to a simple beam with two

submitted to CRSC, May 31.
clamped supports and an overhanging. As a result, the rigidity of the rod was greatly increased and 2- to 3-fold reduction in the scatter of calibration data was noticed.

4. RESULTS AND DISCUSSION

Particle velocity measurements have been completed for the single square cylinder 12.7 cm x 12.7 cm, and for the simulated tube bank. Computer printout for the horizontal and vertical components of the ensemble-averaged particle velocities have been submitted to CRSC*. They were based on data obtained in the CAPTF during an accumulated total of 40 hours of test run. The data for the simulated tube bank have also been transmitted to Dr. Walter Podolski, Argonne National Laboratory, by electronic mail. They will not be repeated here. During the fourth quarter, vector plots for the ensemble-averaged solids velocity field, circumferential distribution of particles' impact frequency on the rod surface, and the directional and velocity distribution function of particles hitting selected surfaces of three of the five 5.08 cm rods of the simulated tube bank have been obtained. These are presented in this report.

4.1 Ensemble-Averaged Solids Velocity Field

The simulated tube bank and its location in the 3.81 cm x 40 cm two-dimensional bed is shown in Fig. 2. It consists of two rows of round cylinders, 5.08 cm in diameter, in staggered arrangement with a horizontal spacing of 15.2 cm and a vertical spacing of 7.62 cm. Bed particles are soda lime glass beads having a material density of 2490 kg/m$^3$ and a mean diameter in the range of 425 to 500 μm. The static bed height was 40.6 cm and the minimum fluidization velocity $U_{mf}$, determined from pressure drop measurements, was 20.4 cm/s. The superficial air velocity $U_o$ was 39.0 cm/s (specified by ANL), thus $U_o/U_{mf} = 1.91$. The relative humidity of the fluidizing air ranged from 0.33 to 0.39. The tracer's position was tracked at 5 ms interval for a total of 40 hours. The individual rods are identified with numerals 1 through 5 as shown in Fig. 2 for the convenience of later referral when the results are discussed.

Figure 3(a) and 3(b) are the vector plots of the ensemble-averaged particle velocities in the two-dimensional bed. The plotting was done on the Convex minisupercomputer using the NCAR plotting routine. A square grid with $\Delta x = \Delta z = 5$ mm was used. The plotting routine nullifies all vectors that exceeds 5 mm and when it occurs a small dot is printed instead. Hence, the resolution of the resulting plot can be altered by changing the scale chosen for the velocity vectors. In both


Figure 2  Key Dimensions and Location of Simulated Tube-Bank in Two-Dimensional Air Fluidized Bed (numerical designation of various surfaces of the rod is illustrated in the upper right hand corner)
Figure 3  Ensemble-Averaged Particle Velocity Field in Two-Dimensional Air Fluidized Bed with Simulated Tube Bank. 425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s  
(a) speeds > 20 cm/s appear as a dot,  (b) speeds > 10 cm/s appear as a dot
figures, the length of the longest vector is shown in the upper left corner. In Figs. 3(a), it corresponds to a speed of 20 cm/s while the solids flow patterns are discernible, the resolution is generally poor, particularly at the surface of the immersed rods which is of the greatest interest in tube erosion studies. In Fig. 3(b), the maximum velocity scale is 10 cm/s. It is seen that an improved resolution of the velocity field surrounding the rods is obtained. Figure 3(b) is useful in that it displays the particular portion or portions of the rod surface where the velocities are high (appear as dots). As such, these are regions where enhanced tube erosion is expected to take place. Accordingly, the directional distribution function and the speed distribution function for the particle hitting these regions were evaluated. It should be noted, however, that the revelation of these regions of interest on the rod surface can also be achieved by carefully examining the tabulated data of the x- and z-components of the particle velocities in the neighborhood of the rod surface. But such endeavor is extremely time consuming and would require a tabulation of sufficiently small spatial increments.

4.2 Ensemble-Averaged Solids Density Field and Mass Balance

The number density of the tracer's occurrences in the sampling compartment is directly proportional to the solids density when the number of occurrences is sufficiently large. A procedure of determining the ensemble-averaged solids density distribution was explained in the Third Quarterly Report and thus will not be repeated. With the availability of the ensemble-averaged velocities and densities, the self-consistency of the measured data was examined by calculating the net mass flow through four imaginary horizontal surfaces extending over the entire cross section of the bed and four vertical imaginary surfaces of sufficiently large height. Ideally, the net mass flow should be zero. The results of this calculation showed the deviation from the ideal condition amounted to a few percent as was previously documented in the Third Quarterly Report.

