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MEASURING AND MODELING SOLIDS MOVEMENT IN A LARGE,
COLD FLUIDIZED BED TEST FACILITY

First Quarterly Report

for the Period

1 October 1979 - 31 December 1979

by

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Prepared for

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Assistant Secretary for Fossil Energy

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ABSTRACT

Descriptions of new and redesigned instrumentation, including a system for direct measurement of solids movement, scaled inductor probes and a pneumatic-release magnetic-collection system are presented. Results of various tests conducted to determine the suitability and feasibility of each instrument as well as a comprehensive literature review are also included.

SOLIDS MOVEMENT: AN ALTERNATE METHOD OF MEASUREMENT

An investigation during the previous quarter has been undertaken to determine (on a theoretical basis) the possibility of using a novel technique for studying the movement of solids in the fluidized bed. If it is successful, it will provide direct data on the velocity field of moving solids in the bed.

The present method of measuring solids movement is by the use of ferromagnetic tracer particles. The magnetic tracer particles are released in one part of the bed and their concentration is monitored as a function of time in other parts of the bed. With a sufficient number of samples it is possible to collect enough data to back-calculate the local solids transport velocities in the bed which caused the measured dispersion of particles.

The new method would also make use of the magnetic property of solids, but unlike the magnetic tracer method which uses only about one percent magnetic solids in a bed of magnetically inert material, the new method would use a bed consisting entirely of magnetizable material. The use of such a bed is feasible for our studies since we wish to fluidize solids with a particle specific gravity of about 8.0. There are many kinds of magnetic materials readily available and inexpensive with specific gravities in this region. With the new method local solids transport velocities would be measured directly instead of being inferred from solids tracer concentration measurements. And unlike the tracer measurements, the new method would not require that magnetic material be removed or sequestered at the end of a run.

The basic principle involved is well known: a magnet moving past a coil sets up an emf in the coil which is proportional to the strength of the magnetic field and the velocity of the magnet relative to the coil. The emf is in fact

proportional to the rate at which magnetic lines of force are cut by the detector coil.

A permanent bar magnet with dimensions comparable to the coil diameter causes a large induced emf when either end of the bar is moved through the coil. The sensitivity is minimal when the magnet is centered in the coil since in this case the rate at which lines of force are cut approaches zero. This is illustrated in Figure 1.

Consider now the application of this principle to the detection of the motion of a bed of solid magnetic particles. At this point it is reasonable to ask whether the motion of the bed of uniformly magnetized particles would cause an emf to be induced in a pickup coil. Some of the magnetic particles will have random orientations. Their fields will tend to cancel and hence they can be ignored. The remainder of the particles however will be at least partially aligned with their north poles for instance all tending to point in the same direction. Close to every north pole there will be the south pole of a nearby particle and the lines of force between north and south poles will be mostly confined to the immediate neighborhood of the magnetic solids. A few lines will reach out to the pickup coil. If the particles are aligned in the direction of flow as shown in Figure 2A, then the lines of force near the coil will tend to be parallel to the direction of motion and hence no lines of force will be cut as the solids move, hence no emf will be induced in the detector coil. If the particles are not aligned in the direction of motion as shown in Figure 2B, then the lines of force which extend out to the pickup coil will be cut by the coil as the solids move past it. However, no net emf will be produced in the coil. One side of the coil is close to the net south pole of the solids; the other half is closer to the net north pole of the solids.

Figure 1. When the magnet is centered in the coil the emf in the coil produced by magnetic motion is minimal, since the rate of cutting of magnetic lines of force by the coil is minimal.

Figure 2A. The lines of force around a long chain of aligned magnetic particles are not cut by the detector coil when the solids move in the same direction as the particle alignment.

Figure 2B. Particles aligned off axis do produce lines of force which cut the detector coil as the solids move, however, the lines of force have opposite polarities and the net induced voltage in the coil is zero.

Each section of the coil will therefore produce an opposite emf so that the result from the whole coil is zero. This statement can be made more precisely in terms of line integrals or vectors, but the effect is the same: no voltage is induced in the coil by uniformly magnetized solids.

