Measuring particle concentration with capacitance probes

This manual explains how to carry out successful measurements of particle concentration in gas-solid suspensions using capacitance probes. After outlining their principle, the manual describes available geometries and possible applications of these probes.

1. Principle

What is capacitance?

Take two conductive surfaces facing each other (Fig. 1). If these are held at different voltages, an electric field is created in the gap, and charges of equal and opposite signs appear on each of them: The surface held at the positive voltage attracts negative charges from the other surface, while the negative surface attracts the same number of positive charges. The number of charges q, measured in Coulombs, is proportional to the voltage difference between the plates,

$$q = C\,(V_2 - V_1). \qquad (1)$$

In this expression, the proportionality constant C is called the "capacitance". It is expressed in units of Farads (1 Farad = 1 Coulomb per Volt). The name "capacitance" is chosen because C measures the ability of the system to accumulate charges. The more charges appear, the greater the capacitance. The system consisting of the two plates is called a "capacitor".

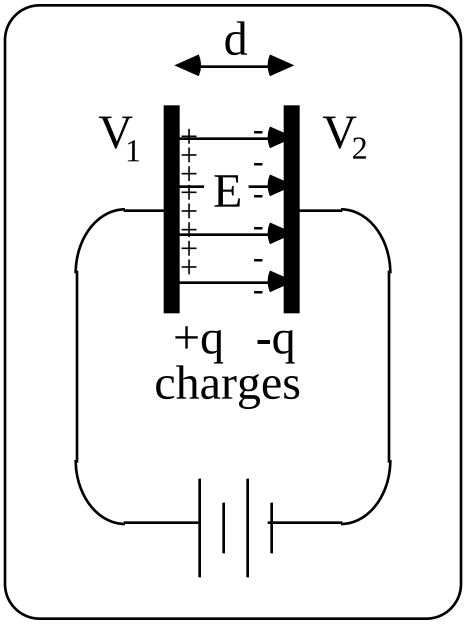

Fig. 1: Capacitance.

Imagine then what would happen if the area of each surface in Fig. 1 was doubled. It is intuitive that the capacitance would be doubled also, as the plates would accept twice as many charges.

Consider now the role played by the "electric field". Just like the gravity field exerts a force on objects with a mass, the electric field exerts a force on charges, which causes them to migrate. At any given location, the force f pulling a charge of value q is proportional to the local magnitude of the electric field E:

$$f = q\,E. \tag{2}$$

Therefore, a stronger electric field promotes a greater accumulation of charges on the surfaces of a capacitor. In fact, the amount of charges attracted to each surface of area A is given by

$$q = \varepsilon\,A\,E, \tag{3}$$

where E is the magnitude of the electric field found at the surface. The constant of proportionality ε is called the "dielectric permittivity". It is a property of the substance where the capacitor is immersed.

Lets consider the example sketched in Fig. 1. For this parallel-plates configuration, the electric field is simply equal to the difference in voltage divided by the gap:

$$E = (V_2-V_1)/d. \tag{4}$$

In the electrical jargon, the electric field is given by the "gradient" (i.e., the derivative with respect to distance) of the voltage. Imagine now the effect of closing the gap by a factor of two. As equation (4) indicates, the electric field is doubled. Consequently, by virtue of equation (3), twice as many charges are brought to the plates so the capacitance doubles also. This effect can be seen by combining these equations with the definition of capacitance in equation (1):

$$C = \varepsilon\,A/d. \tag{5}$$

Generally, a capacitor of arbitrary geometry has a capacitance equal to the product of ε and a quantity L having units of length:

$$C = \varepsilon\,L\,. \tag{6}$$

Here L is only a function of the geometry of the capacitor. As long as the substance between the plates is reasonably homogeneous and non-conductive, ε is not a function of the geometry of the capacitor, but rather it is a property of that substance. If a vacuum or a gas resides in the gap, then the constant is $\varepsilon_0 = 8.854.10^{-12}$ Farad/meter. In the jargon, ε_0 is the "permittivity of free space". A non-conductive substance having a measurable value of ε is called a "dielectric". Generally ε is greater than ε_0.

