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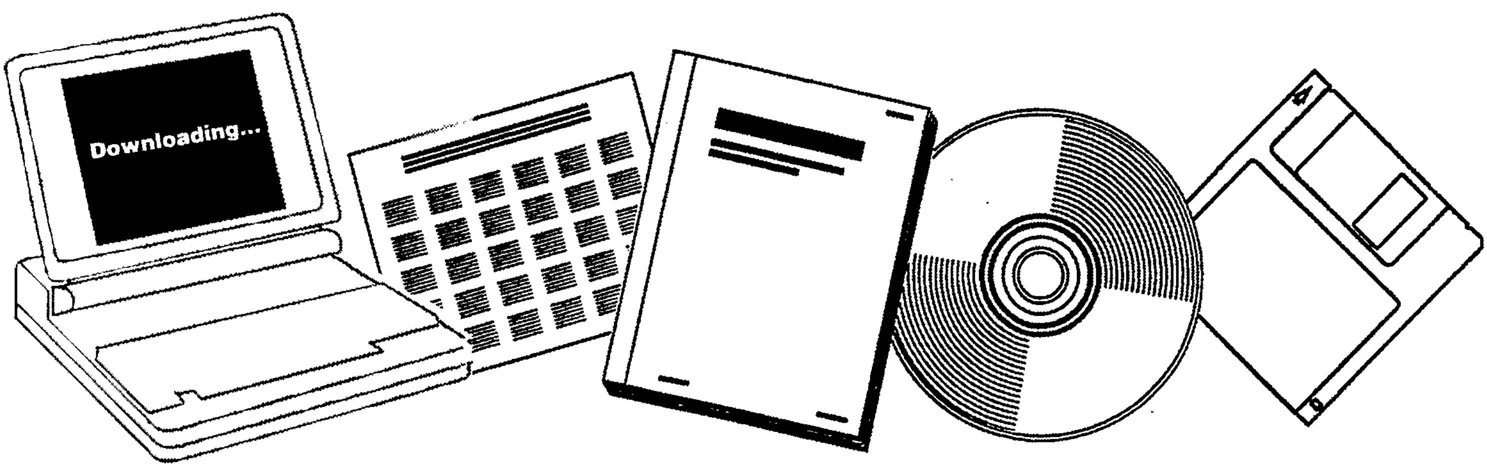
CIRCULATION IN GAS-SLURRY COLUMN REACTORS: FIRST QUARTERLY REPORT, QUARTER ENDING DECEMBER 31, 1987

WEST VIRGINIA UNIV., MORGANTOWN. DEPT.
OF MECHANICAL AND AEROSPACE ENGINEERING

1987



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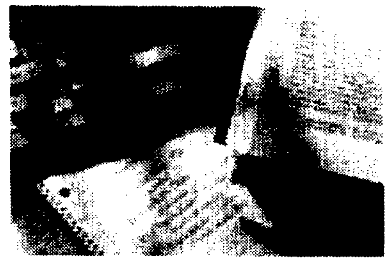

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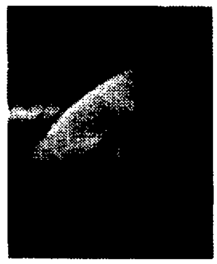

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"CIRCULATION IN GAS-SLURRY COLUMN REACTORS"

DEPARTMENT OF ENERGY. CONTRACT NUMBER DE-FG22-87PC79935

FIRST QUARTERLY REPORT - REPORT DOE/PC/79935-2

QUARTER ENDING 12/31/1987

Prepared by

WEST VIRGINIA UNIVERSITY

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

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DEPARTMENT OF ENERGY, PITTSBURGH

PITTSBURGH ENERGY TECHNOLOGY CENTER

MASTER

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SUMMARY

During the first quarter of this research into circulation patterns in bubble column reactors a literature survey has been undertaken and has revealed new, relevant articles which are currently in review. The laboratory scale bubble column to be used in the experimental research has been designed and is under construction. Preliminary research using a small existing column has verified the use of resistance probes for measuring local gas void fraction in the column although overall voidage measured is a little low. Data from this column are presented to show that the distributor plate has an effect on circulation pattern. A one-dimensional model for circulation in non-Newtonian systems is presented. Research using laser doppler velocimetry and numerical fluids modeling will commence in the next quarter while probe research will continue.

INTRODUCTION

This contract research seeks to describe circulation patterns arising in bubble column reactors, which may be used for Fischer-Tropsch Synthesis of oil. The research involves experimental work in a laboratory scale bubble column, using both probes and laser doppler velocimetry. Theoretical research includes use of computational techniques to model the circulation pattern and the verification of simple one-dimensional models to describe circulation velocities.

