QUANTITATIVE CAPACITIVE MEASUREMENTS OF VOIDAGE IN GAS-SOLID FLOWS

Catherine Acree Riley and Michel Louge
Department of Mechanical Engineering, Cornell University,
Upson Hall, Ithaca, NY 14853, USA

ABSTRACT

New capacitance probes were developed for quantitative, time-dependent measurements of voidage in gas-solid flows. Based on a unique guard circuit which nearly eliminates all stray and cable capacitances, these probes are fast (2kHz) and they do not require *in situ* calibration. Two configurations were studied: small parallel plates for recording voidage profiles, and a non-intrusive design for local voidage measurements near a wall. Static tests were performed using a fixed bed of known voidage and dielectric constant. The probes were also demonstrated in a two-dimensional fluidized bed of glass beads.

1. INTRODUCTION

The behavior of dense particulate flows is a direct result of their detailed flow structure. The determination of local solid volume fractions is particularly important for gas-solid mixtures since these mixtures are often highly heterogeneous and unsteady. Therefore, measurements of solid volume fraction should be local, fast, and quantitative.

Capacitance probes are well-suited for measurements of holdup in weakly conductive media such as gas-solid flows [1]. In most designs, a high-frequency oscillator drives a bridge circuit that records capacitance between its two input leads. In this configuration, the capacitance of the two leads connecting the probe to the bridge is often larger than that of the probe itself. By contributing significantly to the overall measurement, this "cable capacitance" considerably reduces the sensitivity of the system. An equally serious problem is to limit the effect of surfaces held at floating potentials that are located near the probe. Attempts to shorten the cable or to reduce such stray capacitances have allowed careful workers to obtain a sensitivity as small as 0.01pF [2]. But if the cable and stray capacitances are not eliminated, it is difficult to obtain a quantitative measurement of solid holdup using a capacitance probe. As a result, applications of these probes have been confined to gross changes in capacitance such as those occurring at the passage of a bubble in a fluidized bed [3]. Other workers have attempted to calibrate the problem away when the capacitance of the sensing probe is of sufficient magnitude [4,5].

To this date, capacitive measurements of solid volume fraction have been inaccurate. In this paper, we describe new probes based on a unique guard circuit that virtually eliminates all stray and cable capacitances. This circuit, marketed by Mechanical Technology Inc., enables design of ultra-sensitive probes for measuring the local, time-dependent volume fraction of particles in gas-solid flows. Unlike previous designs, these probes do not require *in situ* calibration; they produce a linear output over relatively large ranges of solid volume fractions; and they follow transient variations as rapid as 2kHz.

2. PRINCIPLE

The probes and guard circuit, developed by Mechanical Technology Inc., were originally designed to measure distances between two planes with great accuracy [6,7]. With modifications of the probe geometry, we are applying the same electronic circuitry to gas-solid diagnostics. The probe can be constructed several different ways, provided that a sensing conductor, a ground conductor, and a guard conductor are included in the design. A common configuration is shown in Fig. 1. The ground conductor is connected to the amplifier for reference. The sensing surface is separately connected to the amplifier by a conductor that is entirely surrounded by the guard conductor. The guard conductor is driven at a 16 kHz oscillating voltage that follows both the phase and amplitude of the sensing voltage with great accuracy. This eliminates the cable capacitance, because the only measurable capacitance is that between the sensing surface and ground. For the parallel-plate arrangement, the guard surface also ensures that electric field lines between sensor and ground are left nearly undisturbed by other conductors present in the vicinity. Consequently, there is a drastic reduction in stray capacitances for this geometry.

Because the time-average guard and sensing voltages are kept precisely at the ground voltage, the probes do not induce electrostatics in the gas-solid mixture, nor do they attract charged particles. However, particles may lose static charge by contact with either ground or sensing surfaces. Also, the presence of charged particles in the probe's measurement volume affects the system's output, as expected from Maxwell's eq.:

$$\nabla . \varepsilon \mathbf{E} = \rho, \tag{1}$$

where **E** is the electric field, ρ is the local density of charges held by particles, and ε is the local permittivity of the gas-solid mixture. With these probes, care must be taken to minimize triboelectricity in flowing gas-solid mixtures. Nevertheless, note that we have not observed significant effects of electrostatics in the fluidized bed experiments described in section 2.

