The Ohio State Universityy Research

The following report from Ohio ɔ State University for the period contains these brief chapters:

Highlights

Work Performed
1. Development of Fiber Optic I Probe System
2. Effect of Pressure on the Gasıs Holdup of Slurry Bubble Column

INTRINSIC FLOW BEHAVVIOR IN A SLURRY BUBBLE COLUMN UNDER HIGH PRESSURE AAND HIGH TEMPERATURE CONDITIONS

(**Reportingg Period:** October 1 to December 31, 1997)

Highlights

1. A computer code was developped to process the light intensity signals from a fiber optic probe. The computer code caan calculate the bubble rise velocity and bubble chord length distribution from the signals. :.

2. It was proven in experiments s that the probe system and the computer code can be used to measure the bubble size distriribution in a slurry bubble column under high-pressure, high-temperature, and high-gas velelocity conditions.

3. A new technique was estabilisished to measure gas holdup in slurry bubble columns. The new technique has two major advavantages over other techniques: elimination of uncertain particle density from the measuremennt and the capability to determine if the particles are completely suspended.

Work Performed

1. Development of Fiber Optic c Probe System

In the last quarter, a dual-tip opticical fiber probe was developed to measure bubble size distribution in high-pressure slurrrry bubble columns. Calibration of the probe proved that the probe system can satisfactorily mmeasure the bubble rise velocity and bubble chord length, provided that the signal from the e probe is processed appropriately.

A computer code was developed d during this quarter to analyze light intensity signals. The computer code first normalizes ththe signals based on the following formula:

$$\begin{cases} I_n(t) = 0 & \text{if } I(t) \leq T \\ I_n(t) = 1 & \text{if } I(t) \geq T \end{cases} \qquad (1)$$

where $I_n(t)$ is the normalized lighlht intensity; $I(t)$ is the original light intensity; and T is a threshold value. T is taken as the maximumm value in signals from a gas-free liquid-solid suspension. Then a peak in the lower tip signal is uused as a trigger to match a peak in the upper tip signal. The $\Delta\tau_2$ of these two peaks, shown in Figigure 1, should be smaller than 0.018 second, since the detectable minimum bubble rise velocity is ь 8 cm/s. Also, the ratio of the width of peak (τ) in the upper tip signal to that in the lower tip sigrgnal is between 0.7 and 1, based on a calibration. After the peaks are matched, the bubble rise veloiocity is:

$$U_b = \frac{\Delta L}{\Delta \tau_2} \tag{2}$$

where ΔL is the vertical distancice between the two measuring tips. The bubble chord length is then

$$l = \tau U_b \tag{3}$$

The computer code was used too analyze the signal when the probe was placed in a chain of bubbles. The result from the coomputer program matched well that from visualization.

The computer code was then usised to analyze the signals obtained from slurry bubble columns. Figure 2 shows a typical signal d obtained in a slurry bubble column. The probability density function of the bubble chord lerength is shown in Figure 3. It can be seen from Figure 3 that the bubble size distribution at the aiambient pressure was wide, with a maximum bubble chord length of 6 cm which was more than hhalf of the column size (10.16 cm). This result proves that the bubble column is in the sluggingng regime at a gas velocity of 34.6 cm/s and at 0.1 MPa pressure.

The computer code will be usedd to analyze the bubble size distribution and operating regime in slurry bubble columns under higigh-pressure and high-gas velocity conditions.

2. Effect of Pressure on the GGas Holdup of Slurry Bubble Column

With the probe system developeed during the past two quarters, attention has shifted to investigating the effect of pressisure on the hydrodynamics, including gas holdup and bubble size distribution, in high-pressure shlurry bubble columns at high gas velocities.

The measurement of the gas hobldup is based on the bed collapse technique described in the quarterly report of July 1997. EEfforts were made to further improve that technique, which involves the simultaneous shutatoff of both the inlet and outlet of the slurry bubble column after it reaches a steady state. The dynmamic pressure gradient signal was recorded with a computer data acquisition system during the erentire bed collapse process. The ratio of solids holdup to liquid holdup, K, in a slurry bubble coiolumn at steady state can be calculated from the dynamic pressure drop in the gas-free suspension a stage:

$$K = \frac{\varepsilon_s^0}{\varepsilon_l^0} = \frac{(\Delta P / \Delta z)_d^0}{(\rho_s - \rho_l)g - (\Delta P / \Delta z)_d^0} \tag{4}$$

where ε_s^0, ε_l^0, and $(\Delta P / \Delta z)_d^0$ are the solids holdup, liquid holdup, and dynamic pressure gradient at the gas-free suspensision stage, respectively. At a steady state, the gas holdup can be related to the dynamic pressure e gradient, phase densities, and the constant K by

$$\left(\frac{\Delta P}{\Delta z}\right)_d = \left(\rho_g \varepsilon_g + \rho_l \varepsilon_l + \rho_s \varepsilon_s -- \rho_l\right)g$$

$$= \left\{\frac{K(\rho_s - \rho_l)}{1+K} + \left[\frac{(1+K\zeta)\rho_g - (\rho_l + K\rho_s)}{1+K}\right]\varepsilon_g\right\}g \tag{5}$$

where ε_s, ε_l, ε_g, and $(\Delta P / \Delta z)_d$ are the solids holdup, liquid holdup, gas holdup, and dynamic pressure gradient at the steady state, respectively. Substituting Eq.(4) into Eq.(5), the gas holdup at the steady state can be derived as

$$\varepsilon_g = \frac{\left[(\Delta P / \Delta z)_d - (\Delta P / \Delta z)_d^0\right]/ / g}{(\rho_g - \rho_l) - (\Delta P / \Delta z)_d^0 / g g} \tag{6}$$

Equation (6) was used to evaluatate the gas holdup of high-pressure slurry bubble columns because of its two advantages. The solidxds density, ρ_s, cannot be easily be measured for porous particles in liquids, as hydrocarbon liquids cican partially fill the pores of particles. Eq.(6) eliminates the particle density from the calculatation. This technique can also determine if the particles in the column are completely suspendeled by comparing the dynamic pressure gradient at the gas-free suspension stage, $(\Delta P / \Delta z)_d^0$, obbtained at different gas velocities. $(\Delta P / \Delta z)_d^0$ remains a constant when all the particles are suspenmded. In the literature, sampling of the liquid-solid mixture has been used for the same purpose. . However, the sampling technique at high pressures is tedious and inconvenient to conduct. Alklso, the amount of liquid and particles cannot be maintained constant.