If a different dielectric substance is inserted between the plates, the value of ε changes. For example, a typical mineral oil may have a value of ε twice as large as ε_0. Because C is proportional to ε, a capacitor may be employed to measure ε. However, practical measurements seldom seek to establish the absolute value of ε. Instead, their aim is generally to record the ratio $\varepsilon/\varepsilon_0$. This ratio is often called the "dielectric constant" of the substance, or sometimes the "relative dielectric permittivity". In this manual, we use the symbol K for the dielectric constant:

$$K = \varepsilon/\varepsilon_0 \tag{7}$$

Imagine that the probe capacitance is C_0 when it is immersed in air. If the introduction of a dielectric substance in the gap of the probe produces a capacitance C, then by virtue of equation (6), the ratio C/C_0 is a direct measure of K for that substance:

$$K = C/C_0\,. \tag{8}$$

Measuring the concentration of suspensions

Pure dielectrics are not the only substances with measurable values of K. In fact, a suspension consisting of particles held in a "host" dielectric liquid or gas has a dielectric constant that is a function of the dielectric constant of the particles (K_p) and that of the "host" medium (K_h). The dielectric constant of the suspension is called the "effective dielectric constant" K_{eff}.

For particles suspended randomly in the host, the value of K_{eff} is primarily a function of the relative proportions of the particles and the host medium: If particles are absent, K_{eff} is equal to K_h. At the other extreme, if particles were so arranged as to exclude the host entirely (an impossible situation in most cases, as interstitial gaps always exist between particles), K_{eff} would be equal to K_p. Intuitively, it is clear that the most sensitive measurement of particle concentration[1] will be obtained for suspensions with the largest difference between K_p and K_h.

For most dry powders, a simple semi-empirical function relates K_{eff} to the particle concentration with good accuracy. In this case, a measurement of K_{eff} can be used to infer particle concentration.

In section 3, this manual shows how to measure K_{eff} using capacitance probes. In section 4, it explains how to infer the particle concentration from the measurement of K_{eff}.

Why do traditional capacitance probes fail?

At the level of precision required here, capacitance measurements are not a straightforward affair. Before describing the principle employed in our capacitance probes, let us examine why the traditional method fails.

Traditionally, capacitance measurements are achieved by balancing two legs of a Wheatstone bridge driven by an oscillator of known frequency. The unknown capacitance forms one leg of the bridge. The capacitance of the adjacent leg is changed until the bridge is balanced. In this primitive form, the measurement has two principal problems when it is applied to particle concentration.

The first is that the capacitance of the cables connecting the probe to the bridge constitutes a significant part of the capacitance measured by the bridge. This can lead to significant inaccuracies of the measurement device, as a large part of the signal is unrelated to particle concentration. This drawback of the traditional approach is called the problem of "cable capacitance".

The second, more serious problem is called "stray capacitance". Recall the role of the electric field in attracting charges to the conductive surfaces of the capacitor. If the electric field is disturbed by other conductive surfaces in the vicinity (a human hand, the walls of a vessel, etc), the capacitance measured by the bridge may be more affected by the extraneous capacitance created by these other surfaces rather than the particle concentration.

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[1] In this manual the terms "particle concentration" and "particle volume fraction" have the same meaning. Either term refers to the fraction of the volume occupied by the particles. For example, a particle concentration of 10% means that 10% of the volume is made up of particles. If the particles are suspended in a gas, 90% of the volume would then be occupied by the gas.

These difficulties have severely limited the accuracy of traditional capacitance probes. In contrast, because our capacitance probes virtually eliminate the problems of stray and cable capacitance, they have reached unprecedented accuracies. The "guard surface" is responsible for this considerable improvement.

Guarding the Probe for Maximum Accuracy

Consider the sketch of one of our capacitance probes in Fig. 2. In this system, capacitance is recorded between the "sensor" and "ground" surfaces of the probe. An amplifier drives the voltage of the sensor surface at a high frequency and, by maintaining the average charge q on that surface constant, it delivers a rectified voltage output V of the sensor inversely proportional to the capacitance between the surfaces:

$$V = q / g\,C. \tag{9}$$

In this expression, g is the adjustable gain of the amplifier.