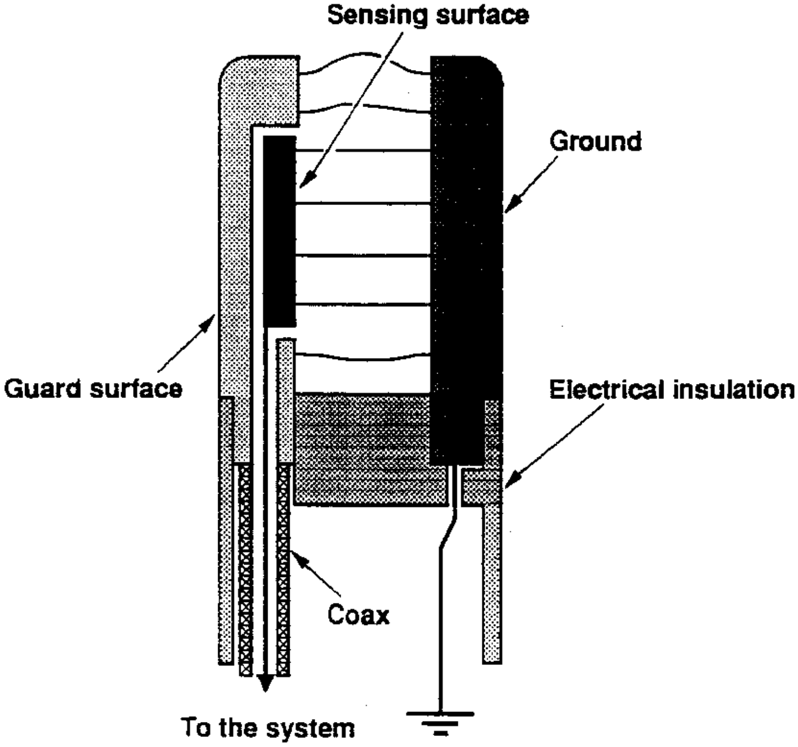

Fig. 1: The parallel-plate probe configuration. Dimensions are not to scale.

The system's amplifier produces an output voltage between 0 and 10 V that is related to C, the capacitance between the ground and sensing surfaces, by:

$$V = \frac{Q_s}{g\,C}, \tag{2}$$

where $Q_s = 3.44\ 10^{-12}$ Coulombs is a system constant and the gain, g, may be adjusted between 1 and 6.5. The bandwidth of this system allows measurements of capacitance variations as rapid as 2 kHz. Typical rms noise levels are of the order of 7.5 mV for a dc signal of 10 V and a gain of 1. An output of 10 V corresponds to C = 0.344 pF; thus a typical rms noise of $\Delta V \approx 7.5$ mV corresponds to an unprecedented sensitivity of $\Delta C \approx 0.3$ fF.

Local changes in solid volume fraction alter the capacitance between the ground and sensing surfaces according to:

$$C = C_o\, K_{eff}\ , \tag{3}$$

where K_{eff} is the effective dielectric constant of the gas-solid mixture and C_o is the probe's capacitance in air. Because of the high frequency of the applied electric field (16 KHz), conduction and space charge effects in the gas-solid mixture are negligible. As a result, the effective dielectric constant K_{eff} is purely a function of geometrical parameters (local voidage, particle size, sphericity and size distribution). For monodisperse, spherical particles, several models have been proposed to relate K_{eff} to voidage [8].

In the next section, we show that the "Lorentz sphere unit cell model" provides the best fit to our data for closely packed, monodisperse, spherical particles with moderate values of K:

$$K_{eff} = \frac{3\,K - 2\,\phi(K-1)}{3 + \phi(K-1)}. \tag{4}$$

K is the dielectric constant of pure solid and ϕ is the local voidage (assumed constant in the measurement volume). All constants are either known (g, K, Q_s, C_o) or their relation with the voidage ϕ can be checked independently (K_{eff}). As a result, the system provides a direct measurement of voidage, and it does not require *in situ* calibration.

