**A Novel Instrumented Heat Transfer
Tube for Fluidization Research**

**Topical Report
January 1991 - June 1992**

**R. Turton
N. Clark**

October 1992

Work Performed Under Contract No.: DE-FC21-87MC24207

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
West Virginia University
Depts. of Chemical, Mechanical, & Aerospace Engineering
Morgantown, West Virginia

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MASTER *als*
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Abstract

A novel heat transfer probe capable of measuring simultaneously the time varying heat transfer coefficient around the surface of a heat transfer tube and the time varying static pressure fluctuations in the vicinity of the tube surface was built and tested. The probe consisted of a 2" OD - 1" ID stainless steel tube with a surface mounted thermocouple and pressure taps above and below the thermocouple flush with the surface of the tube. Simultaneous surface temperature data and local static pressure fluctuations were measured at different fluidizing conditions in beds of fine, 250 micron, sand. Time varying heat transfer coefficients were obtained by solving the unsteady conduction equation in the wall of the tube using the surface temperature measurements as the time varying boundary condition. Heat transfer coefficients obtained by this technique were of similar magnitude to those measured in similar beds at similar conditions. The time varying static pressure fluctuations obtained from the two pressure taps mounted in the tube wall contained considerable noise which made comparison, using Fourier Transform Techniques, of the temperature and pressure data impossible. However, visual observations of the two sets of data suggest that a correlation may exist but would require the filtering or elimination of noise from the pressure transducer.

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1. Introduction

Gas-fluidized beds are known for their excellent heat transfer characteristics due to the extensive mixing of bed solids. High rates of heat transfer between fluidized beds and vessel walls and/or immersed surfaces are possible and represent one of the major reasons for using fluidized beds as combustors and in reacting systems requiring extensive temperature control. Despite the extensive work done in the fluidization area, few attempts have been made to design instrumentation capable of withstanding the harsh and erosive environments present in commercial scale fluidized bed equipment and yet still suitable for capturing the time varying information so critical in the analysis of fluidized bed behavior. As a result the precise mechanisms governing heat transfer in fluid beds remain unverified. Although bubbles in fluid beds clearly contribute to the time-varying nature of the bed-to-tube heat transfer coefficient, experimental work is still needed to elucidate the relationship between hydrodynamic and thermal events in the bed. Further understanding of this relationship could lead to improved distributor design and optimized placement of heat transfer tubes.

2. Objectives

The objective of this work was to design, build, calibrate and test a novel piece of instrumentation capable of detecting time varying heat fluxes and pressure events around the circumference of a thick walled stainless steel, water-heated heat transfer tube and capable of operating under the severe conditions present in a large scale fluidized bed. This instrumented tube would then be used to gather data from a cold bubbling fluid bed.

3. Literature Review

This work focuses on the simultaneous measurement of instantaneous local heat transfer coefficients and local pressure fluctuations. The literature review will consider each of these topics separately.

Measurement of Heat Transfer Coefficients

Since we are interested in measuring heat transfer coefficients under steady bed operation (although time varying coefficients are of interest) the measurement of the bed temperature is assumed to be simple and independent of time. The problem we face then is to measure the surface temperature of a heat transfer probe and the corresponding heat flux from the probe. The types of probe that have been used to measure local heat

transfer coefficients can be categorized into one of the four following groups:

- (i) Electrically heated microfoil heat sensors.
- (ii) Thermopile type heat sensors.
- (iii) Gardon gauges.
- (iv) Surface temperature measurement sensors.

We will look at each type of gauge separately.

Electrically Heated Microfoil Heat Sensors

These types of sensor typically employ an electrically powered thin metal film or foil as the energy source. The foil is typically mounted on a ceramic substrate to minimize heat loss in one direction. The other side of the metal foil is exposed to the fluidized bed or medium of interest and is heated by the passage of electrical current. The metal foil is chosen so as to have a high temperature coefficient of resistance which allows the temperature of the foil to be monitored by measuring the voltage across the foil and the current passing through it. The voltage and current measurements are also used to compute the power dissipated by the foil. By estimating the power dissipated to the ceramic backing the heat transfer coefficient can be found by solving the following equations.

$$\begin{aligned}Q_{bed}(t) &= I(t)V(t) - Q_{sub}(t) \\h_{bed}(t) &= Q_{bed}(t)/[T_{foil}(t) - T_{bed}] \\T_{foil}(t) &= T_{ref} + [V(t)/I(t) - R_{ref}]/[R_{ref} \cdot \alpha]\end{aligned}$$

where Q represents power

h represents the heat transfer coefficient

R represents Resistance

α represents the temperature coefficient of resistance for the metal comprising the foil and bed, sub, foil, ref refer to the bed, substrate, foil and reference conditions respectively.

These types of foil probes were originally developed for determining time varying heat transfer coefficients in boiling liquids by Foltz and Mesler (1) and were adapted for use in fluidized beds by Tuot and Clift (2). Catipovic (3) and Fitzgerald et al (4) have reported instantaneous local heat transfer coefficients between gas fluidized beds and a tube with several such probes inserted into the wall. They measured the response time for their probe (consisting of a 1-2 micron layer of platinum baked onto a glass like substrate) at approximately 1 millisecond. However, due to surface abrasion in the fluidized bed the film was worn away in a very short period of time. To remedy this situation a protective sheath of mylar was placed between the foil and the bed - this increased the response time of the probe to approximately 20 milliseconds which was still fast enough to pick

up the time varying heat transfer coefficients in the bed caused by bubble movement. This type of probe gives accurate data which is easy to interpret and convert into local, instantaneous heat transfer coefficients. However, it is generally unsuitable for high temperature beds where the direction of heat transfer is from the bed to the wall and is rather delicate and not suitable for retrofitting beds operating under severe conditions.