In order to make use of the moving magnet principle one needs a way to create a magnetic domain which is not uniform so that the motion of solids will induce an EMF in the detector coil. This can be achieved by using a second coil to magnetize a non-uniform magnetic field into the particles. When the magnetizing current in this magnetizer coil is turned off, the solids will remain partially magnetized; and at least for a short time, they will maintain the orientation which they had while they were being magnetized. Movement of this array of magnetized particles will now induce an EMF in the detector coil which can be used to determine the velocity of the solids. Figure 3 shows an efficient arrangement of coils to accomplish particle magnetization and detection of motion. A magnetic field is generated in coils A and C which are wound in opposite directions to produce a concentration of magnetic lines of force between them, in the vicinity of detector coil B. When the current in coils A and C is shut off, the moving magnetic solids will produce an emf in coil B which is proportional to the magnetic field strength and the velocity normal to the plane of the detector coil.

As the particles move an appreciable distance from their original position their orientation will change so that the emf generated in the detector coil will no longer be a good indication of the solids velocity. Hence, the velocity measurement can be made only during a short time interval just after the magnetization current is cut off. In order to obtain a subsequent reading it is necessary to magnetize another set of solids. If many velocity

measurements are made in a recirculating solids systems (such as a fluidized bed) then there will be a build up of magnetized material in the bed (unless the solids are demagnetized). Some demagnetization will occur spontaneously, but it would be prudent to get rid of the residual magnetizism in the particles as quickly as possible. This can be done rather easily by using an alternating current of decaying amplitude in the magnetizing coils to demagnetize the particles before they have a chance to move away from the coil. The sequence will now be: 1) unmagnetized moving solids are quickly magnetized by the magnetizing coils, 2) the magnetizing current is shut off and the solids velocity is detected by the induced emf in the detector coil, 3) a decaying, alternating current in the magnetizing coils is then employed to demagnetize the solids. The entire procedure can be accomplished in a small fraction of a second leaving the system ready for another velocity measurement.

We have made preliminary estimates of the power requirements for magnetization. For soft iron, approximately one joule of energy is required to magnetize the solids moving in the vicinity of a 0.1 meter diameter coil. If we attempt to do this in a millisecond then one kilowatt of power is required (e.g. 20 amperes at 50 volts) for a duration of one millisecond. This is not an unreasonably large current or voltage. Heating is not likely to be a problem either, because of the short time during which the power is applied. Magnetizing times of less than one millisecond would require correspondingly higher instantaneous power levels. For a time period of one microsecond an instantaneous power level of one megawatt (e.g. 1000 amperes at 1000 volts) is required. This kind of operation would require high voltage power devices and would be quite expensive. Therefore, it is easier and cheaper to magnetize the solids slowly.

Unfortunately, there are other constraints which require that the solids be magnetized quickly. The overall cycle time from the beginning of magnetization to the end of the demagnetization should be short enough so that the particles will not have moved out of the range of influence of the coils. The second constraint involves the accuracy of the velocity measurement. The change in momentum of the solids is equal to the time integral of the forces acting on them. It is quite possible that the magnetic forces acting on the particles are of little importance compared to mechanical forces, and hence that the magnetization will have but a negligible effect on solids movement. But if the magnetic forces cannot be ignored, then the accuracy of measurement is improved by keeping the time duration during which the solids are subjected to magnetic forces as short as possible.

There are two possible sources of error in applying magnetize particle flow measurement to fluidized bed systems. The first involves possible modification of the particle velocities by magnetic forces. The second involves the magnetic inhomogeneity that would be caused by bubbles. It is difficult to evaluate the magnitude of either effect without experimental studies. Experiments are required to find the effect of magnetic forces on particle motion because the interaction of mechanical forces and magnetic forces in a fluidized bed is not well understood. The effect of bubbles can be calculated by solving the field equations in three dimensions for various assumed bubble and coil configurations. However, it will probably be easier to obtain results by direct experiment. Experimental measurements will be required to find how rapid the magnetization must be to have a negligible effect on measured particle velocity. This experimental program can be broadened to include studies of the effects of bubbles on measured solids velocities.

INDUCTANCE PROBES AND ASSOCIATED ELECTRONICS

The redesign of the inductance probes for 1/2-inch diameter tubes has been completed. Probes of this type have been successfully used to detect a ferrite tracer in previous work at Oregon State University, but redesign was required to scale down the size of the probes to 1/2-inch diameter, rather than the 2-inch diameter used in earlier work. The construction of the probe is shown in Figure 4, along with all pertinent dimensions. It was found that 460 turns of copper wire was sufficient to produce an inductance of 13-16 mH. Because of the smaller size and inductance compared to the 2-inch diameter probes, and because the smaller probes do not contain a ferrite core, the sensitivity to ferrite tracer is considerably reduced. This will necessitate an increase in the gain of the associated amplifier in the electronic circuit by at least ten fold. A schematic diagram of this associated electronic circuit is shown in Figure 5.