Figure 4 shows the gas holdup irin a slurry bubble column with a solids concentration of 20 wt % at 28°C and various pressures. ItIt can be seen that the gas holdup increases with an increase in pressure. The difference betweeien this result and that obtained by sampling of liquid-solid mixture is negligible.
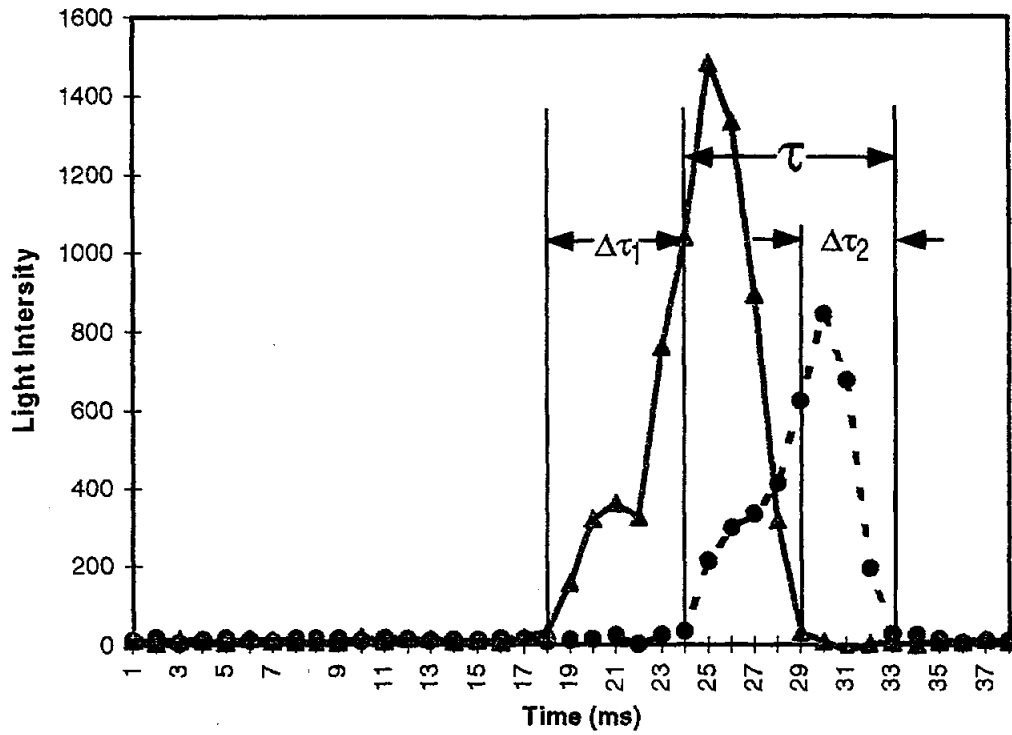
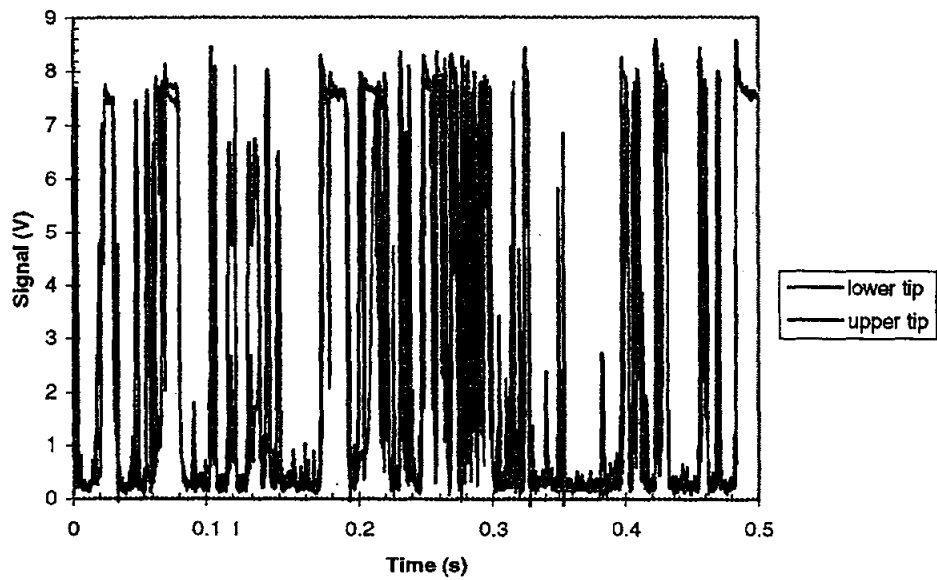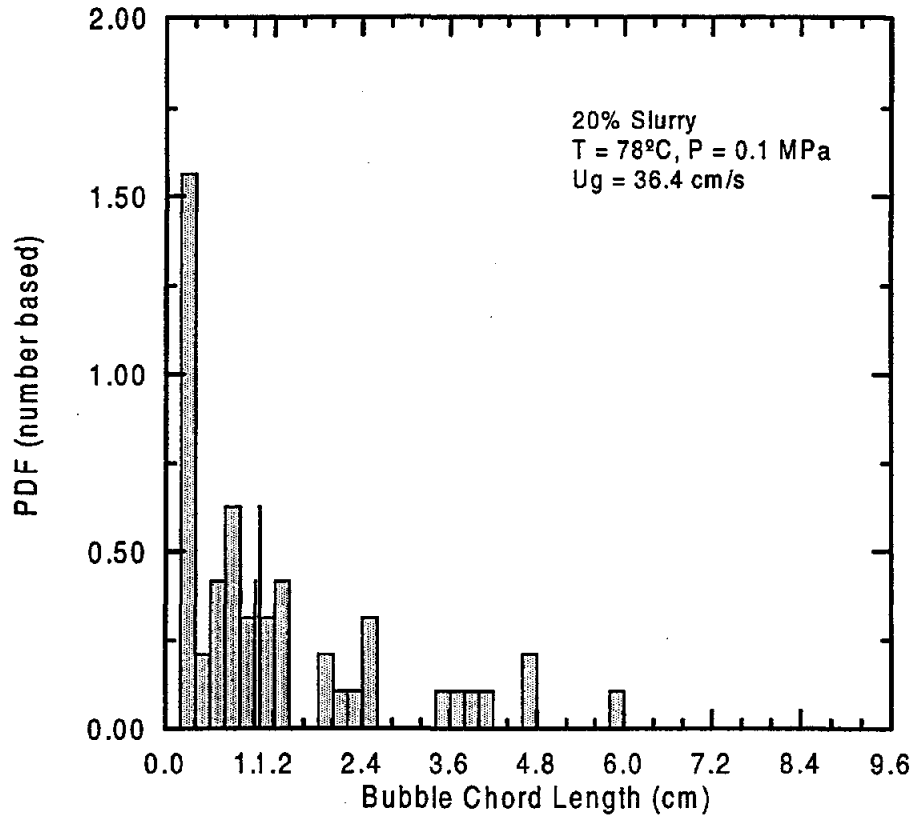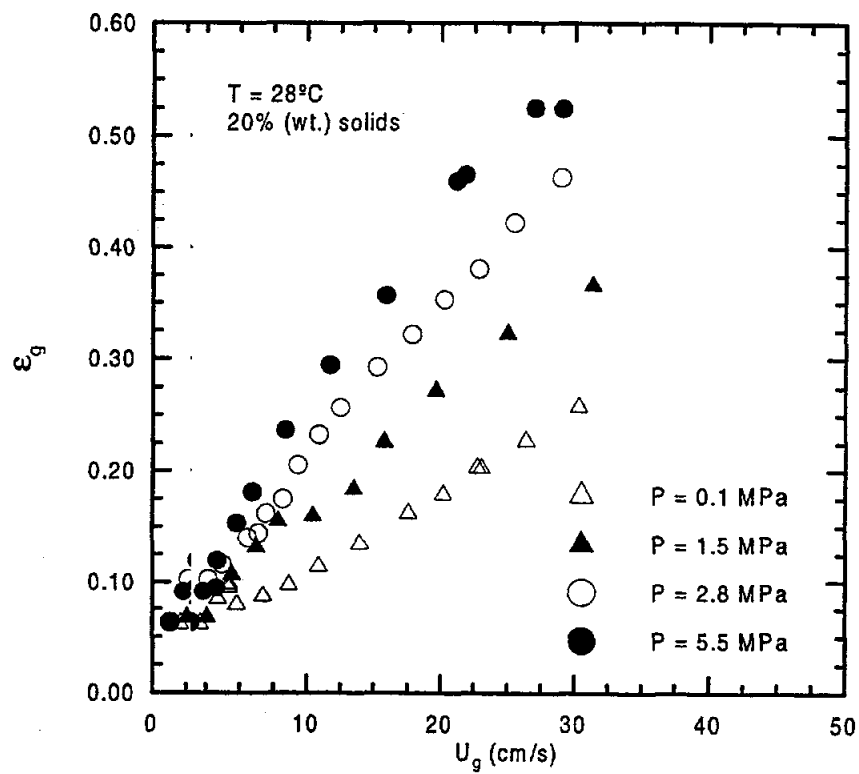**Figure 1. Characterisistics and Notations of Peaks of Light Intensity Signals**