TECHNICAL ACHIEVEMENTS

Literature Survey

A computerized literature survey has revealed seven recent journal papers [1-7] on the topic of Fischer-Tropsch synthesis in bubble columns. These papers are now being reviewed by the investigators. In addition, a large number of papers on bubble column fundamentals were cited in the search: new, relevant papers have been acquired and are being reviewed.

Large Bubble Column

The large bubble column for the experimental research has been designed, and is shown in figure 1. The column will consist of 1/4 inch wall plexiglas (clear acrylic) pipe of 8 1/2 inch internal diameter. Three sections, each of 2 1/2 feet in height will be assembled to produce the desired full column height. Figure 1 shows the location of the ports which will be used to insert probes into the column. The lowest section will be bolted to a plenum chamber provided with a water drain valve. A distributor plate will separate the plenum from the column and will be used to distribute the gas into the liquid. Since it is argued that the nature of gas introduction has a strong effect on the resulting multiphase flow, several distributors have been designed, notably a plate with holes evenly over its surface, a plate with one central hole, and a plate with holes situated to favor annular gas introduction. These are illustrated in figure 2.

Many of the materials required for column construction are at hand and the remainder are on order. Construction has commenced on the distributor plates and the column sections.

Resistance Probes

Two resistance probes have been designed, constructed and tested during the last two months. Resistance probes are used in mixtures of gas and conducting liquid to determine whether at any instant in time gas or liquid is present at a point in the mixture. Figure 3 shows the design of a probe, which consists of a thin stainless steel tube carrying an insulated wire which is connected to a needle insulated except at its tip. The stainless steel tube is invariably in contact with the liquid along much of its length, while the small exposed tip is in contact with whatever phase is present at its location at any given time. Thus when the probe tip is in liquid, resistance measured between the tip and the stainless steel sheath is low, but when the tip is surrounded by a bubble, the resistance is high. The probes used in the present research had the needle set into the end of the stainless steel tube with epoxy. For insulation, the protruding needle was then painted and the tip was lightly sanded to provide a very small sensing area. The probe tip was bent downwards so that it would pierce a rising bubble. The testing of these resistance probes is presented in the experimental section below.

Experimental Work

While waiting for the completion of the large column, the researchers have adapted a smaller 6 inch internal diameter column to perform experimental work with probes. The objective of the work was to establish that a resistance probe was capable of measuring the local bubble void fraction in the air-water system. The six inch column used for the research is shown in figure 4. This column is 18 inches high and is provided with 4 ports for probe access at 4 different heights in the column. Air is introduced into the liquid in the column by means of a plenum chamber and distributor arrangement similar to that designed for the large column. Distributor plates were readily interchangable. Flowrate of air is monitored with a rotameter.

Experimental work was conducted on circulation in an air-water system using this column. Three types of distributor plates, illustrated in figures 5a, b and c were used to introduce the air. This research is similar to that performed by Hills [8].

The probe was incorporated in a resistance bridge circuit shown in figure 6. This circuit communicated with a Metra-byte 5kHz analog to digital (A to D) convertor in an IBM personal computer. The circuit was such that the A to D convertor received a direct current voltage close to 0V when the probe tip was in air and 3.0 to 3.5V when it was in water. It is believed this latter voltage varied somewhat due to electrochemical effects since a direct current circuit was used. Some other researchers have elected to use alternating current to reduce such effects, but this did not appear necessary in this preliminary work.

Theory dictates that the response from such a probe should be a square wave, generated by the switching of phase at the probe tip. Experience has shown that the signal pulses corresponding to bubbles are not square, but rounded because of the finite tip size and the time taken for liquid films to drain from the tip and establish themselves on the tip. It is therefore necessary to select a "cutoff" voltage to decide whether the probe tip is in gas or liquid phase at any instant in time. This was done in the following manner. A BASIC program, listed in appendix A, was written to collect the voltage from the probe at a large number of discrete times (generally 1000) and at a slow sampling rate. Each voltage was then examined to see whether a bubble or liquid was present at the probe at that time, and a time-averaged gas void fraction was computed. To establish a cutoff voltage, the probe was operated at a fixed point with constant two phase flow conditions in the column. Time-averaged void fraction was computed using cutoff voltages varying from 0 to 3V, as shown in figure 7. A voltage on the plateaux of these plots, viz. 1.625V, was selected as cutoff voltage in the preliminary research. This criterion will be examined more carefully in the next quarter, since there is disagreement as to the cutoff voltage that should be selected [8].