In order to ensure maximum system sensitivity for a given probe, the gain is set to generate an output voltage of 10 V in air. The corresponding relationship between output voltage and solid volume fraction is plotted in Fig. 2. Its curvature is relatively small. As a result, the curve is nearly linear over relatively large excursions of solid volume fractions (±10%), which is an advantage for on-line time-averaging, if necessary. The relationship in Fig. 2 is true for any probe configuration, provided that particles are uniformly dispersed throughout the probe's measurement volume. In this study, two geometries were tested: the parallel-plate probe and the wall probe.

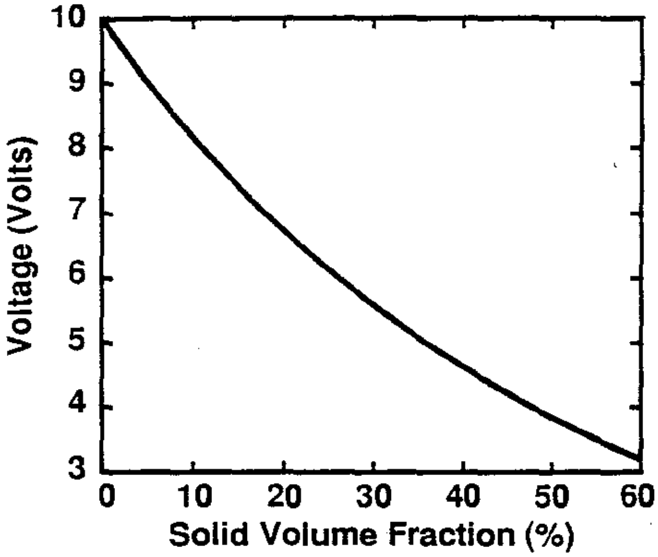

Fig. 2: System output *vs.* solid volume fraction for particles of dielectric constant K = 7.9.

2. EXPERIMENTS

2.1 Parallel-Plate Probe

For the prototype used in this study, the plates were rectangles of 27 x 11 mm^2 separated by a gap of 3.7 mm (Fig. 1). The sensing area was a rectangle of 10.4 x 3.7 mm^2. The width of the guard surface was 3.7 mm on three sides of the sensing rectangle and 12.9 mm to the insulator. We found that equating the width of the guard surface to the distance between the two parallel plates is a reasonable compromise between reduction of stray capacitances and reduction of the overall probe size. For this arrangement capacitance is accurately predicted by:

$$C_o = \varepsilon_o \frac{A}{d}, \tag{5}$$

where ε_o is the permittivity of free space ($8.854\ 10^{-12}$ F/m), A is the sensing area, and d is the gap width. For this prototype, the theoretical capacitance and the value inferred from the system output differed by less than 2%.

A simple test, similar to that reported by Yutani *et al.* [5], was used to check the behavior of the system in the presence of particles, and to find a model that provides the best fit of effective dielectric constant for spherical particles at close packing. In this experiment, the parallel-plate probe was progressively immersed in a closely packed, monodisperse bed of 70 μm spherical glass beads of known dielectric constant (K=7.9±0.1) and packing coefficient ($1-\phi_p = 56\pm2$ %). From the amplifier's point of view, the percentage of the covered sensing area (0 to 100%) simulated the range of capacitance values corresponding to solid volume fractions from complete voidage ($\phi = 1$) to that of a packed bed ($\phi = \phi_p$). For this closely packed, monodisperse bed of spherical particles, Fig. 3 shows best agreement of K_{eff} with the predictions of the Lorentz sphere model. The parallel and isolated sphere models clearly deviate from our results. The Lorentz model falls within experimental error, in agreement with the results of Zahn and Rhee [8]. In this test, we do not attribute errors to the capacitance system, but rather to the difficulty to measure accurately the size of the covered sensing area, and variability in the packing coefficient.