Thermopile type heat sensors

These types of heat probe essentially consist of a pair (or multiple pairs) of thermocouples separated by a thin wafer (or multiple layers of wafers) of insulating material. The direction of heat flow is perpendicular to the insulating material and thus the thermocouples measure the temperature differential across the insulating layer. The probe is then calibrated by measuring the temperature difference as a function of the heat flux through the wafer. Thus when the probe is mounted on a surface and exposed to a medium at a higher or lower temperature the surface temperature of the probe and the heat flux through the probe can be found. From these measurements the local heat transfer coefficient can be obtained. These types of probe have been used by George and Welty (5) and later by Goshayeshi et al. (6,7) to measure the heat transfer coefficients around the circumference of a horizontal tube immersed in a high temperature fluidized bed. Unfortunately, like the microfoil heat sensors reviewed above these probes are also subject to extensive abrasion in fluidized beds and in order to overcome this problem Goshayeshi et al. (7) wrapped the outer surface of the heat transfer tube with stainless steel shim. The presence of this extra layer increased the response time of the probe to approximately 1 second which precluded any time varying heat transfer coefficient measurements.

Gardon Gauges

A circular foil heat flux gauge, also known as a Gardon Gauge (8,9), was first introduced to measure intense thermal radiation. It was later used by Gosmeyer (10) to measure heat transfer coefficients in high temperature fluidized beds. The principle of operation is the simple one of a differential thermocouple set up between the center and circumference of a circular foil. The Gardon Gauge is comprised of a copper tube covered at one end by a constantan foil (other suitable materials can be substituted for copper and constantan). The constantan foil is welded to the copper tube at its circumference and is connected at its center to a copper wire. Thus a differential thermocouple is formed between the center and circumference of the foil. The gap formed in the tube, behind the foil, is filled with a low thermal conductivity ceramic. The Gardon Gauge is installed flush with the heat transfer surface at the point of interest. It is assumed that due to its low thermal mass and high thermal conductivity that the copper tube is in thermal equilibrium with the wall. As heat flows into the gauge

the center of the foil becomes hotter than the circumference because of the presence of the ceramic backing thus resulting in a radial flux of heat from the center of the foil to its edge. It is assumed that equilibrium exists and hence the normal flow of heat to the foil from the bed is equal to the radial flow of heat in the foil. With this assumption and knowing the differential temperature gradient across the foil's surface the heat flux and hence the heat transfer coefficient can be estimated. Ultimately, Gosmeyer (10) found that due to the uneven flux of heat across the full width of the foil's surface, caused by the movement of particles and bubbles in the fluidized bed, the gauge yielded unreliable results. Thus the Gardon Gauge could not be successfully employed to measure time varying heat transfer coefficients in fluidized beds, although time averaged results were obtained.

Surface Temperature Measurement Sensors

In principle these types of heat transfer probes are the simplest to construct and operate. However, the interpretation of data from such devices is probably the most difficult. The principle of operation is to measure the temperature of the surface of an object immersed in a medium (fluidized bed). The experimental set-up is shown in Figure 3.1.

The surface temperature measuring device must have a fast response time in order to follow changes in surface temperature. The device should also be small enough so as not to disturb the local heat transfer process at the surface of the probe (i.e. the device should be flush with the wall). Finally the measuring device and associated electronics should be sensitive enough to accurately discriminate small changes in surface temperature (maybe of the order of 1°F or less). The heat flux and consequently the heat transfer coefficient are computed by solving the conduction equation in the wall of the tube using the boundary condition of the varying surface temperature. The heat transfer coefficient and temperature on the cooling medium side are also required for the calculation but are easily measured. If the wall or length of the probe is large a semi infinite heat transfer assumption may be made with negligible error.

The application of surface thermocouples has been used widely in the area of heat transfer. Specifically George (11) used a probe comprised of thin alumel and chromel ribbons separated by thin mica sheets to measure heat transfer coefficients between fluidized beds of fine particles (100 micron) and the wall of the vessel. Khan (12) used three similar probes located circumferentially around a heat transfer tube (50.4 mm in diameter) to measure heat transfer coefficients between high temperature (900 K) fluidized beds and the tube. Both George (11) and Khan (12) report time varying, local heat transfer coefficients.

Figure 3.1 : Sketch illustrating the principle behind surface temperature measuring heat transfer probes.

The simplicity and robustness of the last technique is ideally suited to the current research and the use of surface thermocouples imbedded in the wall of a circular tube has been adopted in the current work.

Measurement of Pressure Fluctuations and Local Voidage

The current research uses the change in local static pressure to imply the presence or absence of bubbles. This technique has been extensively researched and there exists a wide body of published data on this subject. In general pressure probes and the pressure fluctuations which they measure fall into two broad categories: overall pressure measurements across the bed; local differential pressure measurements.