Testing to determine the characteristics of this probe in a bed containing copper powder, rather than the previously used limestone, has begun. Dynamic tests of this prototype have been carried out in one quadrant of a 3-foot square fluidized bed containing copper powder using a ferrite tracer. Tests were run for two phase angles, 54° and 108° . A phase angle of 54° produces maximum sensitivity to copper, while a phase angle of 108° produces minimum sensitivity to copper. In each case, an initial test with no material in the bed was conducted to establish a base line as well as a noise level for the output.

The actual tests in the fluidized bed were conducted as follows: The bed was loaded with 923 pounds of copper powder with an average size of 320μ . This produced a bed depth of approximately 12 inches. The bed was then fluidized

Figure 4. Inductor probe for detection of ferrite tracer. The dimensions in parentheses are for probes used in the 3' x 3' test facility at Oregon State University. While the other dimensions are for the probes at the Morgantown Facility.

Figure 5. Inductance probe amplifier circuit.

with air at a velocity of 3.5 ft/sec (which scales to approximately 8.5 ft/sec with an industrial bed), and 20 pounds of 525 μ ferrite tracer was introduced at the top of the same quadrant of the bed in which the probe was located. The output of the inductance probe was recorded for tests with each of the previously mentioned phase angles.

The results of these tests are shown in Figure 6. The data showed that for a phase angle of 54° (maximum copper sensitivity), the copper produced a positive signal. When the ferrite was added, the signal became negative. For a phase angle of 108° (minimum copper sensitivity) the results were similar, but the magnitude of the signal dropped almost 50% when the ferrite tracer was added. Because of the dynamic characteristics of the bed, absolute results could not be obtained. Static tests must now be performed to obtain absolute results, i.e., to calibrate the probe. These tests will be performed after the gain in the electronic circuit has been modified to increase sensitivity.

TRACER RELEASE AND COLLECTION

A small prototype ferrite collection-release module is partially assembled. This device is illustrated in Figure 7. Tracer will be collected and/or released at appropriate locations in the bed by using sections of a pneumatic-release magnetic collection system (see Figure 8). This device has been constructed except for the latex sleeve which is an integral part of the release mechanism. Tests will be conducted to determine the saturation values for the device when the latex sleeve is obtained. These collection/release systems can be operated so that a variety of transient tracer flow experiments can be conducted, and easily replicated.

Figure 6-A: Phase angle 54° (maximum copper sensitivity)

Figure 6-B: Phase angle 108° (minimum copper sensitivity)

Figure 6: Output of inductor probe tested in a cold fluidized bed with air as the fluidizing gas and copper as the bed media.

Figure 7. Ferrite tracer pneumatic-release magnetic collection system.

Figure 8. Ferrite tracer pneumatic-release magnetic-collection system in the collection phase (A) and the release phase (B).

A LITERATURE REVIEW

INTRODUCTION

This review presents a brief summary of instrumentation systems which have been devised to operate in fluidized beds. The systems measure temperature, gas composition, pressure, freeboard particle size, velocity of solids and gas, apparent bed viscosity, heat transfer and mass transfer coefficients, bed density and the presence or absence of bubbles. The primary sources of information are the instrumentation systems described or referred to in articles on fluidized beds which have been published in the last 10 years in the CEP and AIChE Symposium Series that deal with fluidized beds, as well as the articles on fluidized beds which have appeared during that time in the AIChE Journal, Chemical Engineering Science, Industrial and Engineering Chemistry Process Design and Development, Industrial and Engineering Chemistry Fundamentals, and the monographs which have come from the fluidization conferences held by the Engineering Foundation at Asilomar, California in 1975 and in Cambridge, England in 1978.

Most of the instrumentation systems described have been put together in order to obtain data which is useful in studying or modeling the behavior of a fluidized bed. Instrumentation systems which are directly useful for monitoring the behavior of the fluidized beds which are used in the chemical process industries are rarely described; in fact, with a few exceptions, the only variables which can be readily measured with available instrumentation in an operating fluidized bed are solids temperature, exit gas composition, pressure, and overall heat transfer coefficients.

There are a number of techniques which have been used to investigate the behavior of fluidized beds which involve no special instrumentation. An example of such a technique is the introduction of colored solid particles into a fluidized bed followed by slumping and searching to study how the solids disperse. A technique such as this, while it provides very important information, does not involve any special instrumentation and hence is not described in this report.