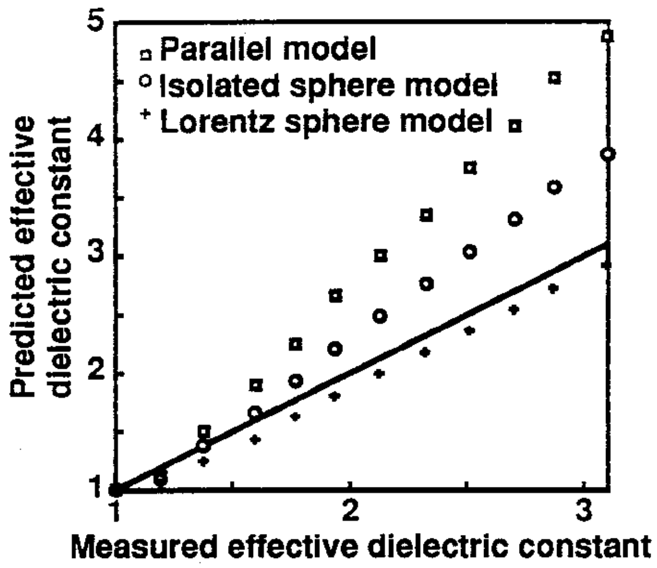

Fig. 3: Comparison of the effective dielectric constants measured using the parallel-plate probe and their values predicted using three different electrostatic models.

2.2 Wall Probe

Unlike the parallel-plate probe, the wall probe is not intrusive. In this configuration, the ground, sensing, and guard surfaces lay in the same plane, allowing the probe to be mounted flush with the wall of a vessel. The probe possesses cylindrical symmetry about the axis shown in Fig. 4. The ground surface is a disk, and the sensing surface resembles a washer. For a guard surface extending to infinity on all sides, theory predicts that the electric field is tangent to circular surfaces of revolution normal to the ground and sensing surfaces.

For design purposes, we approximated the axisymmetric potential field using a two-dimensional conformal mapping solution [9], and derived the capacitance between the sensing and ground surfaces from the resulting complex potential field:

$$C_o = 2\, a\, \varepsilon_o \ln \left[\frac{c^2 - a^2}{b^2 - a^2}\right] , \tag{6}$$

where a, b, and c are found in Fig. 4.

A measure of the probe's spatial resolution is given by the electric field lines emerging from the edges of the sensing surface (Fig. 4). Using the complex solution, these field lines are circular arcs of radius $r_o = (c^2 - a^2)/2c$ and $r_i = (b^2 - a^2)/2b$. With cylindrical symmetry, they correspond to a measurement volume bounded by two semi-toroidal surfaces. The prototype tested in this study had dimensions: a = 2.97 mm, b = 3.81 mm, and c = 5.72 mm. The approximate expression of eq. (6) predicts a capacitance of 75 fF. The measured capacitance was 73 fF, in good agreement with the simple two-dimensional solution. The predicted measurement volume of 0.14 cm^3 extends approximately 2.1 mm from the probe surface. The true extent of the measurement volume was checked by covering the probe, including the entire guard surface, in a bed of 70 µm glass beads of increasing thickness. The bed thickness did not affect the resulting signal once it reached a value slightly below 2 mm, thus confirming the predicted extent of the measurement volume.