Overall Bed Pressure Measurements

Overall bed pressure fluctuations have been used to define an index of fluidization by various researchers, Shuster and Kisliak (13), Winter (14) and Kang et al. (15), and have also been used to discriminate the onset of turbulent fluidization, in small particle beds by Yerushalmi and Crankurt (16) and in large particle beds by Canada et al. (17). Considerable work has been done by Fan (18,19) and coworkers in interpreting the signals obtained from overall bed pressure fluctuations. They concluded that the major cause of these fluctuations is due to the movement and eruption of bubbles in the upper part of the bed.

Local Differential Pressure Measurements

The measurement and interpretation of time varying local pressure fluctuations has also received considerable attention in the literature. Sitnai (20) has shown local pressure fluctuations can be used to determine the presence of bubbles in the vicinity of the probe. He demonstrated that several bubble parameters can be measured by a pair of pressure probes located on the same vertical axis and connected to a differential pressure transducer. Specifically, Sitnai (20) measured bubble velocity, apparent bubble size or height, bubble frequency and local void fraction. Sitnai (20) also simulated the pressure profile around a rising bubble by applying the Davidson and Harrison (21) model for a bubble in a fluidized bed. Atkinson (22) and Atkinson and Clark (23) also used a Davidson model to interpret local differential static pressure signals from a pair of vertically aligned probes in order to obtain further information about the bubble movement. They also were able to discriminate between rising bubbles and choose from which bubbles to sample.

The choice of the separation distance between the probe stems, the diameter of the stems and lines to the transducer and the dead volume of the transducer can all effect the signal recorded from the fluidized bed. The effective response time and amplitude

reduction caused by these factors has been studied previously, Clark and Atkinson (24) and Turton and Clark (25), and design criteria are available to minimize errors in interpreting data from such probes.

Finally the interpretation of intersected chord length data or the equivalent intersection time data from differential probes has also been studied by Clark and Turton (26) and Turton and Clark (27), who have shown that true bubble size distributions may be obtained from such data if a representative bubble shape may be assumed. The effect of non-vertically rising bubbles intersecting probes has been looked at by Lim and Agarwal (28) who conclude that if non-vertically rising bubbles are filtered from the data then the resulting bubble size distributions are representative of the whole bubble population intersecting the probe.

4. Theoretical Background

Surface Temperature Measurement and the Evaluation of Time Varying Heat Transfer Coefficients

The problem of converting surface temperature measurements into time varying heat transfer coefficients involves describing the conduction heat transfer occurring in the wall of the tube which is immersed in the fluidized bed. Figure 4.1 illustrates the problem:

The surface temperature is measured using a thermocouple located on , but electrically isolated from, the wall of the tube. It is assumed that the fluidized bed temperature is essentially constant over the time scale in which we are interested. The inner surface of the wall is in contact with a rapid flow of hot water and it is assumed (and controlled in the experiments) that the flow rate is high enough to insure that the inside heat transfer coefficient is so large that the temperature of the water and the inside tube wall are the same. The temperature of the inside surface is therefore $T_{\text{hot water}}$ and thus the temperature difference across the tube wall is always known.

In order to obtain time varying heat transfer coefficients between the tube and the fluidized bed we must first solve the appropriate partial differential equation describing the conduction of heat through the tube wall. Thus we may write:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (4.1)$$

with boundary conditions

Figure 4.1 : Important variables in the measurement of time varying heat transfer coefficients using surface temperature measuring probes.

$$T[r=R_o, t] = T_{surface}(t)$$

and

$$T[r=R_i, t] = T_{hotwater}$$

The initial condition is not known since data will start to be taken at some point in time rather than when the experiment is first started. We may assume that the temperature profile is that at steady state, using the appropriate time averaged wall temperature $\langle T_{surface} \rangle$. This gives the following initial condition:

$$T(r, t=0) = T_{hotwater} + \frac{\langle T_{surface} \rangle - T_{hotwater}}{\ln \frac{R_o}{R_i}} \ln \frac{r}{R_i}$$

Using this approach it is necessary to take data for a long enough time that the error involved in using the above initial condition is completely damped out. Khan (12) has shown that approximately 40 secs of data at 100 hz is sufficient to obtain the true time varying temperature profile in the tube wall.

The procedure for obtaining time varying heat transfer coefficients from the temperature profile in the wall is straightforward. The profile is differentiated at the surface in contact with the fluidized bed and the heat transfer coefficient then calculated from :

$$h(t) = - \frac{k_{wall}}{[T(r=R_o, t) - T_{bed}]} \frac{\partial T}{\partial r}_{r=R_o} \quad (4.2)$$

Thus the algorithm for obtaining time varying heat transfer coefficients from surface temperature measurements is as follows:

- (i) Record time varying surface temperatures at surface of the probe exposed to the fluidized bed.
- (ii) Solve Equation (4.1) using the temperatures from (i) above as the forcing function and the initial condition given above.
- (iii) Differentiate the temperature profiles in the wall and calculate $h(t)$ from Equation (4.2).
- (iv) Use values of $h(t)$ from (iii) above obtained after the

effect of the initial condition has died away.

Details of Numerical Algorithm used to solve Equation (4.1) and (4.2) are given in Chapter 6.