4.3 Particle Hitting Frequency at Surface of Immersed Rods

The circumferential distribution of the solids hitting frequency at the rod surface can be determined by counting the total number of impacts the tracer hit a specified area of the rod surface during the 40 hour test run. The measured results are shown in Figs. 4(a), (b), and (c) for Rod 1, 3, and 4, respectively. In a recent ANL report*, a simple theory of tube erosion was examined and compared with several other erosion models. While the reliability of the models is uncertain, they all indicate that the rate of tube erosion increases with increasing of particle velocity as shown in Fig. 5 which was reproduced from a that report. Of interest is the fact that when \( \frac{U_p}{U_{mf}} \leq 0.8 \), erosion virtually ceases. Hence, two sets of data are plotted in Figs 4(a),

Particles from all directions and of all speeds
- Particles from all directions but only of speeds \(>U_C\), \(U_C/U_{mf} = 0.8\)

Figure 4  Circumferential Distribution of Particle Hitting Frequency Per Unit Area (\(cm^{-2}s^{-1}\)) of Rods 1, 3 and 4 of Simulated Tube Bank

425-500 \(\mu\)m glass beads, \(U_{mf} = 20.4\) cm/s, \(U_0 = 39.0\) cm/s
Coal Research Establishment (CRE) Few Tube
Geometry Comparison of Average, Time-Averaged
Erosion Rates for Three Aluminum Tubes
4(b), and 4(c). The squares are for the case when particles of all speeds are counted and the circles are for the case where only particles with speeds $\geq 0.8 \ U_{mf}$ or 16 cm/s are counted. In both cases, particles hitting the surface from all directions are included in the counting.

Lyczkowski, et al.* studied the influence of solids velocity and impinging angle on the erosion rates of aluminum impacted by aluminum oxide particles, using the erosion model proposed by Nielson and Gilchrist.** It was found that for a fixed speed maximum erosion rates occurred at an impinging angle of around 20° (or 70° from the surface normal). Hence, the directional distribution functions of particles hitting the various surfaces of the immersed rods of the simulated tube banks were determined. The surfaces of each rod are identified by a numeral as illustrated in the insert of Fig. 2.

The directional distribution functions of particles hitting surfaces 4, 5, 6 of Rod 1 are shown in Figs. 6(a), (b), and (c), respectively. The locations of the surfaces under consideration are illustrated in the figure. The direction along which the particles hit the surface are defined by the angle $\beta$ which ranges from -81° to +81° with 18° increment, i.e., $\Delta \beta = 18°$. Details of the analysis used for the calculation of these functions and the speed distribution function along a specified direction, to be given later, have been presented in the project's first Final Annual Report for the period 1 February 1987 to 31 March 1988 and thus will not be repeated here. As pointed out in that report, the directional distribution function, as the name implies, describes how the particles hitting the surface distribute among themselves in the two-dimensional half-space external to the surface. Two distribution functions are shown in each figure. One is based on particles of all speeds (empty bars), and another is based on particles with speeds greater than the critical speed $U_c$ with $U_c/U_{mf} = 0.8$ and hence $U_c = 16$ cm/s. Referring to Fig. 6(a), it is seen that, when particles of all speeds are counted, 14.7 percent of the incoming particles are inside a wedge whose center plane is at an angle $\beta = -81°$ from the surface normal and whose opening angle $\Delta \beta$ is 18°. Particles inside a neighboring wedge ($\beta = -63°, \Delta \beta = 18°$) constitute 13 percent of the total. When only particles with speeds greater than $U_c$ are counted, the corresponding values are 24.8 percent and 15.0 percent, respectively. These particles hit the surface with a large, upward tangential component of velocities. Again, when particles of all speeds are counted 9.1 percent are inside the wedge with $\beta = +81°$ and $\Delta \beta = 18°$ and 11.1 percent are in its contiguous neighboring wedge with $\beta = +63°$. The corresponding values are 16.1 percent and 11.6 percent when only particles with speeds greater than $U_c$ are considered. For a wedge whose

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Figure 6  Directional Distribution Function of Particles Hitting Surfaces 4, 5, and 6 of Rod 1 of Simulated Tube Bank
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
center plane coincides with surface normal \((\beta = 0^\circ, \Delta \beta = 36^\circ)\), particles of all speeds constitute 16.3 percent. The corresponding value for particles with speeds greater than \(U_c\) is 9.3 percent. Thus, there is a significant redistribution of the relative proportion of particles hitting surface 4 when consideration is given to the existence of the critical speed. Similar redistribution can be seen in Fig. 6(b) for surface 5 and in Fig. 6(c) for surface 6.

The directional distribution functions for particles hitting surfaces 4, 5, and 6 of Rod 3 and Rod 4 are plotted in Figs. 7(a), (b), (c) and Figs. 8(a), (b), (c), respectively. The redistribution for all three surfaces of Rod 4, as a result of incorporating \(U_c\) in the calculation, is similar to the corresponding surfaces of Rod 1. On the other hand, a minimal of redistribution is seen in Fig. 7 for all three surfaces of Rod 3. More work is needed to understand this finding.