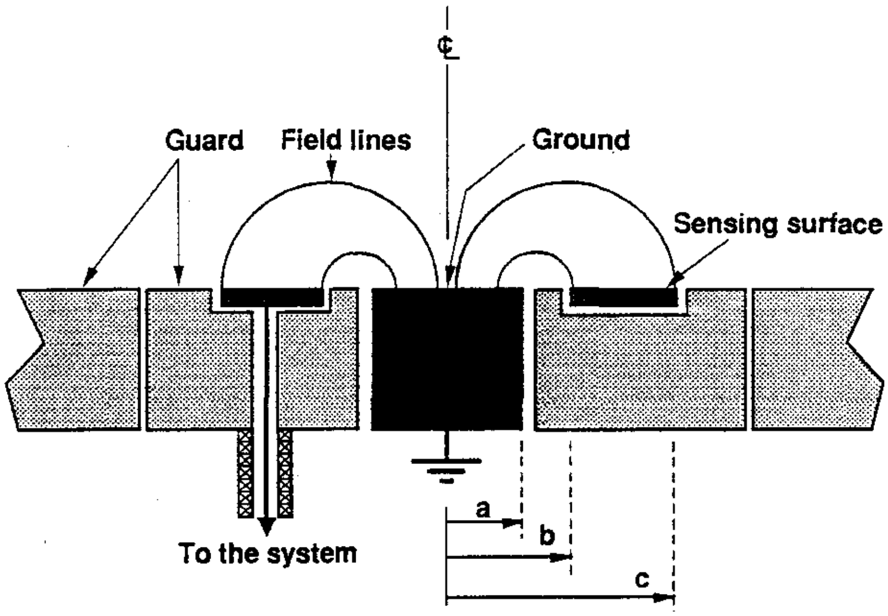

Fig. 4: Wall-probe configuration. Dimensions are not to-scale.

In this configuration, the guard surface should extend to infinity on all sides. In practice, only a portion of the vessel wall adjacent to the probe needs to be electrically connected to the guard circuit. For this particular prototype, the guard diameter ceases to affect the output signal once it reaches a value of 17 cm. As a result, the system provides a quantitative voidage measurement without calibration, as long as the diameter of the guard surface is greater than 17 cm, and no freely-charged, conducting surfaces are present in the vicinity of the probe.

Nevertheless, the system may still measure solid volume fractions accurately with guard surfaces of diameter smaller than 17 cm, and in the presence of surfaces held at floating potentials. In this case, the system's gain should be set to provide an output voltage of 10 V when no particles are present. The system is now self-calibrated, so that its output may still satisfy the relation plotted in Fig. 2. Tests were conducted with guard disks 8 cm and 15 cm in diameter, and with freely-charged metal surfaces as close as 8 cm from the probe's centerline. To evaluate the system's accuracy in these situations, we recorded measurements of the probe covered with a packed bed of 70 μm glass beads of known voidage. The relative error in these tests was better than 2%. Therefore, using self-calibration, the wall probe may provide accurate measurements for certain non-ideal configurations. However, in the presence of surfaces held at floating potentials, the gas-solid mixture between the probe and the conductor should be homogeneous for accurate measurements, because the new orientation of the electric field lines induced by the conductor increases the size of the measurement volume. Measurements in the presence of freely-charged, conductive surfaces should therefore be treated with caution.

2.3 Fluidization Tests

The dynamic performance of both probes was evaluated in a two-dimensional air-fluidized bed. A plexiglas vessel of cross-section of 2.5 x 25 cm was filled with 70 μm glass beads of density 2.55 g/cc to a packed height of 61 cm. The probes were immersed in the bed at a distance of 45 cm above the gas distributor. Probe signals were acquired using a digital oscilloscope. Simultaneous videotaping of the experiments allowed comparisons between the probe output and visible changes in solid volume fraction. The guard plane of the wall probe was 8 cm in diameter.

Experiments were first conducted in the bubbling bed regime with superficial gas velocity $u \approx 4\ u_{mf}$, where $u_{mf} \approx 5$ cm/sec is the measured minimum fluidization velocity. Sudden increases in output voltage coincided with observations of bubbles passing in front of the probe (Fig. 5). On the largest peak, two coalescing bubbles can be distinguished. Smaller peaks correspond to bubbles that did not completely cover the probe. Between bubbles, the emulsion phase voidage returned to a value of 48 %. Similar signals were obtained using the parallel-plate probe. However, that probe detected more bubbles than the wall probe, because its measuring volume covered a larger fraction of the bed width. The voidage measured with the capacitance probes agreed within 5% with the voidage inferred independently from wall pressure measurements.