Figure 2. Typipical Signals Obtained in Slurry Bubble Column

Figure 3. A Typical Bubbble Chord Length Distribution from the Computer Code

Figure 4. Gas Holdup in a Slslurry Bubble Column at 28°C and Various Pressures

NOVEL TECHNIQUES 1 FOR SLURRY BUBBLE COLUMN HYDRODYNAMICS

First Annualxl Report for Grant DE-FG 22-95 PC 95212

July 1, 1996

SECTION IV: **REPORRT FROM OHIO STATE UNIVERSITY (HEATT TRANSFER MEASUREMENTS)**

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OBJECTIVE

A special heat transsfer probe is developed which is used to measure instantaneous local heat transfer coefficieients due to the passage of single gas bubbles injected in liquid and liquid-solid systems. AAlso the reliability and accuracy of the probe are validated.

INTRODUCTION

High heat transfer rarate is one of the most important characteristics in the operation of a slurry bubble column ι which results in effective reaction temperature control in such reactors. Fundamental hdheat transfer studies have been concerned mainly with the measurement of time-averagaged heat transfer from the column wall to the bed and/or from the surface of immersed heieating object to the bed under steady state conditions. Due to inherent complexity of multitiphase flow systems, however, little has been known in the past about the intrinsic mechaniaism underlying the enhanced heat transfer in bubbling systems over non-bubbling systemsns. Therefore, a better understanding of the heat transfer behavior and the underlyingg mechanism is essential for the design, control, and optimum operation of such reactors. .

The heat transfer pproperty in the bed is intimately associated with the bubble motion, bubble, size, and plphase holdups which are affected by fluid flow including wake flow. The wake flow behavvior, such as temporal variations in the shear flow at the bubble edge, chaotic primary wakke, and vortex-vortex interaction, differs distinctively from the fluid flow behavior in the ι bulk region (Fan and Tsuchiya, 1990). Thus, a fundamental understanding of bubble-ν-wake dynamics forms a necessary basis for a complete

description of various trannsport processes in these systems, and to predict fully the heat transfer performance of gaas-liquid and gas-liquid-solid systems, effects of bubble wake need to be considered. Thhe bubble wake effect on heat transfer can be quantified by the measurement of the instanintaneous local changes in the heat transfer coefficient, which depends strongly on the locical hydrodynamics of the bed.

The complex behavvior of bubble columns is a direct result of the local flow structure which are time-vivariant due to the intrinsic dynamic behavior of the dispersed gas-phase motion and assssociated wake interaction. Therefore, to obtain a better understanding of the extreemely complex flow structure in bubble columns and its effects on the pertinent hydrodynaiamic properties and heat transfer characteristics, it is necessary to understand a simplified l system involving a single bubble moving in liquid and liquid-solid systems.

To measure local irinstantaneous changes in heat transfer coefficients due to the passage of single gas bubbbble, a special heat transfer probe is developed. This report highlights the design of the e novel heat transfer probe and its uniqueness and capability for accurately measuring the lolocal instantaneous heat transfer coefficients in multiphase flow systems. Moreover, discussssions of the mechanism of heat transfer enhancement due to the presence of bubble in simpplified systems involving single bubble injection in liquid and liquid-solid systems is preseiented.

EXPERIMENTAL

A schematic diaggram of the experimental apparatus is shown in Fig. 1. The experiments are performeced in a three-dimensional Plexiglas column, 150 cm high and 1.62 cm ID. Liquid enters thdhe column through a packed layer of 6 mm glass beads and a perforated-plate distributctor ensuring uniform distribution of liquid in the column. The support for the fluidized p particles is provided by a 200-mesh wire cloth. A steady liquid velocity is maintained by ϵ circulating water through a reservoir and a rotary pump. Tap water is used as the liquid d phase in the experiments. Fluidized particles used are 163 μm (GB163) and 326 μm (GBB326) glass beads. The physical properties of solid particles are given in Table 1.

Experiments involvlve single bubble injection in liquids and liquid-solid suspensions as shown in Figs. 2(a) and d 2(b). A three-dimensional cup bubble injection system in Fig. 1 is designed in this study tcto introduce single bubbles without pressure perturbation or any satellites generation. A heiemispherical cup of 2.5 cm diameter is inserted through the wall at 10 cm above the distribubutor. A known volume of air is injected into the cup through the stainless tube using a syriringe. The trapped bubble is then released by turning the cup. The bubble volume varied d from 3 cm^3 to 10 cm^3 with the corresponding bubble Reynolds number (based on equivalalent bubble diameter) Re, ranging from 5,300 to 9,000. Under these values of Re, the b bubble is of spherical cap shape and the wake configuration is symmetric along the vertrtical axis of bubble. Furthermore, the bubbles rose almost rectilinearly. Miyahara et a al. (1988) reported that for Re, beyond 5,000 the bubble tends to discharge vorticity symmmetrically and rises rectilinearly.

INSTANTANEOUS HEATT TRANSFER MEASUREMENT / PROBE DESIGN

The instantaneous loocal heat transfer rate is measured by a heat flow sensor/heater assembly (heat transfer probeje). Figure 3 shows the details of the probe design. The probe assembly consists of five commponents; microfoil heat flow sensor, copper plate, foil heater, thermosetting material (insulalator), and support. The foil heater is 2.54 cm high and 1.91 cm wide, and is heated by a ciconstant voltage DC power source.

The local heat flux is s measured directly by a microfoil differential heat-flow sensor (RdF corporation, Model 200453-1; Table 2). The overall dimension of the sensor is 1.27 cm × 1.27 cm × 0.008 cm. ˙ This sensor utilizes thin foil type thermopile bonded to both sides of a known thermal b barrier (Fig. 4). The difference in temperature across the thermal barrier known, the seiensor is factory-calibrated to provide the relation between the sensor output (voltage) and ↕ the local heat flux (Fig. 5). The unique construction of the sensor provides it with low ㅁthermal capacitance (204.41 $J\cdot m^{-2}/K$), low thermal impedance (5.28×10^{-4} $m^2\cdot K/W$), high seiensitivity (8.56×10^{-3} $\mu V/W\cdot m^{-2}$), fast response time (0.02 s), and minimal thermal perturbaiation to the heat flow. The microfoil heat flow sensor is flush mounted on the copper platete which is attached to the micro-foil heater and insulator as shown in Fig. 3.

The sensor can accurarately measure the heat flux and its surface temperature over a small surface area. The heateter/sensor probe assembly is usually positioned in the center of the column with the help of a a support as shown in Fig. 1. Due to the rectilinear motion of bubbles, there is a high probalability of bubbles striking the probe surface or at least passing very close to it. The probe i; is located at about 50 cm from the point of bubble injection,

which allows sufficient distatance for the bubble to reach its terminal velocity (Miyahara *et al.*, 1988). Since the widtħth of the probe at a horizontal section of the column is small (0.32 cm), the disturbance ɛ to the flow in the vicinity of the probe is minimal and the fluidized state remains ı relatively undisturbed. A sheathed copper-constantan thermocouple located at tłthe column wall is used for the measurement of the bulk temperature. The average bıbulk temperature is also monitored by a digital thermometer.