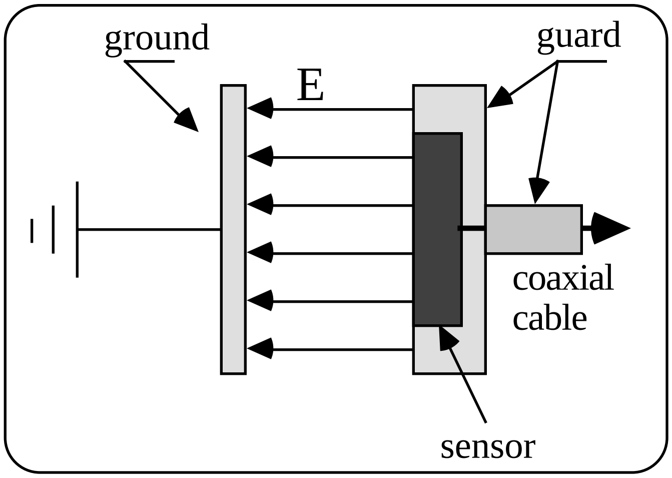

Fig. 2: A typical guarded capacitance probe.

In addition to the ground and sensor surfaces, a third, independent conductor called the "guard surface" surrounds the sensor everywhere except at the measurement's location. The guard surface is driven by a separate circuit, but its voltage is precisely matched to that of the sensor. Consequently, no charge can accumulate in the cable between the "guard" and the "sensor", so the cable capacitance is effectively cancelled.

The guard surface has the further advantage of shielding the sensor from any charged surface in the vicinity of the probe. In that way, stray capacitances are virtually eliminated. Although guarding a capacitance probe is not trivial - it requires precise matching of amplifier components, for instance -, our amplifiers permit the measurement of capacitances as small as a few femtoFarad (10^{-12} Farad). This extreme precision has led to unprecedented accuracies in the measurement of particle concentrations.

2. Description and Usage of the Probes

Our capacitance probes[2] are now available in two basic geometries: the "wall sensor" and the "tuning fork". Each geometry has specific applications. Other customized probes to record particle concentration and/or solid mass flow rate can be manufactured

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[2] Acree Riley, C. & Louge, M.Y.: "*Quantitative Capacitive Measurements of Voidage in Dense Gas-Solid Flows*", Particulate Science & Tech., **7** 51:59 (1989).

upon request for special industrial applications. In this section, the manual describes the two standard geometries. As explained in the previous section, each probe includes three conductive surfaces, the "sensor", the "ground" and the "guard".

The Wall Probe

The "wall probe" is a non-invasive design that records particle concentration near the wall where it is inserted. A sketch is shown in Fig. 3. In this configuration, the ground surface is at the center of the probe. The sensor surface is a concentric ring around the ground surface. The guard surface surrounds the sensor and, through direct contact with the vessel, it drives the wall at the guard voltage. Here the lines of electric field form a measurement volume confined to a narrow region near the wall. The volume extends a distance approximately equal to 16% of the probe diameter away from the wall.

To ensure that the lines of electric field adopt the circular shape shown in Fig. 3, it is essential that a sufficient portion of the wall surrounding the probe be held at the guard voltage. To clarify this point, imagine instead that a large grounded surface was located directly in front of the wall probe. In this case the electric field lines would likely shun the ground surface at the center of the probe, and "jump" to the grounded surface in front of the probe. Of course this would create a measurement volume of unpredictable extent i.e., variations of particle concentration far away from the wall would affect the probe's output.

Therefore with the wall probe it is important to guard a portion of the wall in the vicinity of the probe. From a practical standpoint, we have found that, in a vessel with non-conductive walls (e.g., glass) it is necessary to guard a surface of diameter approximately 15 times the probe diameter. For a cylindrical vessel with conductive walls, the probe should be mounted in a guarded section of the vessel with a height on each side of the probe at least equal to one half the vessel diameter.