TEMPERATURE MEASUREMENT

Solids temperature in a fluidized bed is readily measured by inserting a thermocouple or other thermometer directly into the fluidized solids. Using the sensible heat of the solids as a tracer its possible to study solids movement by heating particles in one region of the bed and measuring the temperature of the particles in another portion of the bed. A rapid response thermocouple probe

has been devised for this purpose by Thiel and Potter (1978). If the bed particles are at a high enough temperature to be incandescent, then the solids temperature can be readily measured by optical pyrometry. The use of an optical pyrometer to obtain bed temperature is described by Juveland, et al. (1964). A similar pyrometry technique is described by Makhorin, et al. (1978) in which infrared sensitive photographic film is used to determine bed temperature.

Gas temperatures are not so easy to measure as solids temperatures. The gas phase in the fluidized bed has a much lower heat capacity than the solid phase (primarily because of the difference in densities) and as a result the gas quickly comes to the same temperature as the solids. However, in the case of large bubbles or very energetic reactions, the gas can have a substantially different temperature than the solids do. Special techniques are needed to measure gas temperature, particularly at high temperatures where the radiation from solids can affect the measuring instrument. The usual method for obtaining a gas temperature is to withdraw the gas through a sampling tube at a relatively high velocity over a thermocouple or similar temperature measuring device. The tube shields the temperature device from radiation and the high velocity improves gas-to-thermometer heat transfer. The paper by Juveland, et al. (1964) describes such a device and a similar application is described by Shakhova and Lastovtseva (1975). McGaw (1977) worked with a bed at a moderate temperature where radiation from the solids was unimportant and hence was able to use an exposed hot wire (not shielded from radiation) to measure the temperature of gas erupting from bubbles at the surface of the bed.

GAS COMPOSITION MEASUREMENTS

Gas compositions in the fluidized bed are usually obtained by withdrawing a small sample of gas through a small diameter tube and analyzing the gas external to the bed. Depending on the method of sample withdrawal and on the method of analysis the gas composition measurements can either be steady or transient. The measurements can be made above the bed or in the bed.

Steady State Measurements

Steady gas measurements in the bed are described by Gabor and Mecham (1964), Yoshida, et al. (1969), Behie, et al. (1976), Fryer and Potter (1976) Hsiung and Thodos (1975), Gibbs and Hedley (1978) and Nguyen, et al. (1977). The last paper describes the use of multiple probes. Steady gas composition above the bed have

been measured by Lange (1972) and Bartock, et al. (1972). The kinds of probes used for sampling above the bed are not very different from those used to sample in the bed. In both cases a filter is used at the tip of the probe in order to keep particles from entering the sampling line. Most of the systems operated in laboratory sized beds and the measurements were made in order to evaluate a parameter in a fluidization model. The paper by Gibbs and Hedley, however, describes gas sampling from an operating fluidized bed coal combustor; hence the probe they describe ought to be useful in many industrial applications.

Transient Measurements

Transient gas composition measurements have been used by a number of investigators primarily in attempts to understand the kind of gas mixing which occurs in an operating fluidized bed. A novel technique which does not require that gases be withdrawn for analysis makes use of an ultraviolet detector for measuring ozone concentration in bubbles. The technique works in situ and is described by Chavarie and Grace (1975) and Chavarie and Grace (1976). A more common approach for obtaining transient concentration data in a fluidized bed is to use sample withdrawal through a small diameter tube. A rather large vacuum pump is used to move the material quickly through the tube and minimize the blurring effect of gas backmixing. High speed gas sampling techniques are described by Drinkenburg and Rietema (1972), Drinkenburg and Rietema (1973), Goedecke and Schugurl (1973).

In a special setup the gas sampling probe was synchronized with the injection of bubbles, so that the gas composition was measured only in the bubbles (Rowe, et al. (1971)) and in a similar set of experiments the gas composition was measured only in the emulsion rather than the bubbles (Evans and Rowe (1974)). Transient gas measurements have also been made at very high fluidizing velocities where bubbles as such do not exist. Cankurt and Yerushalmi (1978) describe such an application.

By combining the gas sampling probe with another device which measures the presence of bubbles, it is possible to distinguish between the gas which is sampled from the bubble phase and from the emulsion phase in a freely bubbling fluidized bed. A resistance measuring device was incorporated with the gas sampling probe in the study by Fitzgerald (1967), and by Calderbank, et al. (1976). Simultaneous capacitance bubble measurements were made along with gas sampling by Rietema and Hoebink (1976).