MEASUREMENT TECHHNIQUE

Signals for the heat t flux as well as the temperature difference between the probe surface and bulk are sampleæd simultaneously at the rate of 186.2 Hz for 11 seconds. The signals from the sensor (typpically in microvolt range) are amplified to millivolts range by the amplifier/multiplexer sys/stem (Metrabyte EXP-16) and interfaced with the high speed microcomputer data acquisıtition system (Metrabyte DASH-16). Digital signals stored in the computer are convertedd to the corresponding heat transfer rate and the temperature difference using proper calibıbration.

To reduce the higħgh frequency noise in the original signal, software signal processing is performed. Thħe signals are smoothed by employing a low-pass filter and the computations are performedd using Fast Fourier Transforms. A typical raw and filtered signal of the temperature diffifference ΔT_i (= T_{si} - T_{∞}) for a signal bubble injection in a liquid-solid fluidized bed containinṇg GB163 is shown in Fig. 6. There is a significant change in temperature difference due e to the passage of bubble, but the change in q_i is not so significant compared to the t temperature difference. Also, there is a large fluctuation in q_i

as compared to ΔT_i. Since tl the change in the instantaneous heat transfer rate depends on many factors including the ththermal balance on both sides of the heater, the instantaneous heat transfer coefficient, h_i, it is obtained from the instantaneous change in the temperature difference, ΔT_i, and the time a averaged heat transfer rate, Q.

$$h_i = \frac{Q}{\Delta T_i} \qquad (1)$$

Typical differential teiemperature ΔT_i in the stagnant liquid medium is 10°C, while that in the bubble column is ↷ 4°C. Due to the small dimension of the probe and minimal alteration in the hydrodynammic condition near the heat transfer surface, the measured instantaneous heat transfer coefficient in Eq. (1) is a direct measure of the local instantaneous heat transfer cicoefficients in the bed at that particular location. The local time-averaged heat transfer ɾ coefficient can be obtained by averaging the instantaneous heat transfer coefficient data a over a number of sampling points (2048) as

$$h_{av} = \frac{1}{n} \sum_{i=1}^{n} \frac{Q}{\Delta T_i} \qquad (2)$$

The small dimensionn of the probe (20 to 30 times smaller heat transfer area compared to conventional prorobes employed by Baker *et al.*, 1978 and Magliotou *et al.*, 1988), ease of installation, ; and high accuracy in measurements render its application limitless. For example, the pprobe could easily be positioned at any location in the bed to measure the instantaneous auand time-averaged heat transfer coefficient. Also, since the heat transfer measurements aiare local in nature, the probe may be used for locating in-bed non homogeneity in a multipbhase flow system. Thus, the probe is capable of instantaneous and local hydrodynamic chiharacterization of a particulate multiphase reactor, thereby

providing significant informaation regarding the radial and axial variation of heat transfer in an industrial and pilot size r reactor which would be of enormous practical significance in better design and control of f such systems.

PROBE VALIDATION

The reliability and acccuracy of the probe are validated by performing heat transfer measurements in liquid (waater) systems and liquid-solid fluidized beds. Time-averaged local heat transfer coefficiennts in liquid-solid fluidized beds agree well with the immersed object-to-bed heat transfer r coefficients data and correlations reported in the literature (e.g., Baker et al., 1978 annnd Kato et al., 1984). Also, a good agreement is obtained between the measured heat t transfer coefficient in stationary water with that predicted by the heat transfer correlationin for laminar free convection on a vertical plate immersed in stationary water reported in n the literature (e.g., Incropera and De Witt, 1985).

INSTANTANEOUS HEAlT TRANSFER COEFFICIENT

Figures 7, 8, and 9) show the instantaneous heat transfer coefficient due to the passage of a single gas bubbble in liquid, in liquid-solid systems containing GB163, and in liquid-solid systems containining GB326, respectively. The instantaneous heat transfer coefficient increased rapidly.y, attained a maximum value, and then gradually recovered to the initial value in liquid andd liquid-solid systems. It should also be noted from Figs. 7, 8, and 9 that due to the preseeence of secondary wake in liquid and liquid-solid systems, the heat transfer coefficient dooes not completely recover to the baseline value within the

sampling time of around ¡ 11 s. The effect of single bubble injection on heat transfer enhancement in the liquid ¡ system lasts much longer than in liquid-solid systems. Larger primary and secondary vwakes and stronger vortex in such systems are primarily responsible for this phenommenon. All figures show that increased bubble volumn V_b causes increased enhancement due e to larger bubble wake and stronger vortices.

Particle sizes in liqquid-solid systems affect the bubble-wake induced heat transfer enhancement. In Figs. 8 a and 9, heterogeneous effects caused by the larger particle size reduce the bubble-wake inchduced enhancement in heat transfer although the baseline value is increased. The baseline e values (time-averaged heat transfer coefficient with no bubble injection) for liquid is 285 5 W/m^2·K, for GB163 system is 808 W/m^2·K, and for GB326 system is 815 W/m^2·K.

CONCLUDING REMARRKS

A novel heat traransfer probe is developed which accurately measured the instantaneous changes in heieat transfer due to the passage of single gas bubble in liquid and liquid-solid systems. For a a bubble passing through the probe, the maximum heat transfer is observed in the wake reggion at a short distance behind the bubble in the upward flow of fluid rising along the wake c central axis.

In both liquid and l liquid-solid systems, the observed local maximum in the heat transfer coefficient behind ¡ a rising bubble is due to the effect of bubble wake. The local maximum in heat transfer,r, however, is more pronounced in liquid than in liquid-solid

systems. Also, the heat transfsfer enhancement due to the bubble passage increases with the bubble size due to larger bubblble wake and stronger vortices.

NOMENCLATURE

h_{av} time-averaged heat traransfer coefficient over the sampling time, $W/m^2 \cdot K$

h_i instantaneous heat trannsfer coefficient, $W/m^2 \cdot K$

n number of sampling pooints, 2048

Q time-averaged heat fluuix, W/m^2

V_b bubble volume, cm^3

ΔT_i instantaneous temperaature difference between the probe surface (T_{si}) and bulk (T_∞), K