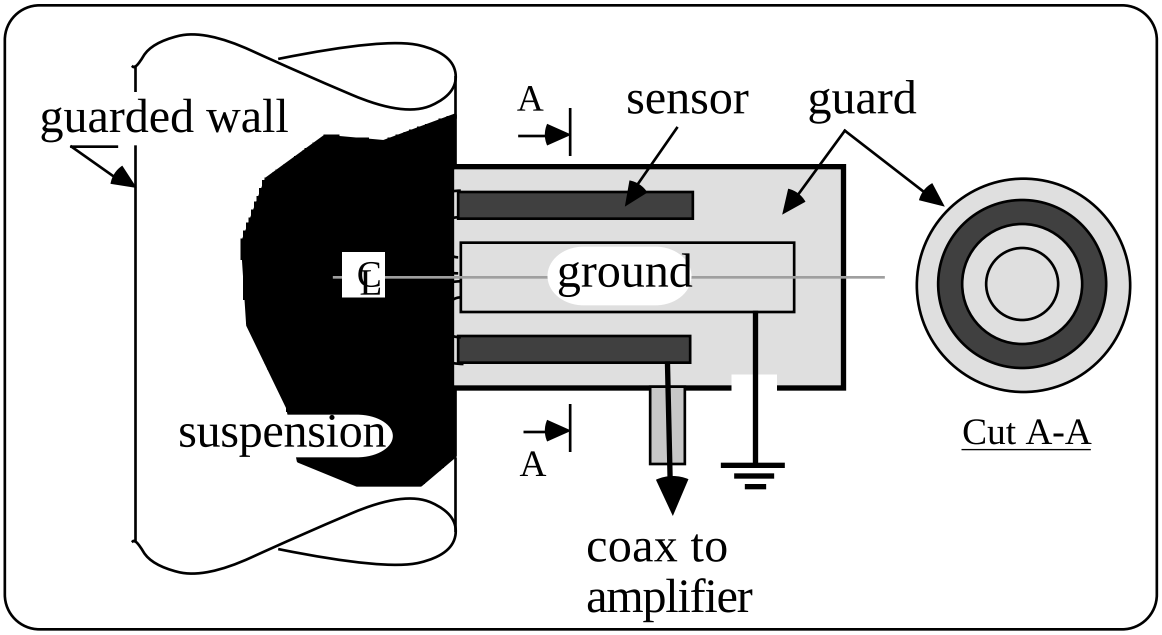

Fig. 3: Wall probe mounted in a vertical tube. Dimensions are not to-scale.

As its name suggests, the wall probe is used to record particle concentration near the wall of a conductive vessel. Because it does not protrude into the flow, the wall probe is non-invasive. The standard probes are manufactured with a flat face that the user inserts flush with the vessel wall. In case the wall has significant curvature, with a special order we can hone the exposed face of the probe to fit the outline of the wall.

A major advantage of the wall probe is that it may be combined easily with another instrument inserted in the central ground rod. In this way, one can record particle concentration and another flow parameter simultaneously. For example, the ground rod may be drilled to insert an optical fiber[3]. The only constraint is that the additional instrument should not interfere with the electrical operations of the probe. Thus it is inappropriate to combine the wall probe with a device that creates large electromagnetic disturbances in its vicinity or that includes an outer surface at a live voltage.

For other applications, the ground rod supplied with the standard probes may be removed altogether. However, in order to retain the appropriate pattern of electric field lines, it is essential to ground a significant portion of the surface exposed to the suspension. For example, the ground rod may be replaced by a heat flux sensor with a face covered by a grounded conductive layer of silver paint.[4]

We can provide advice on sensor combinations upon request.

The "Tuning" Fork

A sketch of the "tuning fork" is shown in Fig. 4. Here the sensor surface faces a grounded plate, so that field lines define a measurement volume confined between the two parallel plates of the probe. The guard surface is designed to minimize the effects of stray capacitance as the probe is traversed through a suspension. We make "tuning forks" of two sizes. In most applications (e.g., fluidized beds, pneumatic transport) the user can thus choose a probe smaller than the expected size of typical flow structures and reap the benefits of quantitative, instantaneous measurement of particle concentration inside a suspension with a minimum of intrusion. To permit the uninterrupted flow of particles in the probe gap, we recommend that the diameter of the largest particle in the flow be less than approximately 15 times the probe gap.