5. Experimental Equipment

A 12" x 12" fluidized bed was constructed of 1/2 inch, clear cast acrylic sheet. See Figure 5.1. The bed section, measuring 24 inches in height, had two 2 inch diameter holes drilled in opposite sides to accept a single heat transfer tube. The bed materials chosen for this study were white millet seed, which had a particle diameter on the order of 2500 microns, as determined by sieve analysis and a white sand of 200 to 300 micron diameter. From the data of Wayne (29) the particle density of the millet seed was calculated as 883 kg/m^3 . A powder number of $\phi = 3.59$ was calculated according to equations given by Clark et. al. (30) indicating a borderline B/D particle according to Geldart's classification (31). The minimum fluidizing velocity for this particle was 1.25 ft/s corresponding to a volumetric flow rate of 75 scfm. The sand had a density of 2600 kg/m^3 and was a type B powder.

The fluidizing air was supplied by a Sullair Sulliscrew compressor capable of delivering 200 scfm at a pressure of 125 psig. The air was purified by a Gas Drying Inc. gas filtration and drying system to remove any oil residues which might foul the distributor and bed material. The air then entered the laboratory through a 1.5 inch galvanized iron supply line and was regulated to a pressure of 20 psig. The flow rate was controlled by a 1.5 inch gate valve located downstream of a flow metering orifice designed according to ASME standards. For lower flow rates associated with the fine sand a 50 scfm Dwyer rotameter was used.

The orifice meter (see Figure 5.2) consisted of a 1 inch diameter, stainless steel, square-edged orifice with "D" and "1/2 D" pressure taps and a Dwyer differential pressure gage with a range of 0 to 100 inches of water head. The meter was calibrated previously by Wayne (29). The air continued through a 1.5 inch, flexible supply line and entered the plenum chamber through a single 1.5 inch diameter inlet in the lower left side. The air then entered the fluidized medium through a multi-orifice distributor plate sandwiched between the plenum and data sampling section of the bed. Both plenum and distributor were used previously in the research of Wayne (29).

4.3 Distributor Design

A multi-orifice distributor plate was designed according to equations given by Geldart and Baeyens (32). Constructed of 1/2

FIGURE 5.1 : 12" X 12" Gas -Solid Fluidized Bed

(Drawing Not To Scale)

FIGURE 5.2: Orifice Assembly

inch thick aluminum plate, the distributor consisted of 900 drilled holes, $3/32$ of an inch in diameter, spaced 0.40 inches apart on a square pitch (see Figure 5.3). O-ring seals between the plenum chamber and the distributor and between the distributor and the lower section of the bed prevented leakage of the working fluid. The pressure drop across the distributor (see Figure 5.4) was calculated to ensure that its operation would be stable across the intended range of flow rates. Since the pressure field around a bubble close to the gas distributor was to be examined, jetting was also a concern in the design of the distributor. Jets penetrate no more than one inch above the distributor at the highest anticipated flow rates (operating on millet seed).

The first thermocouple used was identical to that described by Khan (12). The probe consists of three transducers installed, 120° apart in the wall of a 2" O.D. stainless steel tube. The transducers may be broadly described as stainless steel cylinders furnished with extremely fast responding and non-intrusive surface thermocouples at their outer face. These transducers serve to measure the local instantaneous temperature variations at the outer surface of the tube. A thick tube wall and a high rate of hot water flow through the tube ensure that the temperature at the inner surface may be considered constant for all practical purposes.

Requirements for the heat transfer probe are as follows.

1. The transducer was to be completely non-intrusive i.e., its presence was in no way to affect the flow of the bed medium past the tube surface. The variations seen in the heat transfer coefficients around the circumference of the tube are a result of the hydrodynamics of the flow of the bed medium past the tube surface. Any alteration in the flow patterns, therefore, would lead to erroneous results.
2. The thermal properties of the material of construction of the transducer were to closely match those of the heat transfer tube material. Even slight differences in the thermal properties could result in a disturbance of the temperature distribution within the tube wall.
3. The thermal properties of the material of construction of the transducer were to be such that the variations induced in the surface temperature due to the instantaneous heat transfer coefficient fluctuations would be large enough to be easily measured. This would greatly reduce the demands on the sensitivity and accuracy of the data acquisition system.
4. The length of the transducer was to be large enough so that fluctuations in temperature at the outer surface of the tube would be damped out before reaching the inner surface. With the

(Drawing Not To Scale)

FIGURE 5.3: Multi-orifice distributor plate consisting of 900 drilled holes $\frac{3}{32}$ of an inch in diameter, spaced 0.40 inches apart on a square pitch.

FIGURE 5.4: Pressure drop across the distributor for intended range of air flow rates.

added help of a high coolant flow rate, this would ensure a constant temperature at the inner surface of the heat transfer tube. While this condition is by no means necessary for a possible mathematical solution, it greatly reduces its complexity.

5. The thermocouple was to have a low enough response time to follow accurately any variations in the surface temperature. The necessity for this has been stressed in Chapter 2.

6. The thermocouple was to be placed as close as possible to the surface so that the measured temperature was that of the surface and not that at a point even slightly above or below it. This was necessary, as the temperature gradients at the surface, while the surface temperature is varying, are very large. Even a slight error in the placing of the thermocouple would result in highly erroneous surface temperature data.