While the information revealed by the directional distribution function is obviously most appropriate, it is incomplete insofar as the study of erosion is concerned. As has been pointed out by Lyczkowski, et al., erosion of metals by a stream of particles depends not only on the direction of impingement but also on the impact speed. Such information is embodied in the velocity distribution function. The velocity distribution functions of particles hitting surface 4 of Rod 1 along six indicated directions are plotted in Fig. 9(a). The directions are identified by numerals as illustrated in the insert at the lower left corner of the figure. Numerical codes used in the computer for the identification of the rod (r), surface (s), and direction (j) are printed in each figure. This eliminates possible identification error associated with the very large number of such distribution functions that can be investigated (5 rods x 8 surfaces/rod x 10 directions/surface = 400). It is seen from Fig. 9(a) that the speeds of particles hitting surface 4 are generally higher along the directions (1,2) and (9,10) and those along the directions (5,6) are lower. The impinging angle corresponding to directions (1,9) is 9° and that corresponding to directions (2,10) is 27°. If the analysis of Lyczkowski, et al. is applicable, the local erosion rate is expected to be caused mainly by particles coming in these directions which are also of higher speeds. From the information provided by the directional distribution function shown in Fig. 6(a) and the velocity distribution function shown in Fig. 9(a), one may speculate that particles hitting surface 4 in the directions (1,2) would cause the maximum damage, those in directions (9,10) would be next in severity, and those in directions (5,6) would be the least harmful. It remains to be seen if these predictions can be verified by erosion measurements. The velocity distribution functions of particles hitting surface 5 and 6 of Rod 1 are displayed in Figs. 9(b) and 9(c), respectively. Examination of these figures reveals that the speed of particles impacting on these surfaces are also generally higher in the directions (1,2 and 9,10) and lower in the directions (5,6). However, Fig. 6(b) shows that there were more particles coming in the directions (9,10) than (1,2) for surface 5, and Fig. 6(c) shows that still greater number is coming in the directions (9,10) for surface 6. In all cases particles hitting the surface in the near normal direction are not only less frequent but also of lower speeds.
Figure 8  Directional Distribution Function of Particles Hitting Surfaces 4, 5, and 6 of Rod 4 of Simulated Tube Bank
425-500 μm glass beads,  $U_{mf} = 20.4 \text{ cm/s}$,  $U_0 = 39.0 \text{ cm/s}$
Figure 9a  Velocity Distribution Function of Particles Hitting Surface 4 of Rod 1 Along Directions (1, 2, 5, 6, 9, 10) 425-500 μm glass beads, $u_{mf} = 20.4$ cm/s, $u_0 = 39.0$ cm/s
Figure 9b  Velocity Distribution Function of Particles Hitting Surface 5 of Rod 1 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
The velocity distribution functions of particles hitting surfaces 4, 5, 6 are plotted in Figs. 10(a), 10(b), and 10(c) for Rod 3 and in Figs. 11(a), 11(b), and 11(c) for Rod 4. Qualitatively, the phenomenon just described for the three surfaces of Rod 1 remain true although they differ in detail. We recall that Rod 4 was situated symmetrically along the vertical centerline of the two-dimensional bed. Hence, the velocity distribution function of particles hitting its surface 5 in the (1,2) directions should ideally be the same as those in the (9,10) directions. Such symmetry is not disclosed in Fig. 11(b). However, this is not surprising since the lack of symmetry exists even in the vector plots for the ensemble-averaged particle velocities as can be seen in Fig. 3.

In this report, the directional distribution function and the velocity distribution function are presented only for surfaces 4, 5, and 6 of Rods 1, 3, and 4. These were requested by Dr. Podolski of Argonne National Laboratory. Selected results for surfaces 1, 2, 3, 7, and 8 and for Rods 2 and 4 will be included in a forthcoming MS thesis by Yihong Ai.
Figure 10a  Velocity Distribution Function of Particles Hitting Surface 4 of Rod 3 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
Figure 10b: Velocity Distribution Function of Particles Hitting Surface 5 of Rod 3. Along directions (1, 2, 5, 6, 9, 10) for 425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s.
Figure 10c  Velocity Distribution Function of Particles Hitting Surface 6 of Rod 3 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
Figure 11a  Velocity Distribution Function of Particles Hitting Surface 4 of Rod 4 Along Directions (1, 2, 5, 6, 9, 10) 425-500 µm, glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s
Figure 11b
Velocity Distribution Function of Particles Hitting Surface 5 of Rod 4 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, \( U_m = 20.4 \text{ cm/s} \), \( U_o = 39.0 \text{ cm/s} \)
Figure 11c  Velocity Distribution Function of Particles Hitting Surface 6 of Rod 4 Along Directions (1, 2, 5, 6, 9, 10)
425-500 μm glass beads, $U_{mf} = 20.4$ cm/s, $U_0 = 39.0$ cm/s