In addition, the response of the probes was tested in de-fluidization experiments, where the air flow was suddenly interrupted using a quick-closing valve actuated by a solenoid. A typical trace for the wall probe is shown in Fig. 6. The rapid closure of the valve induced a spike that provided a convenient reference time for the probe signal. A clock display triggered by the solenoid was superimposed on the videotape recording the collapse of the bed surface.

For this powder of Geldart's class A, the initial stage of bed collapse corresponds to bubbles escaping from the bed [10]. In this experiment, bubbles left the bed for approximately 3 sec. As shown in Fig. 6, the wall probe did not record dramatic voidage fluctuations while the bubbles escaped, because few bubbles had traversed its measurement volume. After all bubbles had left, the emulsion phase slowly reached a loosely packed state of voidage $\phi = 44.8$ %.

In Fig. 6, a sudden compaction of the bed is clearly observed on the voidage trace. This event was simultaneously recorded on the videotape. It is characteristic of a stick-slip

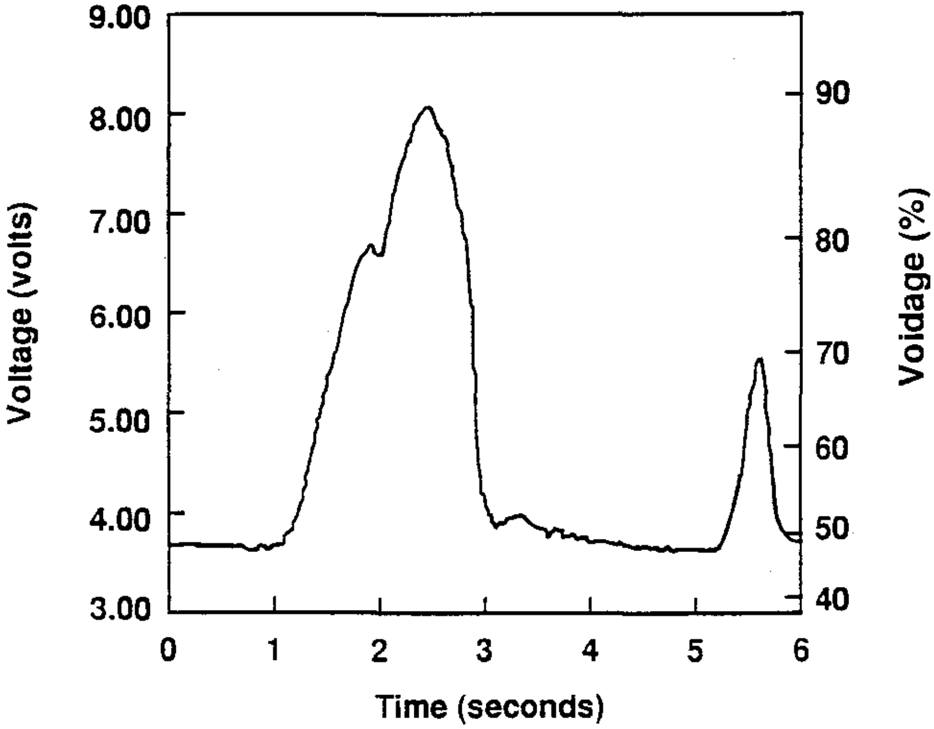

Fig. 5: Passage of bubbles in front of the wall-probe at $u \approx 4\ u_{mf}$. The powder was 70 μm glass beads of density $\rho_s = 2.55$ g/cc and dielectric constant K=7.9. The amplifier gain was set at g = 4.5.

behavior that is often observed in narrow beds of powders showing degrees of cohesiveness. The detection of this event by the wall probe illustrates the exceptional sensitivity of this capacitance system. Within experimental error, the change of voidage associated with this event was consistent with the magnitude of the drop of the bed surface recorded on the videotape.