7. The transducer was to be resistant to the highly abrasive environment of the fluidized bed.

A detailed diagram of the transducer designed by Khan (12) is shown in Figure 5.5. An exploded view of the same is shown in Figure 5.6. The fluxmeter is comprised of two SS-304 half cylinders, sandwiching a chromel and an alumel ribbon running along the axis of the composite cylinder. The ribbons are insulated electrically from each other and the half cylinders by extremely thin sheets of mica. This unit is force-fitted into a SS-304 sleeve, thereby, preventing any movement in the mica or the ribbons once they have been laid in place. The chromel and alumel ribbons are part of a typical type K thermocouple and are created by rolling the ends of the thermocouple wires. The thermocouple for the rest of its length is sheathed in a SS-304 tube filled with a ceramic insulation.

Once the transducer has been assembled, polishing it on its outer surface with sand-paper results in the creation of abrasive welds between the thermocouple ribbons themselves and the ribbons and the surfaces of the half cylinders. These welds may be best described as being formed by a smearing of the ribbons at the surface. As might be expected, the resulting thermocouple junction has an extremely small thermal mass and therefore a very low response time. The response time of the thermocouple was measured by Khan (12) and shown to be less than 11 ms. In addition to a very fast response, such a thermocouple has the advantage of being accurately positioned at the surface.

Furthermore, the creation of the junction being due to abrasion, the junction has the advantage of being "self renewing", i.e. while abrasion may wear off an old junction, it creates a new junction in its place. This property of the thermocouple junction to renew itself was tested by placing the probe in a fluidized bed

Figure 5.5 : Heat Transfer Probe due to Khan (12)

Figure 5.6 : Exploded view of Khan's probe.

and measuring the junction resistance periodically. At no point during the 48 hour test did the resistance of the junction change perceptibly. In order to ensure the non-intrusiveness of the transducers, they were filed on their outer surfaces until flush with the tube wall.

Tube Design

The tube, shown in Figure 5.7 with the transducers in place, is constructed of SS-304. Its outer diameter is 2", a typical diameter for heat transfer tubes used in fluidized bed boilers. The inner diameter of the tube is 1", dictated by the 1/2" thickness of the transducers. In order to facilitate easy installation of the transducers and other instrumentation that may be added in the future, the tube is split along its axis into two equal halves. These two halves are bolted together using allen-head bolts spaced 4" apart. Flanges have been added at the ends of the tube to allow for the connection of a water supply. The tube is equipped with thermocouples at each end for the measurement of the water inlet and outlet temperatures. Preliminary work in the bed with millet seed as bed material produced noisy data using Khan's probe. It was discovered that the thermocouple was grounding to the tube, and that this action marred the weak thermocouple signal (approximately 10% that of Khan (12)) to the extent that it was unusable. The thermocouples proved difficult to repair satisfactorily, and so a new design, philosophically identical to Khan's, was employed. The stainless steel plug was drilled with a hole of 0.025 inches diameter, and a miniature thermocouple available as a standard item from Omega was inserted into the hole with the junction at the plug surface. The void in the hole around the thermocouple was packed with an electrically insulating epoxy material with a conductivity of 16.6 W/m.K at 100°C, available from Omega. This epoxy conductivity is close to that of the stainless steel used for tube and plug construction. The plug was then inserted in the tube to form a smooth surface for heat transfer measurements. No grounding problems were experienced with this design.

To determine the presence of bubbles in the bed, the "differential" pressure in the region of the heat transfer probe was measured. This was achieved by drilling two holes of 0.05 inches diameter, one above the plug and one below the plug, 0.5625 inches vertically apart. These holes were connected by 0.04 inches diameter tubing 14 inches in length to a Validyne pressure transducer, capable of low pressure difference measurement with rapid response.

Data Acquisition

To acquire data the instrumented tube had to be supplied with fluid at a temperature significantly different from that of the

Figure 5.7 : Design of instrumented tube.

bed. Near-boiling water was supplied using a pump, tank, two 1 kw immersion heaters, and flexible hose. Temperature in this circulation system was stabilized at about 99°C before a run commenced. Velocity in the circulating system was sufficient to ensure that the inner tube wall was held at constant temperature.

Bed temperature was measured with an immersed mercury thermometer.

6. Data Processing

Data acquired by the computer was stored and displayed graphically. Time-varying surface temperature data were subjected to fast Fourier analysis to yield major frequencies associated with heat transfer events. In addition, a program was written to yield the time-varying temperature distribution through the tube wall, with the knowledge of the inner temperature and the time-varying surface temperature.

For a unsteady one dimensional heat transfer problem of a cylindrical tube, on which one of the boundary temperatures is fluctuating with time, one may use the following equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) = c\rho \frac{\partial T}{\partial t} \quad (6.1)$$

where

$$\begin{aligned} T(r_1, t) &= T_L \\ T(r_2, t) &= T_w(t) \\ T(r, 0) &= T(r) \end{aligned}$$

The control volume formulation method is used to solve this problem numerically by using the fully implicit method. The physical interpretation of the control volume method is that the calculation domain is divided into a number of nonoverlapping control volume such that there is one control volume surrounding each grid points. The most attractive feature of the control-volume formulation is that the resulting solution would imply that the integral conservation of quantities such as mass, momentum, and energy is exactly satisfied over any group of control volumes and, of course, over the whole calculation domain.

Since time is a one-way coordinate, we obtain the solution by marching in time from a given initial distribution of temperature. With given grid-point values of T at time t , the values of T at time $t + \Delta t$ can be computed. The "old" (given) values of T at the grid points will be denoted by T_p^0 , T_N^0 , T_s^0 , and the "new" (unknown) values at time $T + \Delta t$ by T_p^1 , T_N^1 , T_s^1 .