Transient measurements of the gas exiting the fluidized bed are usually made in order to determine the residence time of the gas in the bed. The first transient measurement of gas leaving the fluidized bed is described in the 1952 paper by Gilliland and Mason. A slug of tracer gas was introduced at the bottom of the bed and the gas at the top of the bed was sampled by a device that resembled a gattling gun working in reverse. Discrete samples were collected at time intervals and analyzed by conventional techniques. In more recent work continuous measurement has been used. Perry and Gibbs (1971) used a mass spectrometer; Zalewsky and Hanesiam (1973) used a thermal conductivity cell; Goedecke and Shurgerl (1973) used a mass spectrometer; Yates and Constans (1973) used a flame ionization detector; and Bohle and vanSwaay (1978) used a thermal conductivity cell.

PRESSURE MEASUREMENTS

It is relatively easy to measure pressure in an operating fluidized bed, whether it be a small room temperature laboratory model or a large high temperature fluidized bed reactor. Pressure measuring lines to industrial fluidized beds are usually back-purged by a constant flow of inert gas to prevent particles from entering the lines and to prevent corrosive fluids from coming into contact with the pressure measuring device.

The time-averaged pressure drop across the fluidized bed is commonly used as an indication of the amount of material in the bed--when the bed is in a fluidized state the pressure drop is approximately equal to the hydrostatic head of bed material: if the bed has a constant cross-section the pressure drop is equal to the weight of solid material in the bed divided by the superficial cross-sectional area.

The pressure drop across the fluidized bed is not constant; it fluctuates with a frequency approximately equal to the rate of eruption of bubbles at the surface of the bed. The magnitude of the pressure fluctuations is of the same order as the hydrostatic head displaced by a bubble. Transient pressure measurement therefore become a useful tool for characterizing the behavior of a fluidized bed. A large number of studies have been performed to relate the pressure fluctuations to the bed hydrodynamics, but it is difficult to precisely determine any hydrodynamic bed property from the simple bubble trace measurements. Because of this, pressure fluctuations are used as a qualitative guide for describing the "quality" of fluidization. Transient measurements are described by Lirag and Littman (1971), Baird and Klein (1973), Kilkis, et al. (1973), Taylor, et al. (1973), Verloop and Heertjes (1974) and Bayens and Geldart (1974).

By the use of multiple pressure transducers, it is possible to obtain much more information than can be obtained with a single transducer. For instance, if two transducers are located a vertical distance apart from each other and if they both simultaneously show the same pressure, then the reasonable conclusion is that both of them are inside the same bubble. By the use of an array of transducers with simultaneous pressure measurements, it is possible to map out not only bubble sizes, but bubble rise velocities. Multiple pressure transducer systems are described by Kang, et al. (1967), Littman and Homolka (1970) and Catipovic, et al. (1978).

PARTICLE SIZE MEASUREMENTS

No instrumentation has been described for measuring the size of particles in an operating fluidized bed, but two instruments are described which use light scattering techniques to measure continuously the size distribution of particles in the freeboard above the bed. Both techniques use lasers and are designed to operate in the hostile environment of a fluidized bed combustor, thus the devices ought to be useful in most industrial applications. The devices are described by Busch (1977) and by VanValkenburg and Moly (1977).

GAS VELOCITY MEASUREMENTS

The overall gas velocity through a fluidized bed is usually measured by an orifice meter or venturi meter and the instrumentation involved is conventional. Local gas velocity measurements in the bed have been performed with Pitot tubes and hot wire anemometers. Nguyen, et al. (1975) measured the velocity of gas inside rising bubbles in a fluidized bed using a small Pitot tube. Donadono and Masamilla (1978) used a Pitot tube to measure the velocity of an entering gas jet at the bottom of a fluidized bed. Filla, et al. (1976) and McGaw (1977) used standard hot wire anemometer techniques to measure the gas velocity inside bubbles in the fluidized bed.

BED VISCOSITY MEASUREMENTS

Bed viscosity, like eddy viscosity, is an operational characteristic of a fluidized bed; it is not a property of the materials themselves. Bed viscosities are obtained in much the same way as the viscosity of a liquid would be measured. A surface is moved through the bed and the drag force on the surface is measured. Ashwin et al. (1960), Hagyard and Sacerdote (1966) and Lehman, et al. (1973) used couette

flow viscometers and Finnerty, et al. (1969) used vibrating paddles to measure bed viscosity. Measurements were made near minimum fluidization conditions in order to keep the interference caused by bubbles to a minimum.