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FIGURES AND TABLESS

Figure 1   A schematic of experimental setup.
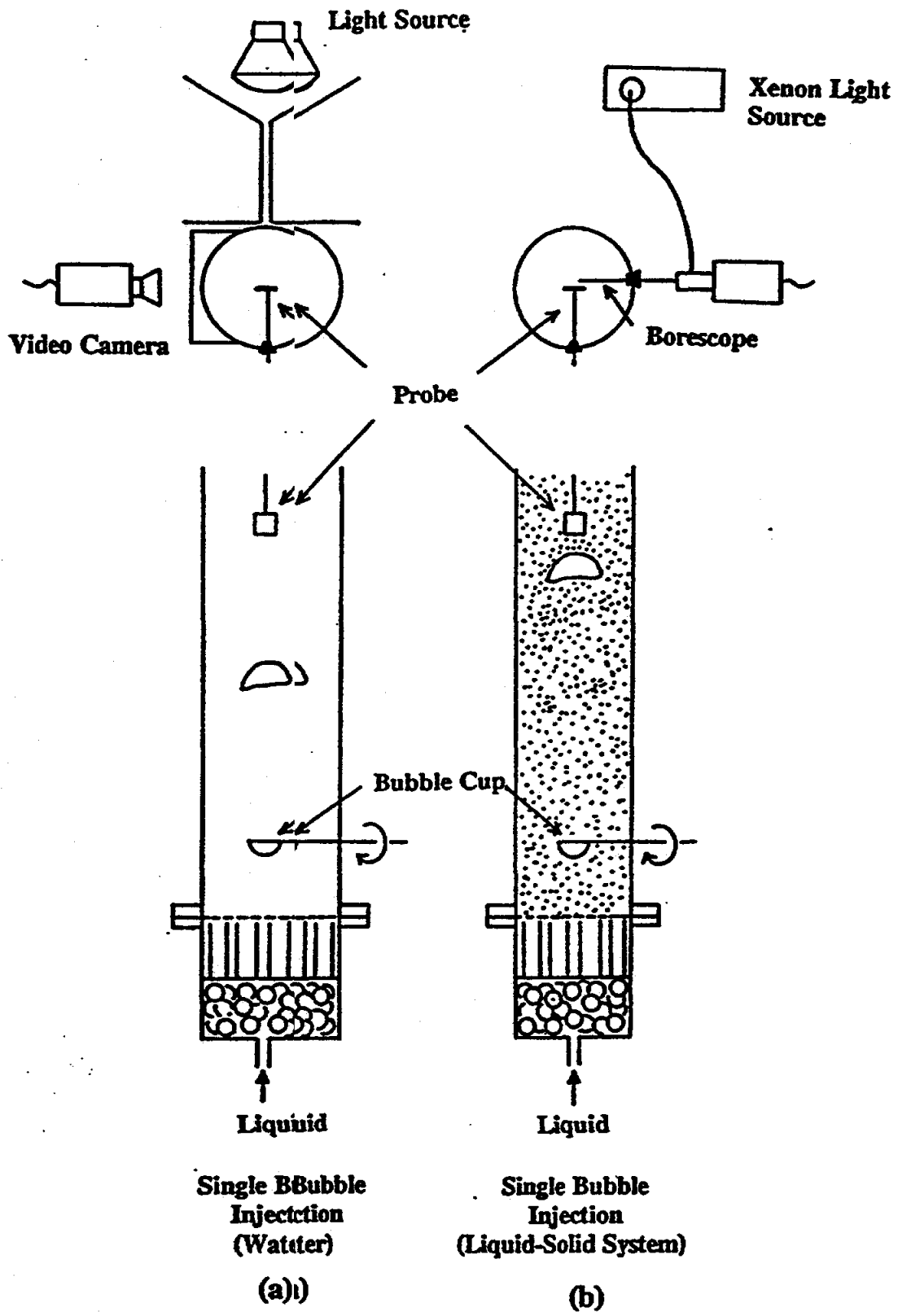
Figure 2   A schematic of experimental conditions.

Electrical Leads

2.54 cm

1.91 cm

Sensor

Cu Plate

Heater

Insulator

Support

Probe Assembly

Probe Components
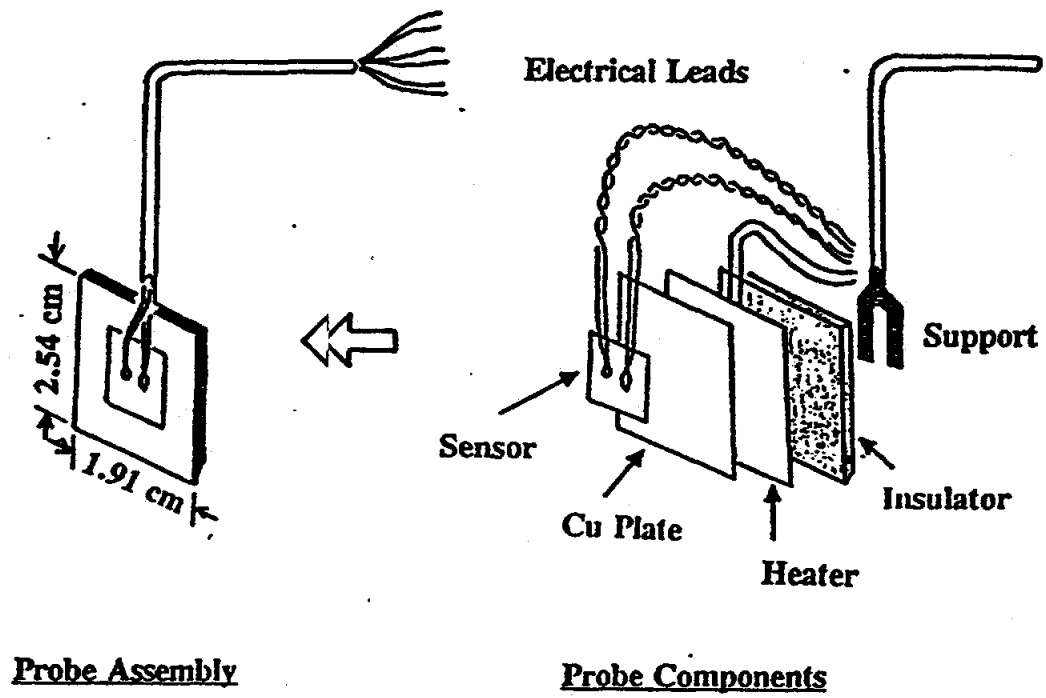
Figure 3   Heat-transfer probe design.

Thermmoelectric Materrtrial (Alumel)

Thermoelectric Material (Chromel)

Q

S

Thermal Barrier

Copper Output Leads

Upper T/C Junctions at Temperature T_1
Lower T/C Junctions at Temperature T_2
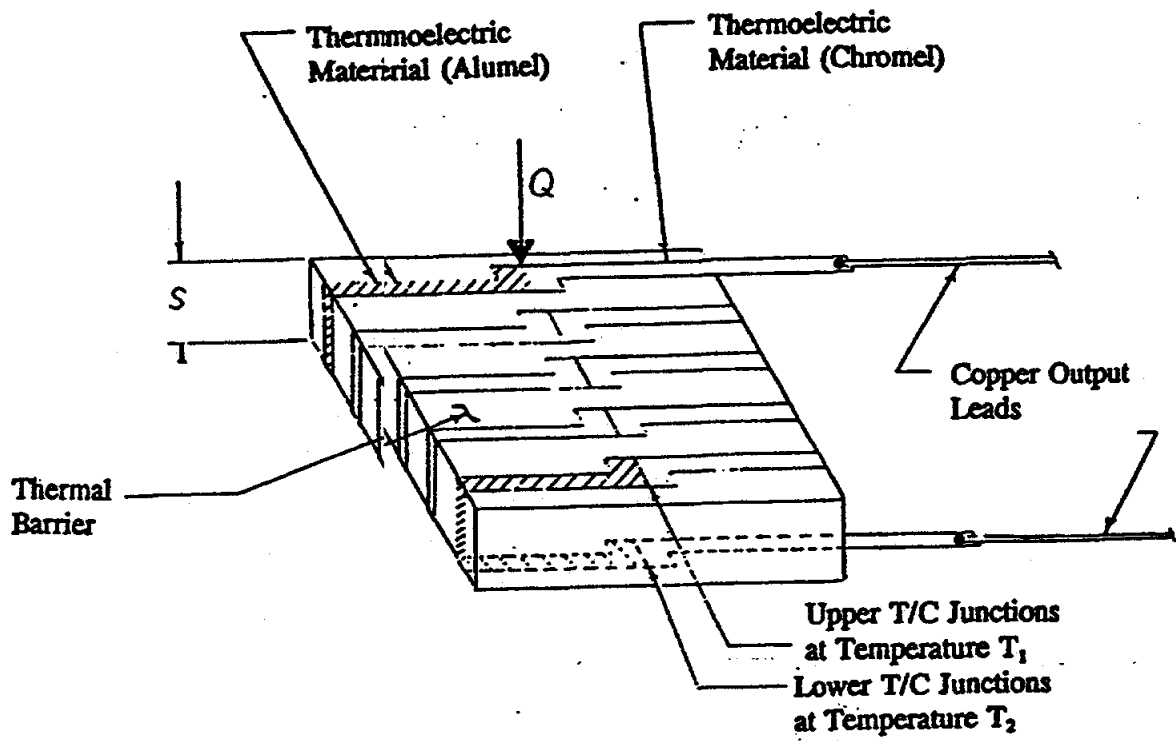
Figure 4   A schematic of heat flow sensor.