The program shown in appendix A was also used to collect local voidage data from the column with different distributor plates, as shown in figures 5a, b and c, and at different gas flowrates, using an air-water system in the 6 inch diameter column. Static height of liquid in the column was typically 11.5 to 12 inches. In each case the probe traversed a diameter of the column. Data are presented as follows:

Figure 8: Distributor plate, even, fig. 5a,
Air flow, 7.41 scfm., traverse 5" above plate.

Figure 9: Distributor plate, even, fig. 5a,
Air flow 12.87 scfm., traverse 5" above plate.

Figure 10: Distributor plate, even, fig. 5a,
Air Flow 10.46 scfm, traverse 10.5" above plate.

Figure 11: Distributor plate, even, fig. 5a,
Air flow 11.95 scfm, traverse 10.5" above plate.

Figure 12: Distributor plate, even, fig. 5a,
Air flow 10.46 scfm, traverse 5" above plate.

Figure 13: Distributor plate, even, fig. 5a,
Air flow 10.46 scfm, traverse 10.5" above plate
(Note poor agreement with fig. 10 at same conditions)

(Note good agreement with fig. 12 for traverse 5" above plate at same conditions)

Figure 14: Distributor plate, 9 hole, fig. 5b,
Air flow 5.18 scfm, traverse 10.5" above plate

Figure 15: Distributor plate, 9 hole, fig. 5b,
Air flow 7.41 scfm, traverse 10.5" above plate

Figure 16: Distributor plate, center hole, fig. 5c,
Air flow 5.18 scfm, traverse 5" above plate
(Note high center voidage)

Figure 17: Distributor plate, center hole, fig. 5c,
Air flow 8.78 scfm, traverse 5" above plate

Figure 18: Distributor plate, center hole, fig. 5c,
Air flow 5.18 scfm, traverse 10.5" above plate
(Note more even voidage distribution than for fig. 16, which shows data taken closer to the plate)

Figure 19: Distributor plate, center hole, fig. 5c,
Air flow 8.78 scfm, traverse 10.5" above plate
(Note more even voidage distribution than for fig. 17, which shows data taken closer to the plate)

These data firstly show that the resistance probe technique is working reliably in predicting relative void fraction across the column. Void distributions were generally high at the center and low at the walls, which is the expected distribution. Figures 16 and 17 also demonstrate the ability of the probe to detect the "jetting" of air from the single central orifice. Although figures 10 and 13 show disagreement between two sets of data under similar operating conditions, careful inspection of the other data suggest that voidage readings for figure 10 are unreasonably low.

Nevertheless, it was also shown that the probe generally read too low a void fraciton in the following way. Voidage data were taken using the even distributor plate with air flow of 10.46 scfm across the column diameter at 5" and 10.5" above the distributor plate (figures 12 and 13). This data was used to estimate an average gas void fraction of 9.42% in the whole column. By comparing the aerated column mixture height to the unaerated column liquid height, the holdup was found to be 17%. Although there was some difficulty in estimating the mixture height, this does show that the probe was measuring low voidages. This is attributed to the deflection of bubbles from the probe tip, the fact that the tip is of finite size and, perhaps, selection of too low a cutoff voltage. Figure 7 suggests that an increase in voidage reading would result if cutoff voltage were raised to 2.5 volts. This problem will be examined in the next quarter, as discussed below.

Probe Angle Effects

It was surmised that bubbles were deflected from the probe tip more easily than they would be in a faster pipe flow. Data show that the angle at which the probe tip was bent influences the measured voidage, as presented in figure 20. This will be investigated in more detail next quarter since these results contradict the report of Hills [8].

One-Dimensional Model

The proposal for this research discussed the one-dimensional turbulent model of Clark et al. [9] and the fact that a similar model could be developed for non-Newtonian viscous systems. This model was developed prior to the award of this contract, but a full copy of the research results in the form of a paper is provided in appendix B. The program used to generate the velocity profiles appearing in the paper is now available for use in the current research.

PLANNED RESEARCH FOR NEXT QUARTER

Column Construction

The large column will be completed and situated in a fluids laboratory during the next quarter. Two more probes will be assembled for use in the column and the three distributor plates designed for the column will be machined. Utilities will be connected to the column. Viscous liquids for later use in the column will be identified and acquired.

Probe Research

Firstly, the data taken from the small column will be more completely analyzed. Secondly, following some preliminary runs to test the new column, probe research will proceed in the new column with a more careful examination of cutoff voltage criteria, so that local voidage may be measured more accurately.