BUBBLE DETECTION

Almost all gas solid fluidized beds operate with bubbles in the bed--only when the ratio of solids density to gas density becomes smaller than about 10 do bubbles disappear. The position and velocity of bubbles in the bed determines how both solids and gas will move. Thus the bubbles determine the heat transfer properties at the walls and the gas-solid exchange coefficients. Because of the fundamental importance of bubbles in modeling and also because of the comparative ease with which bubbles can be measured, there are more kinds of bubble detecting instruments than any other class of instrumentation for fluidized beds. The applications described in the literature invariably are for experimental facilities in which the hydrodynamics of the bed is to be characterized. Some of the techniques are very simple and could be readily put to use in operating industrial fluidized beds. Many different physical properties have been measured by probes which are used to detect bubbles. Since the density ratio between the solids and gases is on the order of 1000:1 almost any physical property measurement will do, so long as it is local.

Light Transmission Measurements

Yasui and Johanson (1958), Put, et al. (1973), Kilkis, et al. (1973) and Yoshida, et al. (1978) measured the presence of bubbles by light transmission. The articles from 1973 on made use of fiber optics bundles and the early work by Yasui and Johanson used quartz rods. In the study by Yoshida, et al. the light transmission probe was used in conjunction with simultaneous heat transfer measurements.

Conductivity Measurements

Fluidized coke particles conduct electricity rather well, thus allowing electrical resistivity to be used to indicate the presence of bubbles in a fluidized coke bed. Park, et al. (1969), Rigby, et al. (1970) and Burgess and Calderbank (1975) and Calderbank (1976) used point resistivity measurements to indicate the presence of bubbles in fluidized coke beds. Burgess and Calderbank used a five-element probe to obtain the shape and diameter of the bubbles as well. Resistivity

measurements to detect bubbles were made with simultaneous transient gas measurements by Calderbank (1976), so that the composition of the gas and in the emulsion and bubble phases could be differentiated.

Capacitance Measurements

Capacitance-type bubble detection probes have been used more frequently than any other type, presumably because they work well with nonconducting materials such as sand and glass spheres which are commonly used in laboratory fluidized beds. Various configurations have been used, from parallel plates to small flush mounted probes.

Parallel plate devices typically use plates which are 10 mm or so on a side and which are separated from each other by a distance of approximately 10 mm. The capacitance change which occurs when the sand or a similar dielectric material is placed between the probes is of the order of one picofarad and hence the capacitance can be measured by a simple bridge imbalance techniques. Morse and Ballou (1951), Yoshida, et al. (1969) and Matsen (1973) used parallel plate capacitance detectors. Dotson (1959) modified the parallel plate geometry slightly into a parallel rod form in order to reduce flow obstruction.

Flush mounted large area capacitance probes have been described by Ormiston, et al. (1965), Angelino, et al. (1965), Nguyen, et al. (1973), Baskakov, et al. (1973) and Thiel and Potter (1977). Because of the relatively large area involved, the capacitive changes were quite large and could be detected with conventional bridge circuitry.

Very small flush mounted probes were used along with simultaneous heat transfer measurements by Catipovic, et al. (1978). The measured capacitance change was on the order of .01 picofarads, and high-frequency diode detector probes were built for this application. They function rather like the radio frequency-diode probes described by Lanneau (1960).

Lanneau's probe was the first of the very small or pencil point type probes. It has been modified to a multi-pin probe by Rooney and Harrison (1976) in order to measure bubble size on a surface. Werther and Molerous (1973) and Werther (1976) used a very small pencil point type probe to measure bubbles with minimal flow obstructions. For Werther's probe the change in capacitance is detected by a shift in the frequency of an oscillator. The circuit has more sensitivity than a conventional bridge circuit, but it does have the disadvantage of measuring the

distributed capacitance of the leads along with the capacitance of the probe itself. The high frequency diode techniques used by Catipovic and Lanneau get around this difficulty and make it possible to locate the probe at a substantial distance from the measuring instrument.