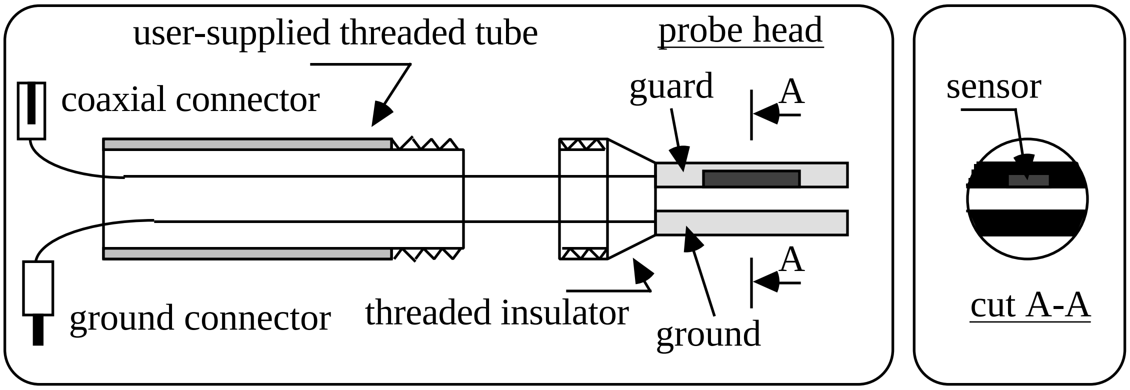

Fig. 4: Tuning fork and user-supplied traversing tube.

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[3] Lischer, D.J. & Louge, M.Y.:*"Optical fiber measurements of particle concentration in dense suspensions: calibration and simulation"*, Applied Optics **31**, 5106 (1992).

[4] Mohd. Yusof, J.: "*Heat Transfer in the Pneumatic Transport of Massive Particles: Modeling and Diagnostics*", Master of Science Thesis, Cornell University, January 1992.

To provide maximum flexibility for the user's application, we can deliver the head of the tuning fork alone without a supporting tube. Depending on the specific application, the user can then attach the head to a threaded tube with any length and shape. Nonetheless, we can provide a standard support tube. Other support tubes may be manufactured on special order.

3. Practical Measurements

This section provides a step-by-step procedure for using the probes.

First, check the integrity of the facility where the probes will be inserted. In the case of the "tuning fork", check that the tube holding the probe head is firmly attached to the head, so the connection will hold inside the suspension. If severe flow conditions are expected, it may be useful to test first the integrity of the mechanical connection by replacing the capacitance probe head by a dummy.

Checking Electrical Continuity

Although the probe amplifier is rugged, it may be damaged by a short circuit among its ground, sensor and guard surfaces, or by the unexpected contact of these surfaces to a conductor held at a different voltage. Before connecting the probes to the amplifier, it is therefore essential to check the electrical continuity of the vessel holding the probe. For this it is convenient to insert the probe at the facility's port where the measurement will be made, and to employ a regular ohm-meter. First, connect one lead of the meter to the guard surface. This is easily achieved by clamping the lead to the outer metal surface of the coaxial cable's connector.

For the "wall probe", recall that the guard surface of the probe head is normally used to drive a suitable portion of the vessel wall by direct contact. Thus it is important that (1) the contact be good and (2) that the wall be properly isolated from grounded surfaces or other surfaces held at a different voltage. To check (1), measure the resistance between the probe guard and the wall. For best results, the resistance should be less than 1Ω. To check (2), measure the resistance between the guard and all surfaces in the vicinity of the measurement except the wall. The resistance between guard and any charged surface at a floating, but reasonably constant potential should be at least 100kΩ. To avoid damage to the amplifier, the impedance between the guard and any surface that may exhibit a potentially high or alternating voltage should exceed 1MΩ.

For the "tuning fork", check that the guard surface is isolated from the vessel wall. If a short is detected (typically when the resistance is less than 100kΩ), check that the head of the tuning fork does not touch the opposite wall. Another reason may be that the electrical insulator joining the head to the user-supplied traversing tube is broken or cracked.

Plugging the probes and Setting the Gain

After inserting the probe in the facility and checking electrical continuity, connect the ground and coaxial cables to the probe amplifier. In a typical measurement, the first step is to set the amplifier gain. For maximum accuracy, it is recommended to tune the gain until the amplifier output reads V_0=10 Volts in the absence of particles i.e., when the probe is immersed in a gas.

The system is now ready. Because the amplifier has negligible drift, it is superfluous to readjust the gain often. By virtue of equations (8) and (9), the voltage ratio V_0/V equals the effective dielectric constant of the suspension:

$$V_0/V = K_{eff} \tag{10}$$

In the next section, this manual describes how to relate the resulting value of K_{eff} to the local particle concentration. For a typical powder, Fig. 5 shows the output voltage of the amplifier as a function of particle concentration.