Heat Flow Sensor Output at 70°F = 8.24 x 10⁻³ μV/W.m⁻²
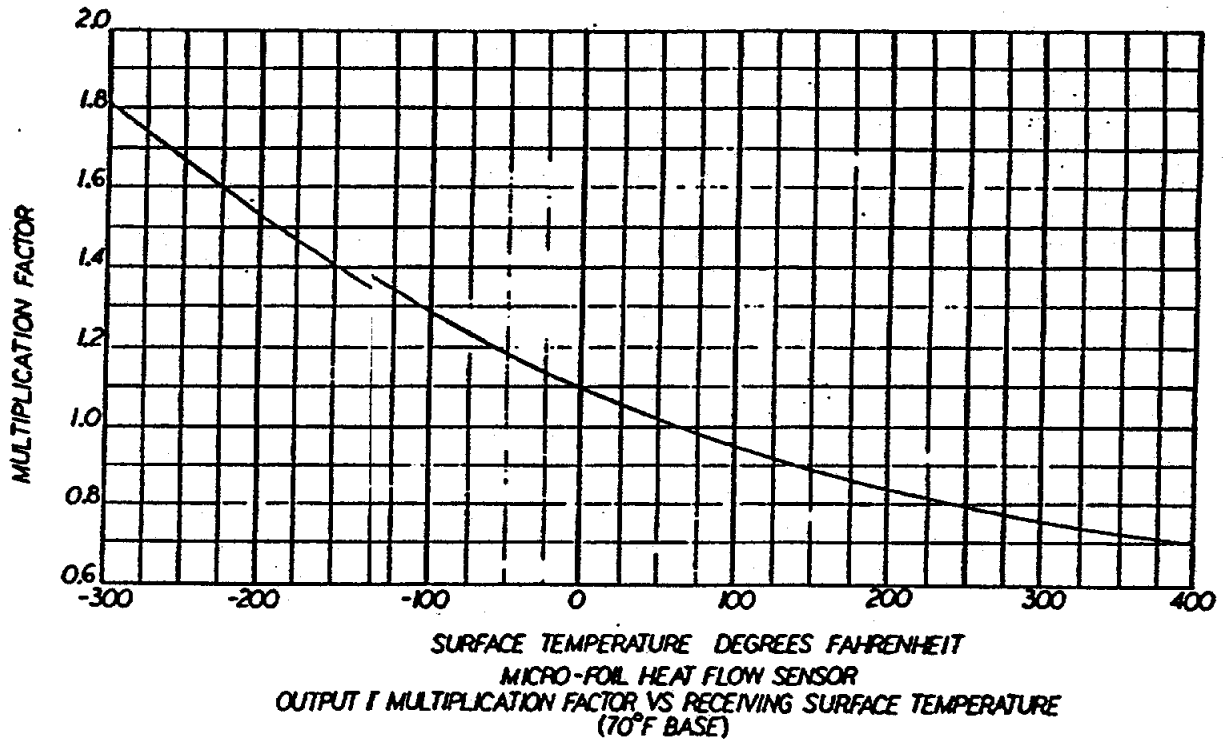
Figure 5   Heat flow sensor calibration.
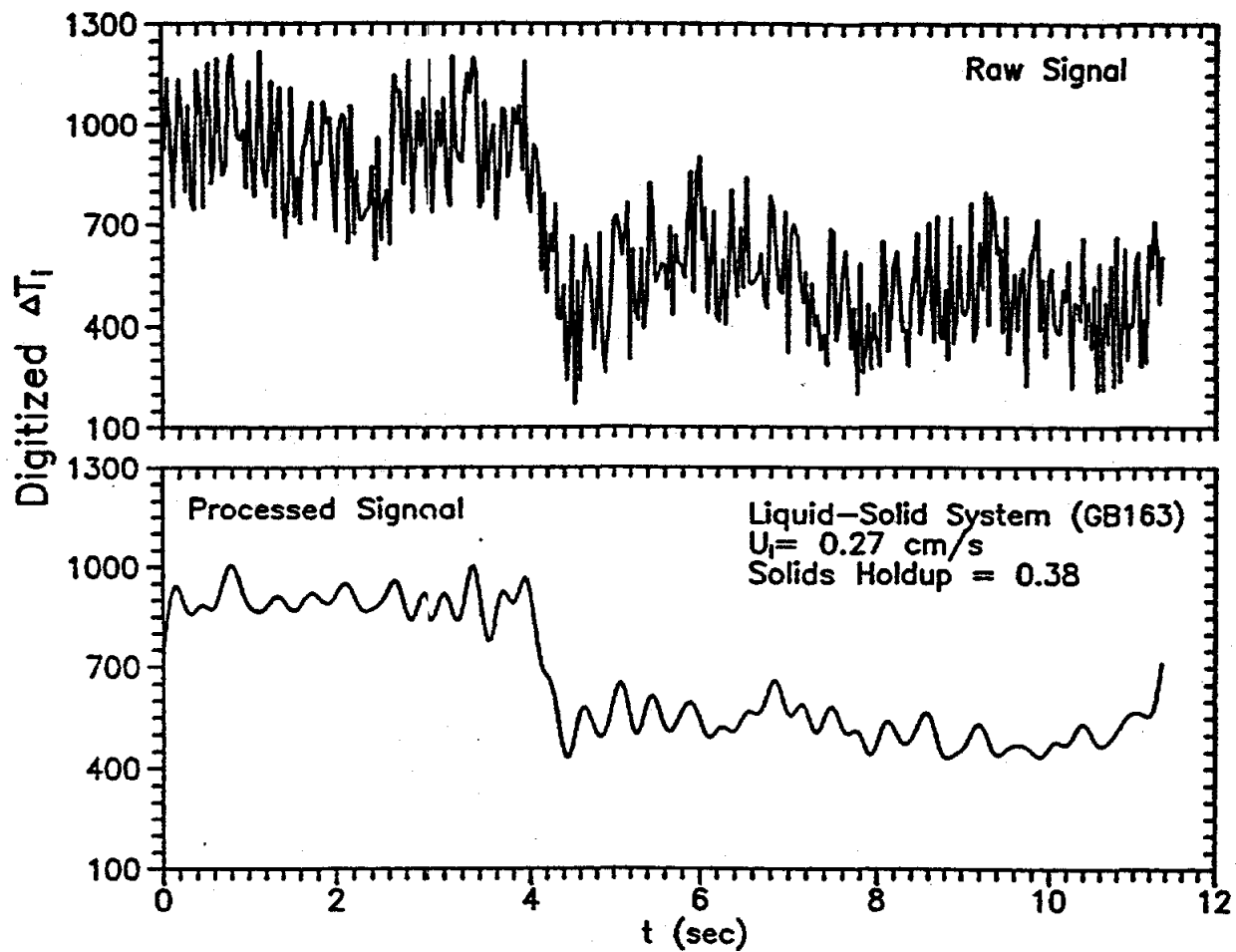
Figure 6   A typical raw and processed signal.
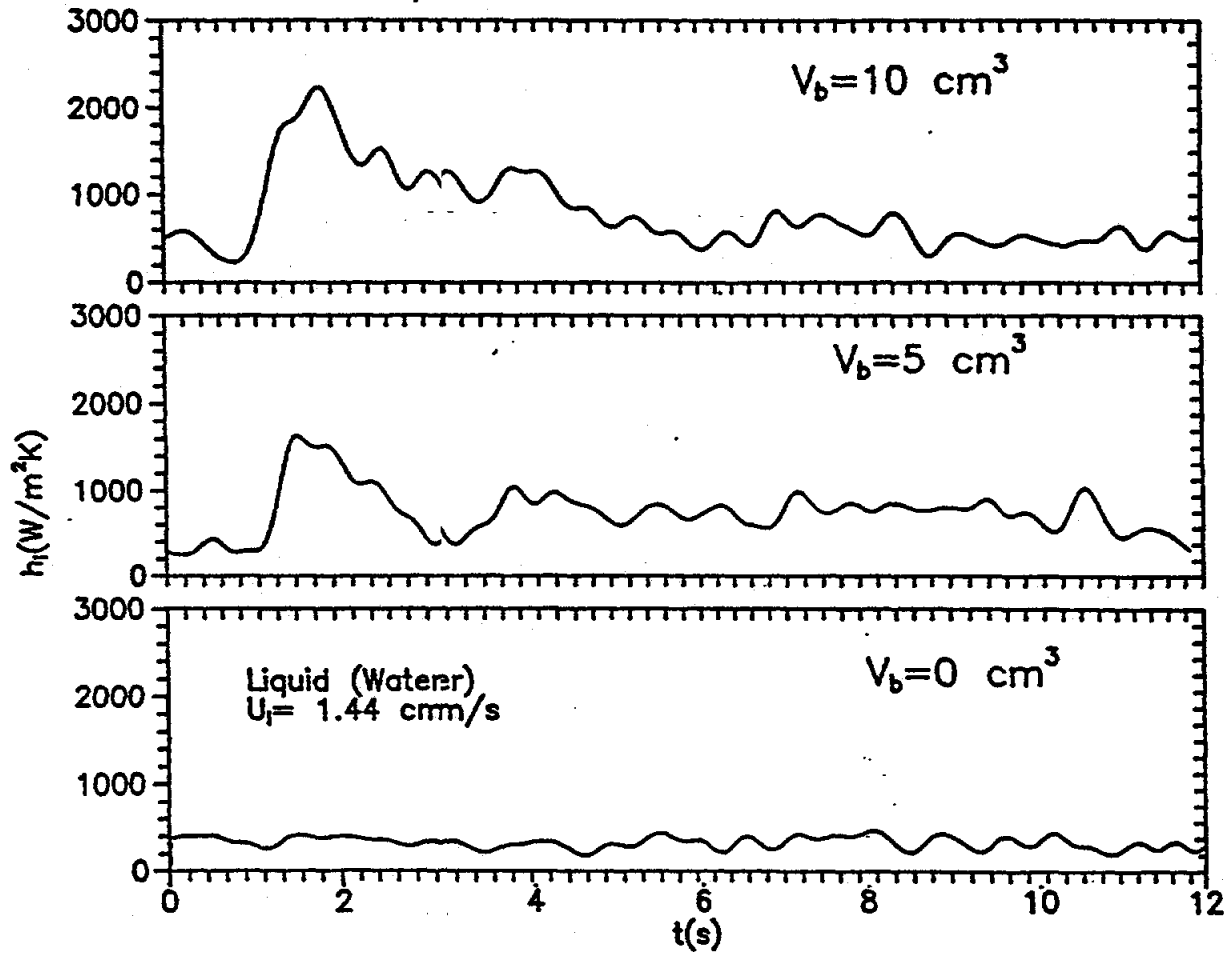
Figure 7   Effects of bubbble size on instantaneous heat-transfer coefficient due to the passage of f bubble in liquid for probe located at the center of column.
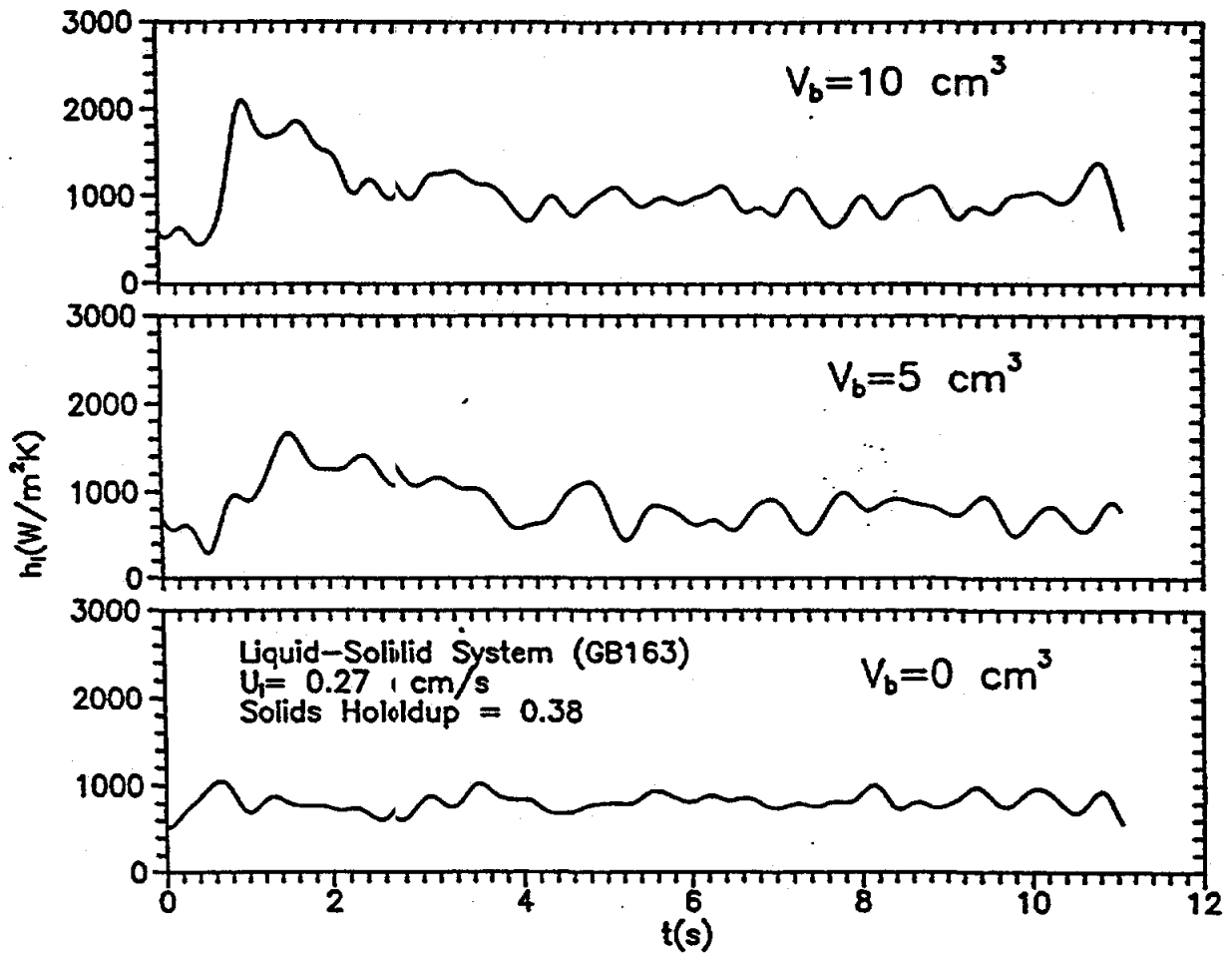