X-Ray Measurements

Bubbles can, of course, be observed directly in a "two-dimensional" fluidized bed, that is a fluidized bed which is sandwiched between two transparent plates of material. The problem is that the two-dimensional constraint modifies the shape of the bubbles. Perhaps the most direct observation of actual bubble shape and bubble rise velocity in a fluidized bed has been obtained by Rowe and Partridge (1965), Rowe and Matsumo (1971) and Rowe (1971), using x-rays and cinephotographic techniques. More recently, Hager and Thompson (1973) and Judd and Dixon (1978) have also used x-rays for measuring bubbles.

Inductance Measurement

Cranfield (1972) devised a small probe with a tip that functions rather like a head on a magnetic tape recorder. The probe can be used to detect the presence of ferromagnetic particles. When the bed studied consists of particles with ferromagnetic properties, the signal at the probe is a direct indication of whether a bubble or the emulsion phase is present. Cranfield points out that such a probe could be used with ferromagnetic tracer particles in order to study solid movement in a fluidized bed.

Piezoelectric Measurement

Gerald (1951) used a piezoelectric transducer to detect the presence of bubbles. In effect, the transducer is a small microphone with an exposed diaphragm. When bubbles are present the diaphragm is undisturbed but when the probe is in the emulsion phase the microphone transmits the impact noise caused by particles contacting the diaphragm.

Gamma Ray Transmission Measurement

Urcutt and Carpenter (1971) used gamma ray transmission to detect the presence of bubbles. A gamma ray source was used and the presence of the emulsion in the measuring gap was indicated by a drop in the detected gamma ray signal.

Thermal Measurement

Wen, et al. (1978) used a small probe containing a self-heating thermistor to locate bubbles. The probe works on the principle that the heat transfer coefficient is always substantially greater in the emulsion phase than in the bubble phase and hence when the probe is in the emulsion phase, its temperature will drop causing an increase in the resistivity of the probe. The resistivity itself is measured and is used as an indication of the presence of bubbles.

HEAT TRANSFER MEASUREMENTS

Many large industrial fluidized beds are instrumented with temperature and flow measuring devices which allow direct calculation of heat transfer coefficients. The instrumentation systems involved are conventional and will not be described in this report; rather the report will describe special heat transfer elements and heat transfer probes which have been used to study the phenomenon of heat transfer in itself.

Steady-State Measurements

Steady-state local heat transfer measurements between a fluidized bed and a heat exchange tube are described by Botterill, et al. (1970), Patel and Simpson (1977), and Canada and McLaughlin (1978). Steady bed-to-heat-exchange-fin measurements are described by Bartel, et al. (1971), Genetti, et al. (1971), and Priebe and Genetti (1977). Steady local heat transfer between the bed and various immersed objects was studied by Sampson (1973) and steady heat transfer from the bed to a central heated rod was measured by Kobayashi, et al. in 1970.

Overall heat transfer from a tube to a fluidized bed was measured by Botterill, et al. (1970), Xavier and Davidson (1978) and Andeen, et al. (1978). Steady bed-to-wall heat transfer was measured by Hoebink, et al. (1978).

Transient Measurements

Transient heat transfer measurements are needed to distinguish between the heat transfer contribution due to the passage of the emulsion phase and the heat transfer contribution due to the passage of a bubble. By their very nature, transient heat transfer measurements are local, that is, they pertain to an area smaller than a bubble. Most of the probes which have been designed to monitor a changing heat transfer coefficient are sensitive to loading, that is, the temperature of the probe drops significantly (if it is a hot probe) when the heat

transfer coefficient goes up and the temperature of the probe rises significantly when the heat transfer coefficient goes down, as when a bubble goes past. As a result, the solids in the emulsion phase which first come in contact with the probe are overheated and the solids that come thereafter to the probe are underheated. The net result is that the heat transfer coefficients obtained from such studies will not generally agree with the heat transfer coefficients which would be obtained between the bed and an isothermal body. Transient heat transfer probes which are subject to load have been described by Mickley, et al. (1961), Wen, et al. (1978), Barker (1967), Khan, et al. (1978), Selzer and Thompson (1977), Agrawal and Ziegler (1970), Tout and Clift (1973), Gardon (1953), Gardon, (1960) and Baskakov (1973). The probes described by Gardon operate at a fairly high temperature with a large temperature differential between the probe and the bed. Hence they are suitable for direct industrial application and because of the high temperature differential the change in the temperature of the device with load has a minimal effect on the measured heat transfer coefficient. The heat transfer probe described by Barker is in fact a small sphere which is free to move through the fluidized bed in which transmits a radio signal that indicates its surface temperature. Heat is generated at a constant rate inside the sphere by a radioactive decay process and hence the surface temperature is an indication of the heat transfer coefficient.