Similar traces were obtained with the parallel-plate probe. The escape of bubbles, the slow collapse of the emulsion phase, and occasional stick-slip jumps were observed. However, as expected from its larger measurement volume, this probe recorded more dramatic voidage fluctuations during the bubble escape period. Also, its response appeared to lag behind that of the wall probe (Fig. 6 & 7). This behavior is expected, because the parallel-plate probe effectively shields its measurement volume from voidage changes in the bed around it.

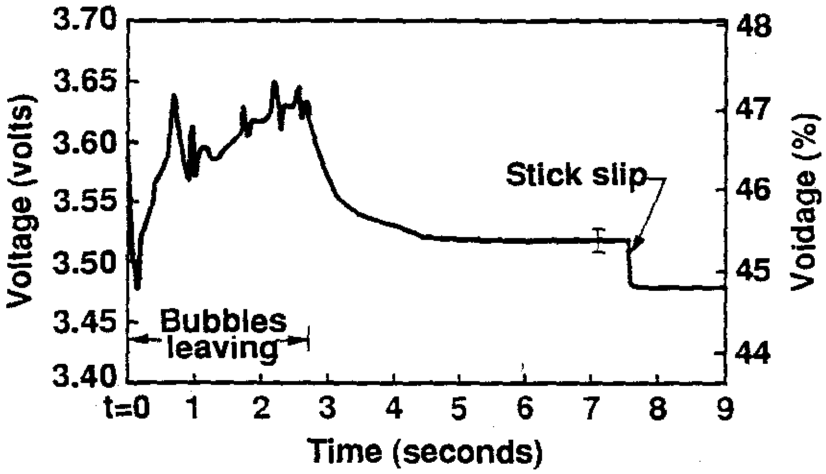

Fig. 6: Bed collapse recorded using the wall probe. Before gas disengagement, $u \approx 1.6\ u_{mf}$. The powder was identical to that in Fig. 5. The amplifier gain was set at $g = 4.5$. The error bar indicates peak-to-peak noise of frequency greater than 2 kHz.

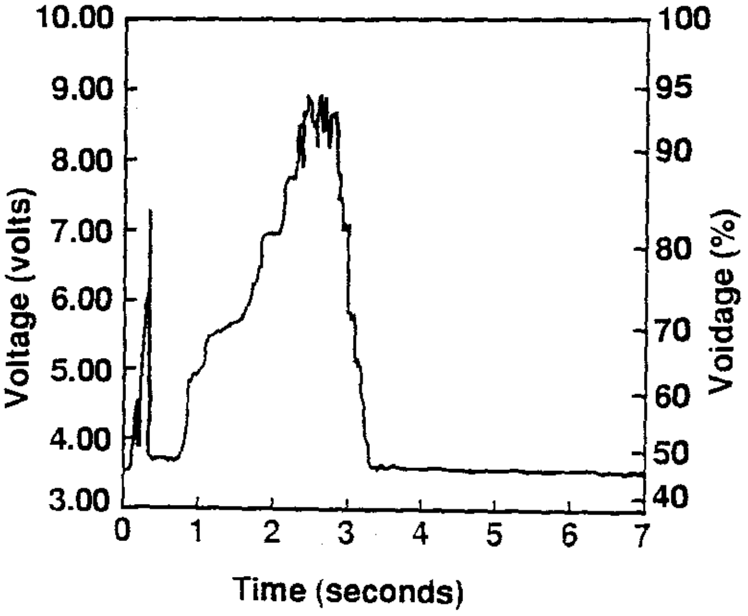

Fig. 7: Bed collapse recorded using the parallel-plate probe. The conditions were identical to that in Fig. 6. The amplifier gain was set at $g = 3.6$.

3. CONCLUSIONS

In this paper, a new technique was outlined for measuring voidage in gas-solid flows. Using the proper combination of guard, sensing and ground surfaces, ultra-sensitive probes of various geometries may be designed. These probes are quantitative and do not require *in situ* calibration. However, self-calibration may be used to virtually eliminate the effect of nearby surfaces held at floating potentials. Prototypes of two configurations were tested. These probes will be used to investigate flow patterns in Cornell's circulating fluidized bed facility.

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