Figure 8   Effects of bulubble size on instantaneous heat-transfer coefficient due to the passage : of bubble in liquid-solid fluidized bed with GB163 for probe locateèd at the center of column.
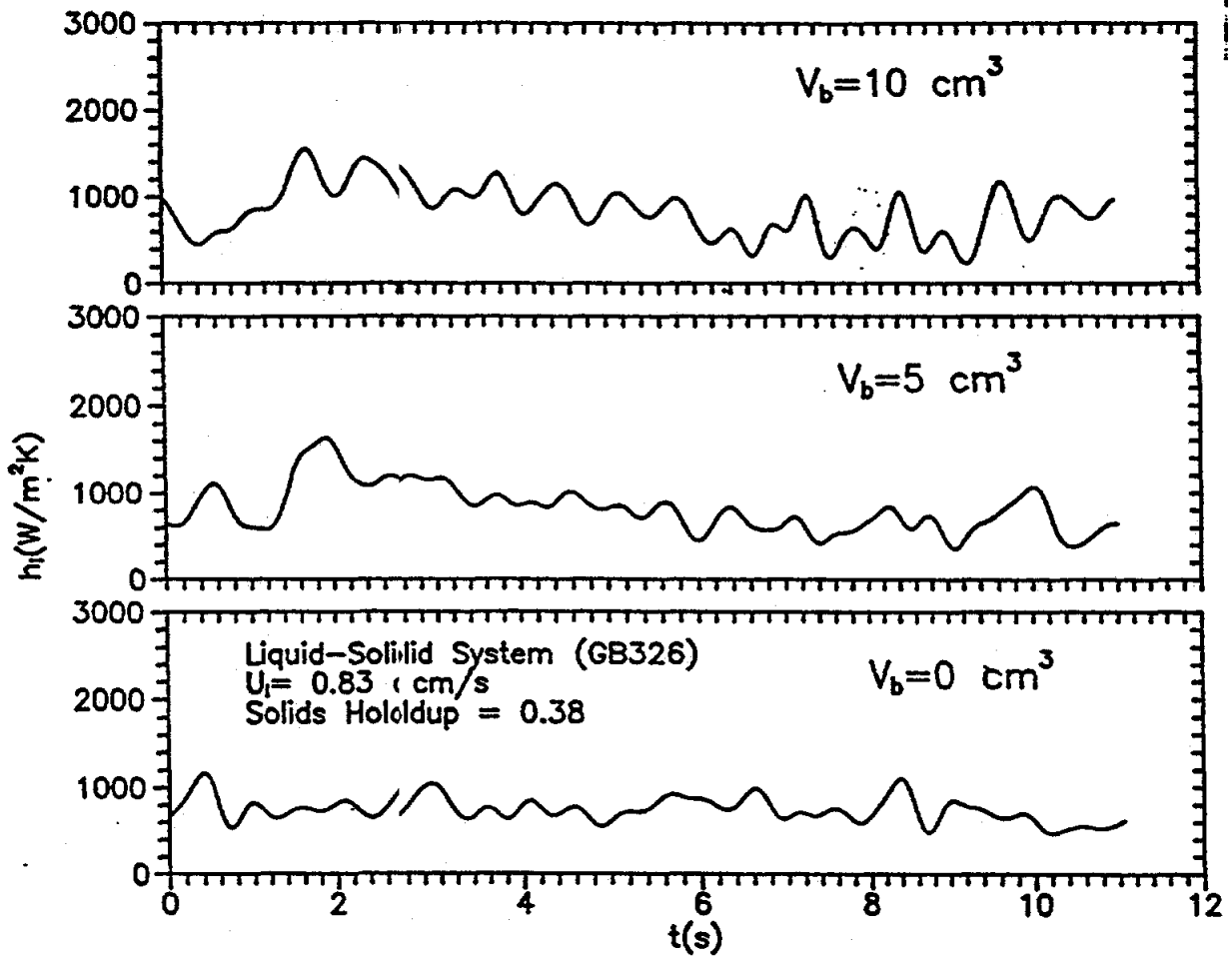
Figure 9 Effects of buubble size on instantaneous heat-transfer coefficient due to the passage ɛ of bubble in liquid-solid fluidized bed with GB326 for probe locateɩed at the center of column.