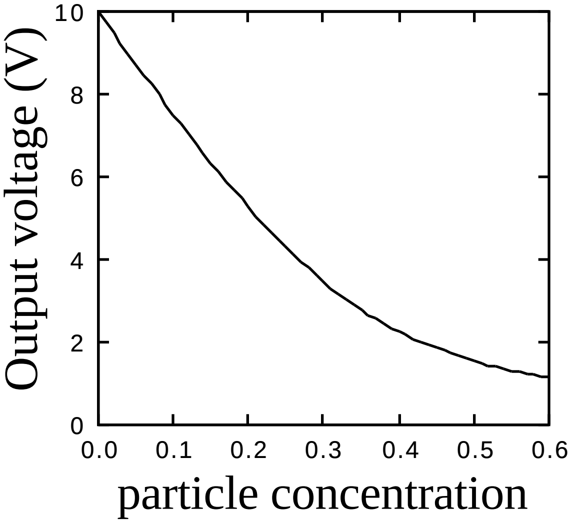

Fig. 5: Typical output of the probe with dry fluid-cracking-catalyst (FCC). Note that a different FCC may exhibit different response characteristics. In this example, the probe gain is set to deliver an output of 10 Volts in air.

4. Probe Calibration

A significant advantage of our capacitance probes is that they do not require any *in situ* calibration i.e., a calibration in the actual unit where the measurement is performed[5]. Instead, it is sufficient to determine separately the effective properties of the powder of interest. For powder suspensions with a well-known dielectric behavior this determination is even superfluous. For example, dielectric spheres satisfy the Meredith & Tobias model[6]:

$$\frac{K_{eff}}{K_h} = \frac{X - 2\varphi + Y - 2.133\ Z}{X + \varphi + Y - 0.906\ Z}, \tag{11}$$

where $X = (2K_h + K_p)/(K_h - K_p)$, $Y = 0.409\ \varphi^{7/3}\ (6K_h + 3K_p)/(4K_h + 3K_p)$, $Z = \varphi^{10/3}\ (3K_h - 3K_p)/(4K_h + 3K_p)$. In this expression, φ is the particle volume fraction ("concentration"), and K_p and K_h are the dielectric constants of the material of the particles and the host medium, respectively.

However, industrial powders are sometimes too complex to permit a straightforward model of their effective properties. In some cases, it is therefore necessary

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[5] Louge M. & Opie M.: "*Measurements of the Effective Dielectric Permittivity of Suspensions*", Powder Tech. **62**, 85-94 (1990).

[6] Meredith, R.E.& Tobias, C.W., J. Appl. Phys. **31**, 1270 (1960).

to establish the dependence of K_{eff} on particle concentration through independent calibration experiments.

For most applications where high precision is not required a simple procedure may be used. The idea is to use a versatile model derived by Böttcher[7] to interpolate between a measurement of K_{eff} under closed-packed conditions and the value of $K_{eff} = K_h$ when only clear dielectric fluid is present. The Böttcher model predicts the following dependence of K_{eff} on concentration φ:

$$\frac{K_{eff} - K_h}{3\,K_{eff}} = \varphi \frac{K_p - K_h}{K_p + 2\,K_{eff}}\,. \tag{12}$$

In this method, the user first immerses any capacitance probe in the packed powder of known[8] concentration φ_{packed}. An empirical estimate of the dielectric constant of the material of the particles K_p follows from Eq. (12):

$$K_p^{est} = K_{eff} \frac{3\,\varphi_{packed}\,K_h + 2\,K_{eff} - 2\,K_h}{K_{eff}\,(3\varphi_{packed} - 1) + K_h}\,. \tag{13}$$

For complex powders, the resulting estimate K_p^{est} may be significantly different from the true value of K_p, the dielectric constant of the material of the particles. Nevertheless, our experience shows that in most cases, K_p^{est} can be used in Eq. (12) to interpolate the dependence of K_{eff} on φ between the clear fluid (φ=0) and the packed powder ($\varphi=\varphi_{packed}$).