Transient heat transfer measurements from small constant temperature surfaces have been reported by a number of investigators. The constant temperature feature of the probe not only gives the correct heat transfer coefficient, it also makes it possible to have a region around the probe which has the same temperature as the probe. Also the constant temperature operation of the probe eliminates the time lag which occurs when the probe changes temperature. The basic technique is well known and is used in constant-temperature, hot wire anemometry. An electrical film is heated, and its temperature is indicated by its resistance. If the temperature (and hence the resistance) begins to fall, then the power is increased to bring the temperature back to its original setting. The power changes almost instantaneously and is a direct indication of the instantaneous heat transfer coefficient. A small immersible hot film constant temperature type probe is described by Bernis, et al. (1976). Multiple hot-film transducers were flush-mounted around surface of a heat exchange tube along with capacitance and pressure systems for simultaneous bubble detection by Catipovic, et al. (1978).

MASS TRANSFER MEASUREMENT

A small sphere was designed by Ziegler and Brazelton (1964) to measure mass transfer between a particle and the gas in the bed. The particle itself was porous and was saturated with a fluid which would evaporate into the bed. Measurement of the surface temperature of the particle during the constant rate drying period allowed the calculation of the mass transfer coefficient.

BED DENSITY MEASUREMENTS

Bed density measurements must be averaged over a volume which is substantially bigger than the volume of an individual bubble. If not, then the bed density measurements indicate nothing more than the presence or absence of bubbles. In gas fluidized beds, microwaves have been used by Goosens (1976) and x-rays have been used by Rowe, et al. (1978). Optical measurements have been used by Anderson and Jackson (1969) to study fluctuations in bed density in a liquid fluidized bed and electrical conductivity has been used to characterize fluctuations in density in a three-phase fluidized bed by Begovich and Watson (1978).

SOLIDS MOVEMENT MEASUREMENTS

A number of instruments have been developed to provide direct information on solids velocity in a fluidized bed. Rezenbaum, et al. (1975) described an instrument which makes use of a ball on a string. As the ball moves through the bed (presumably with the solids) the displacement of the string is measured and recorded. A less complicated device is described by Heertjes, et al. (1970/71) which uses a needle at the end of a probe. The measured stress on the needle indicates the velocity vector of the solids moving past the probe. Oki, et al. (1977) used a fiber-optics probe with correlation techniques to determine the velocity of particles moving along the face of the probe. A two-thermistor probe was described by Marsheck and Gomezplata (1965) for measuring solids movement. The solids were heated by one thermistor and the temperature of the solids was sensed by a second thermistor a short distance from the first. From this measurement, the velocity component in the direction of the thermistors could be deduced.

Another method for measuring solids movement uses tagged particles with special instrumentation for detecting the particles. A small radio transmitter located in a particle (called a "radio pill") was used by Merry and Davidson in

1973 to trace the behavior of a typical particle through a fluidized bed. Radioactive particles have also been used for solid tracer studies by Katz and Zenz (1954), May (1959), Kondukov (1964), Haines (1972), and Blickel, et al. (1973). Particles are introduced at one point in the bed and monitored by radiation detectors at other points inside or outside the bed. If radioactive particles with a short half-life are used, then it is not necessary to move the tracer from the bed before performing a second run. Magnetic tracer particles can be separated by passing bed material over a magnetic drum or similar magnetic separating device. Fitzgerald (1978) used such a technique with 64 inductor probes to map the spread of tracer particles through a fluidized bed.

SYSTEMS NOT INCLUDED

Many instrumentation techniques have been used to monitor or to study fluidized bed performance which make use of conventional instrumentation applied in rather conventional ways. Examples of such uses are sulfur dioxide and nitrogen oxide detectors to sample the exit gases from a fluidized bed combustor. Various other techniques which use instrumentation systems to analyze particles which have been sampled from the bed are likewise not described in this report. They are not included since the emphasis in this report has been on in-situ measurements. It is not fair to conclude, however, that in situ measurements are always preferable. Often they are not and a particular kind of measurement should not be ruled out just because an in situ instrument is not available.

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ABSTRACT

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Descriptions of new and redesigned instrumentation, including a system for direct measurement of solids movement, scaled inductor probes and a pneumatic-release magnetic-collection system are presented. Results of various tests conducted to determine the suitability and feasibility of each instrument as well as a comprehensive literature review are also included.