Table 1   **Physical properties of spherical particles.**

Particle	Notation	Average diameter (mm)	Density (g/cm³)	$\epsilon_o{}^a$	$U_t{}^b$ (m/s)
Glass bead	GB163	0.163	2.50	0.63	1.7×10^{-2}
Glass bead	GB326	0.326	2.50	0.62	4.4×10^{-2}

[a]Packed bed solids fraction
[b]Fan and Tsuchiya (1990)

Table 2   Types of f microfoil heat flow sensor.

CONFIGURATION*	Part Number	Nominal Sensitivity (μv/Btu/Ft²-hr.)	Maximum Recommended Heat Flux Btu/Ft²-Sec.	Response Time (Seconds)	Sensor Resistance (Ω Max.)	Maximum Operating Temp. (°F)	Nominal Thickness In (Inches)	Thermal Capacitance Btu / Ft²-°F	Thermal Impedance Btu / °F per Ft²-hr.
	2040450-1	0.02	50	.020	5	300	.003	.01	.003
	2040450-2	0.06	25	.060	5	300	.005	.02	.005
	2040450-3	0.2	10	.400	5	300	.012	.05	.012
	2040452-1	0.2	50	.020	20	500	.003	.01	.003
	2040452-2	0.6	25	.060	20	500	.005	.02	.005
	2040452-3	2.0	10	.400	20	500	.012	.05	.012
	2040453-1	0.02	50	.020	5	500	.003	.01	.003
	2040453-2	0.06	25	.050	5	500	.005	.02	.005
	2040453-3	0.2	10	.400	5	500	.012	.05	.012
	2707036-1	0.1	50	.020	10	500	.003	.01	.003
	2707036-2	0.3	25	.060	-10	500	.005	.02	.005
	2707036-3	1.0	10	.400	10	500	.012	.05	.012
	2040455-1	0.2	50	.020	20	500	.003	.01	.003
	2040455-2	0.6	25	.060	20	500	.005	.02	.005
	2040455-3	2.0	10	.400	20	500	.012	.05	.012
	2040456-1	1.1	50	.020	100	500	.004	.01	.003
	2040456-2	3.3	25	.060	100	500	.008	.02	.005
	2040456-3	11.0	10	.400	100	500	.013	.05	.012
	2040457-1	1.1	50	.020	100	500	.004	.01	.003
	2040457-2	3.3	25	.060	100	500	.008	.02	.005
	2040457-3	11.0	10	.400	100	500	.013	.05	.012
	2040466-1	0.2	50	.020	15	500	.003	.01	.003
	2040466-2	0.6	25	.060	15	500	.005	.02	.005
	2040466-3	2.2	10	.400	15	500	.012	.05	.012
	2040472-1	0.2	50	.020	50	500	.003	.01	.003
	2040472-2	0.6	25	.060	50	500	.005	.02	.005
	2040472-3	2.0	10	.400	50	500	.012	.05	.012
	2040480-1	0.2	50	.020	20	500	.195	.01	.003
	2040480-2	0.6	25	.060	20	500	.195	.02	.005
	2040480-3	2.0	10	.400	20	500	.195	.05	.012