5. Examples of Applications

Measurements in Fluidized Beds

Fluidized beds represent an important class of applications for the capacitance probes. There, the quantitative knowledge of local particle concentration is essential to understand the flow of the suspension. Using the wall probe for example, Louge, Lischer and Chang measured the concentration of particles near the wall of a circulating fluidized bed riser[9].

Simultaneous Measurements

A major advantage of the wall capacitance probe described earlier is that the central ground rod may be replaced by another instrument covered with a thin layer of conductive, grounded material. In this way, the user can perform simultaneous measurements of local particle concentration and another parameter of interest. For convenience, the ground rod of our wall capacitance probes can be removed and replaced by any instrument supplied by the user. For example, Lischer and Louge combined the wall capacitance probe with an optical

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[7] Böttcher, C.J.F., Rec. Trav. Chim. **64**, 47 (1945).

[8] For the determination of the actual volume fraction of the packed powder, the user should perform an independent measurement of the material density of the particles ρ_p; then, from the measurement of the bulk density ρ_{bulk} of the packed powder, the packed volume fraction is $\varphi_{packed} = \rho_{bulk}/\rho_p$.

[9] Louge M., Lischer D.J. & Chang H.: "*Measurements of Voidage near the Wall of a Circulating Fluidized Bed Riser*", Powder Tech. **62**, 267-74 (1990).

fiber that also measures the particle concentration[10]. In this way, they calibrated the optical fiber signal against the known output of the capacitance probe.

6. Limits of the technique

Electrostatics

Because they are sensitive to electric fields, the capacitance probes can be affected by excessive amounts of static charges accumulated on the particles. In general, moderate amounts of electrostatics do not perturb the amplifier, because its carrier frequency of 16kHz is much greater than typical variations induced by the parasite charges. However, powders like plastics or resins can generate charges of such magnitude that the stability of the amplifier may be affected.

Our experience is that the wall probes are much less sensitive to electrostatic charging that the tuning fork, because particles can easily discharge on the wall. In most cold gas-solid suspensions where electrostatic is a concern, small amounts of fine powder additives can suppress nearly all electrostatics by promoting the discharge of particles on the wall. One such additive is Larostat® 519. It is manufactured by Mazer® Chemicals, a division of PPG® Industries.[11]

Unusual applications

In general, capacitance probes are used to measure the concentration of dielectric (i.e., non-conductive) powder suspended in a gas. However, we have successfully used the probes in two unusual situations.

The first involves conductive powders in a dielectric host[12]. There, we recorded effective dielectric constants at particle concentrations below approximately 20%. Beyond that concentration, too many particles are brought in electrical contact to permit a meaningful measurement. In the technical jargon, this limiting concentration lies near the "percolation threshold" of the powder.

The second is a suspension of glass beads in water. In principle, such a measurement is difficult because regular water is far too conductive to behave as a dielectric. To alleviate problems associated with the conductivity of water, we cover the conductive surfaces of the capacitance probe with a thin layer of plastic, and we employ demineralized water. With these precautions the capacitance measurement can be related to particle concentration in a meaningful way.

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[10] Lischer, D.J. & Louge, M.Y.: *Optical fiber measurements of particle concentration in dense suspensions: calibration and simulation,* Applied Optics **31**, 5106 (1992).

[11] PPG® Industries, Inc. Chemicals Group, 3938 Porett Drive, Gurnee, IL 60031, tel: (708) 244 3410.

[12] Louge M. & Opie M.: "*Measurements of the Effective Dielectric Permittivity of Suspensions*", Powder Tech. **62** (1990), p. 91.

Symbols

A	probe sensor area (m^2)
C	capacitance (farad)
C_0	capacitance of the probe in air
d	probe gap (meter)
E	electric field (volt/meter)
f	force on a charge (newton)
g	amplifier gain
K	dielectric constant
K_{eff}	effective dielectric constant
K_h	dielectric constant of the host fluid
K_p	dielectric constant of the material of the particle
K_p^{est}	estimated value of K_p
L	characteristic length (meter)
q	charge (coulomb)
V	voltage (volts)
X, Y, Z	constants in Eq. (11)

Greek

ε	dielectric permittivity (farad/meter)
ε_0	permittivity of free space = $8.854.10^{-12}$ Farad/meter
φ	particle concentration (volume fraction occupied by the particles)
φ_{packed}	concentration of closely-packed particles