The main principle of the fully implicit scheme is that the new value T_p prevails over the entire time step.

The discretization equation is derived by integrating Eq. (6.1) over the control volume and over the time interval from t to $t + \Delta t$.

Thus,

$$\int_t^{t+\Delta t} \int_s \frac{\partial}{\partial r} \left(Kr \frac{\partial T}{\partial r} \right) dr dt = \int_t^{t+\Delta t} \int_s r c_p \frac{\partial T}{\partial t} dr dt \quad (6.2)$$

where the order of the integrations is chosen according to the nature of the term. After the integration this becomes;

$$a_p T_p^1 = a_N [f T_N^1 + (1-f) T_N^0] + a_s [f T_s^1 + (1-f) T_s^0] + [a_p^0 - (1-f) a_N - (1-f) a_s] T_p^0$$

For a fully implicit method $f=1$, the discretization equation becomes;

$$a_p T_p^1 = a_N T_N^1 + a_s T_s^1 + a_p^0 T_p^0$$

where the coefficients are

$$\begin{aligned} a_p &= \frac{\rho c r_p \Delta r}{\Delta t} \\ a_N &= \frac{k r_a}{\delta r_n} \\ a_s &= \frac{k r_s}{\delta r_s} \\ a_p^0 &= a_p - a_N - a_s \end{aligned}$$

From the computed temperature profile the heat transfer coefficient is determined by equating the conduction near the tube surface to the convection between the bed and tube surface.

The program has been verified by examining the response to a step change in tube surface temperature, as shown in Figure 6.1.

7. Results and Discussion

Data was gathered from the bed operating with both millet seed and fine sand, but only the sand data were deemed to be sufficiently noise free to justify processing and presentation.

Figure 6.1 : Response to a step change in the tube surface temperature.

Figure 7.1 shows a time-varying surface temperature trace with the heat transfer probe on the side of the tube (i.e. 90°) and the bed not fluidized. Noise is low and the accompanying fast Fourier transform exhibits low amplitudes. Figures 7.2 to 7.4 show data for the same circumstances when the 12" x 12" bed is fluidized with 15, 20 and 30 scfm of air respectively. It is evident that amplitudes increase with increasing flowrate of air, which can be attributed to increasingly violent bubbling in the bed.

Figure 7.5, at 30 scfm, shows that the time-varying nature of heat transfer is quite different when the probe is at the base of the tube (0°), with lower amplitudes in the variation. On top of the tube (180°), as shown in Figure 7.6, amplitudes are reduced due to the stagnant solids which often deposit on the tubes. Additional runs are shown in Appendix A.

Figure 7.7 shows various time-varying temperature profiles through the tube wall for a 32 second run at 20 scfm. It is evident that the temperature gradient is steady over most of the wall thickness, with fluctuations limited to a zone near the surface. Figure 7.9 shows computed time-varying heat transfer coefficients over a 32 second run at 20 scfm while Figure 7.10 shows an expanded view of the first four seconds of this run. The coefficient varies between 150 and 750 $\text{W/m}^2\text{K}$, which averages to a credible value for fine sand.

In addition to obtaining time varying surface temperature data from the probe, a series of experiments were performed in which simultaneous surface temperature and differential pressure measurements were taken. The results of these runs are shown in Figure 7.11 and Figure 7.12. Figure 7.11 compares simultaneous temperature and differential pressure data while Figure 7.12 compares the Fourier Transform of the two data sets. Visual inspection of Figure 7.11 suggests that there is some correlation, as expected, between the pressure events monitored around the tube and the temperature fluctuations measured at the surface of the tube. The Fourier Transforms do not, however, confirm this observation. Rather, Figure 7.12 shows that the temperature fluctuations at the surface of the tube vary with a dominant frequency of between 1 and 2 Hz which is a typical frequency for bubble events in a bed. This suggests that the pressure fluctuations should also have a dominant frequency in this range, however the transducer appears to be picking up considerable high frequency noise. It is believed that this noise, which is in the 6 - 20 Hz range, is masking the larger amplitude fluctuations caused by bubble events.

The problems causing the noisy pressure signals noted above were investigated. The high frequency component was attributed to a combination of pump and other extraneous acoustic noise and consequently has been eliminated. A final series of runs were performed using a pulsed bubble generator located vertically

beneath the heat transfer sensor immersed in a bed of fine sand at minimum fluidizing conditions. A pulse of bubbles at 5 Hz frequency was generated and simultaneous measurement of surface temperature and local differential pressure were taken. These data along with the corresponding Fast Fourier Transforms, Auto and Cross Correlations are given in Figures 7.13 and 7.14. From these figures it can be seen that the dominant frequency for both the temperature and pressure fluctuations lies very close to the expected 5 Hz (4.9 and 5.1 Hz respectively). The pressure signal is now very clean with the major peak on the FFT clearly showing 5 Hz. The surface temperature FFT also shows a peak at 5 Hz but with some lower frequency signals also contributing. This lower frequency component in the temperature measurement is due to a slight drift in the signal over the period of the experiment and does not represent other periodic information. The Auto and Cross correlations show a much clearer picture of the two signals and the dependency of the surface temperature fluctuations on the movement of bubbles close to the probe is clearly seen.

Figure 7.1 : Data from slumped bed.

Figure 7.2 : Four second trace at 15 scfm, fine sand bed material, probe at 90° from vertical.

Figure 7.3 : Four second trace at 20 scfm, fine sand bed material, probe at 90° from vertical.

Figure 7.4 : Four second trace at 30 scfm, fine sand bed material, probe at 90° from vertical.

Figure 7.5 : Four second trace at 30 scfm, fine sand bed material,
probe at 0° from vertical.

Figure 7.6 : Four second trace at 30 scfm, fine sand bed material,
probe at 180° from vertical.

Figure 7.8 : Temperature gradients in the surface region of the tube (enlarged from Figure 7.7)

Figure 7.9 : Computed heat transfer coefficients based on temperature gradients in the tube (30 seconds of data)

Figure 7.10 : Computed heat transfer coefficients based on temperature gradients in the tube (4 seconds of data)

Thermocouple Data, 15scfmdp

DPT data, 15scfmdp

Figure 7.11 : Simultaneous surface temperature and differential pressure traces at 15 scfm, fine sand bed material, probe at 90° from vertical.

FFT of Thermocouple Data

FFT of DPT Data

Figure 7.12 : Fast Fourier Transforms for simultaneous surface temperature and differential pressure traces at 15 scfm, fine sand bed material, probe at 90° from vertical.

Figure 7.13 : Thermocouple, differential pressure traces and fast Fourier transforms for a 5 Hz bubble stream in a bed of fine sand at minimum fluidizing conditions, probe at 90° from vertical.

Figure 7.14 : Auto and cross correlations for signals from thermocouple and differential pressure transducer for 5 Hz bubble stream in a bed of fine sand at minimum fluidizing conditions, probe at 90° from vertical.

8. Conclusions

A heat transfer tube capable of measuring simultaneously time varying surface-bed heat transfer coefficients and local pressure fluctuations was built, tested and calibrated. The time varying surface temperatures were measured at three locations on the tube surface and at three different fluidizing conditions. Markedly different behavior was observed at the top, side and bottom of the tube with the largest temperature fluctuations being observed at the side of the tube for a given air velocity. Heat transfer coefficients back-calculated from temperature measurements made at the side of the tube fluctuated from between 100 and 750 W/m².K. These observations are all consistent with those of Khan (12) who measured heat transfer coefficients in high temperature beds with a similar type of probe.

Static pressure measurements between the two arms of a dual stem probe located vertically above and below the heat transfer probe were taken simultaneously with the surface temperature data. Initially noise from extraneous sources (the water pump etc.) seemed to corrupt the pressure data, however, by re-engineering the water circulation loop this noise was successfully eliminated. The resulting data for a uniform stream of bubbles passing by and intersecting the probe showed excellent correlation between the pressure and temperature measurements as illustrated by the FFT, Auto and Cross correlations for these signals.

The principle of measuring simultaneously time varying heat transfer and pressure fluctuation data has been demonstrated using a single novel instrumented probe. This probe, it is believed, is robust enough to be used in a large scale bed operating at severe conditions. This instrument thus represents one of only a few probes capable of being used in a fluidized bed boiler or other "real world" fluidized bed.

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Appendix A - Data for runs in fluidized beds of fine sand

Table A1

Figure	SCFM	BED TEMP	WATER TEMP	TUBE ANGLE
A1-A4	15	33	88	180
A5-A8	20	32	90	180
A9-A12	30	33	91.5	180
A13-A16	15	31	96	0
A17-A20	20	35	96.5	0
A21-A24	30	32	96	0
A25-A28	15	31	98	90
A29-A32	20	29	96	90
A33-A36	30	33	98	90
A37	15	28	96.5	90
A38	0	27	98	0

Operating conditions of runs corresponding to figs A1-A37
 Bed material is sand fluidized by air.
 Tube angle of 0 corresponds to probe pointing towards bottom
 of bed.

Fig. A-1

Fig. A-2

Fig. A-3

Fig. A-4

Fig. A-5

Fig. A-6

Fig. A-7

Fig. A-8

Fig. A-9

Fig. A-10

Fig. A-11
56

Fig. A-12

Fig. A-13

Fig. A-14

Fig. A-15
60

Fig. A-16

Fig. A-17

Fig. A-18

Fig. A-19

Fig. A-20

Fig. A-21

Fig. A-22

Fig. A-23

Fig. A-24

Fig. A-25
70

Fig. A-26

Fig. A-27

Fig. A-28

Fig. A-29

Fig. A-30

Thermocouple Data, 20scfms

FFT of Thermocouple Data, 20scfms

Fig. A-31

Fig. A-32

Fig. A-33

Fig. A-34

Fig. A-35
80

Fig. A-36

Fig. A-37

Fig. A-38

Appendix B - Program used to determine time varying heat transfer coefficients from time varying surface temperature measurements.

```

C***** This program calculates the temperature distribution *****
C***** and the instantenous heat transfer coefficient *****
C***** in horizonthal tube in fludized bed. It has been applied *****
C***** the fully implicit method by using control-volume formulation.
C***** T(NX)=Temperature on grid points
C***** qi(Nx)=Instantenous heat flux *****
C***** hi(Nx)=Instantenous heat transfer coefficient *****
C***** Tw(Nx)=Measured temperature on the surface of the tube *****

```

```

Parameter(Nx=25000)

```

```

real k,rho,c,dt,dr,n,r2,r1
real Tl,Tb,L,Twa,ht,ha,s,time,maxtime
integer np,tg,npoint,dpoint
dimension r(NX),T(NX),TW(NX),qi(NX),hi(NX)
dimension TO(NX),Rs(NX),Rn(NX),dert(NX),TIMEH(NX)
dimension Rp(NX),Ap(NX),As(NX),An(NX),Ao(NX)
c data dpoint,Tb,Tl,dt,r1,r2,np /20000,340,380,0.001,0.0254,0.0508,20/
open (unit=11,file='ihsan.prn',status='old')
c open (unit=8,file='impllmax.out',status='new')

c open (unit=12,file='temildim.dat',status='new')
c open (unit=13,file='temrldim.dat',status='new')
Write(*,*)'How many data point do you have ?'
Read(*,*)dpoint
do 10 i=1,dpoint
read(11,*)Tw(i)
write(*,*)Tw(i)
10 continue

write(*,*)'Enter the temperature of the fluidized bed Tb'
read (*,*)Tb
write(*,*)'Enter the temperature inside of the tube'
read(*,*)Tl
k=16.0
rho=7900.0
c=477.0

```

```

write(*,*)'enter the time intervall of data'
read (*,*)dt
C tfinal=(dpoint-1)*dt
write(*,*)'enter r1,r2,np(grid point)'
read (*,*)r1,r2,np
dr=(r2-r1)/(np-1)
L=(r2-r1)

```

C-----R-CORDINATE-----

```

do 20 i=1,Np
if (i.EQ.1) then
r(i)=r1
else
r(i)=r(i-1)+dr
endif
C write(*,*) i,r(i)
20 continue

```

```

do 21 i=2,np-1
Rp(i)=R(i)
if(i.eq.2) then
Rs(i)=r(i-1)+0.5*dr
Rn(i)=Rs(i)+dr
else
Rs(i)=Rn(i-1)
Rn(i)=Rs(i)+dr
endif
c write(*,*) 'Rn(i)=',Rn(i),Rs(i),Rp(i)
21 continue

```

C-----TIME-AVARAGED TEMP AT THE BOUNDARY-----

```

Twt=0.0
do 25 i=1,dpoint
Twt=Twt+Tw(i)
25 continue
Twa=twT/dpoint

```

C-----NUMERICAL CALCULATION-----

C-----initial condition-----

```
twb=360.
time=0.0
c write(8,*) 'time=',time

DO 26 I=1,NP
  if(i.eq.1) then
    T(i)=TL
  else
    if(i.eq.np) then
      T(i)=TWb
    else
      T(i)=TL+((Twb-TL)/log(r2/r1))*log((r(i))/r1)
    endif
  endif
c      WRITE(*,*) 'Initial Condition given:'
c      WRITE(8,*) 'T(I)=',T(I),r(i)
  26  CONTINUE

ht=0.0
toler=0.01
maxtime=dpoint*dt

c      WRITE (*,*) 'maxtime:',maxtime
  39  time=time+dt
      iter=0

c      write(*,*) 'iter:',iter
c write(8,*) 'Time=',time
  j=time/dt
  T(1)=Tl
  T(np)=Tw(j)

  41  iter=iter+1
c write(*,*) 'iter=',iter
  do 40 i=2,np-1
```

```

if(iter.eq.1) then
TO(i)=T(i)
endif

Ap(i)=(rho*c*Rp(i)*dr)/dt
An(i)=(k*Rn(i))/dr
As(i)=(k*Rs(i))/dr
Ao(i)=(Ap(i)-An(i)-As(i))
c write(*,*)'ap=',ap(i),'An=',an(i),'AS=',AS(i),'Ao=',AO(i)
T(i)=(1./\p(i))*(An(i)*T(i+1)+As(i)*T(i-1)+Ao(i)*T(i))

diff=abs(T(i)-TO(i))

if(diff.gt.toler.or.iter.eq.1) then
itgerek=1
TO(i)=T(i)
endif
40 continue

if(itgerek.ne.0)then
itgerek=0
goto 41
endif
if(j.eq.1.or.j.eq.100.or.j.eq.3000.
+ or.j.eq.5000.or.j.eq.10000.or.j.eq.20000) then
c write(8,*)'Time=',time
do 45 i=1,np
c write(8,*)'T=',T(i),r(i)
45 continue
endif
C-----DERIVATIVE IF THE TEMPERATURE WITH RESPECT TO RADIUS-----
DERT(j)=(T(np-1)-T(np))/dr
C write(*,*)'derivative=',dert(j)

C-----CALCULATION OF INSTANTENOUS HEAT FLUX-----

qi(j)=k*Dert(j)

C-----CALCULATION OF INSTANTENOUS HEAT TRANSFER COEFFICIENT-----

```

```

TIMEH(J)=TIME
hi(j)=qi(j)/(Tw(j)-Tb)
ht=ht+hi(j)
C write(*,*)'At timestep',j,'h=',hi(j)

C-----CALCULATION OF AVARAGED HEAT TRANSFER COEFFICIENT-----
ha=ht/dpoint
C WRITE(*,*)'AVARAGE H='HA
if(time.lt.maxtime) then
goto 39
endif
DO 50 I=1,DPOINT
C WRITE(*,*)'H=',HI(I),TIMEH(I)
50 CONTINUE

end

```

END DATE
12-01-93