To this end an oscilloscope will be connected to the probe circuit to monitor the signal shape. In addition the investigators may elect to test another type of voidage probe along with the resistance probe. This suction probe, illustrated in fig. 21, extracts a volume of mixture via a very thin tube connected to a glass tube, which is in turn connected to a small vessel and vacuum pump. Void fraction is found from an inspection of relative lengths of gas and liquid in the glass tube.

In addition, direction in which the tip of both the resistance and suction probes point may affect results: this will be carefully examined.

Numerical Simulations

A readily available computer code, JVEST (a code suitable for simulating time dependent, axisymmetric viscous flows) (Leschziner, 1980) will be loaded on the WVU-Computer system. The code will be made operational and tested for a single phase gas and water flow in a vertically situated pipe. The literature review will provide information on the flow regimes in a typical gas-slurry column reactor. A reactor geometry and flow conditions will be selected in the bubble flow regime. Attempts will be made to simulate gas flow in water, representing water with a higher density fluid. The equations for the gas/water mixture will be reviewed and documented.

Laser Doppler Velocimetry

The project is still actively recruiting a student to undertake the Laser Dopple Velocimetry (LDV) research. Rate of progress depends on this recruitment. During the next 6 months, the experimental effort to use LDV will focus on two areas. First, LDV measurements will be made in an existing air jet facility, to familiarize the graduate student with operation of the LDV system. It is planned that the influence of factors such as:

a) Frequency shifting,
b) particle seeding rate, and
c) angle between velocity vector and optical path.

on the data accuracy and data rate will be studied. After this initial phase of study, LDV measurements will be attempted in a single-phase water flow in one of the plexiglass columns. Flow of the water will be generated using a small stirrer. The goal of this second phase of study will be to determine whether or not data can be successfully obtained directly throught the side of the cylindrical plexiglas column, or whether it will be necessary to construct a flat, optical window to view into the cylindrical column using the LDV system.

If needed, this optical window will be constructed using plexiglas, and an oil of equal refractive index to fill the gap between the flat and cylindrical surfaces.

References

1. Deckwer, W., Youssef, L., Ahmed, Z. and Ralek, M., "Hydrodynamic Properties of the Fischer-Tropsch Slurry Process", Industrial & Engineering Chemistry, Process Design and Development, vol. 19, no. 4, pp. 699-708. Octpber 1980.
2. Bukur, D., "Some Comments on Models for Fischer-Tropsch Reaction in Slurry Bubble Column Reactor", Chemical Engineering Science, vol. 38, no. 3 pp. 441-446, 1983.
3. Satterfield, C.N. and Stenger, H. G., "Fischer-Tropsch Synthesis on a Precipitated Mn/Fe Catalyst in a Well-Mixed Slurry Reactor", Industrial & Engineering Chemistry, Process Design and Development, vol. 23, no. 1, pp. 26-29, January 1984.
4. Stern, D., Bell, A. T. and Heinemann, H., "Analysis of the Design of Bubble-Column Reactors for Fischer-Tropsch Synthesis", Industrial & Engineering Chemistry, Process Design and Development, vol. 24, no. 4, pp. 1213-1219, October 1985.
5. Stern, D., Bell, A. T. and Heinemann, H., "A Theoretical Model for the Performance of Bubble-Column Reactors Used for Fischer-Tropsch Synthesis", Chemical Engineering Science, vol. 40, no. 9, pp. 1665-1677, 1985.
6. Stern, D., Bell, A. T. and Heinemann, H., "Experimental and Theoretical Studies of Fischer-Tropsch Synthesis Over Ruthenium in a Bubble-Column Reactor", Chemical Engineering Science, vol. 40, no. 10, pp. 1917-1924, 1985.
7. Sanders, E., Ledakowicz, S. and Deckwer, W.D., "Fischer-Tropsch Synthesis in Bubble Column Slurry Reactors on Fe/K Cathalyst", Canadian Journal of Chemical Engineering, vol. 64, no. 1, pp. 133-140, February 1986.

8. Hills, J.H. "Radial non-Uniformity of Velocity and Voidage in a Bubble Column", Trans. I. Chem. Engrs., Vol. 52, 1974, pp. 1-9.

9. Clark, N.N., Flemmer, R.L.C. and Atkinson, C.M., "Turbulent Circulation in Bubble Columns" A.I.Ch.E. Journal, Vol. 32, No. 12 (1986).

10. Leschziner, M.A., (1980), "A Numerical Scheme for Simulating the Vertical Structure of Time-Dependent Natural Water Flows," Rept. SFB 80/T/167, Sonder for schungsbereich 210, University of Karlsruhe, FRG.

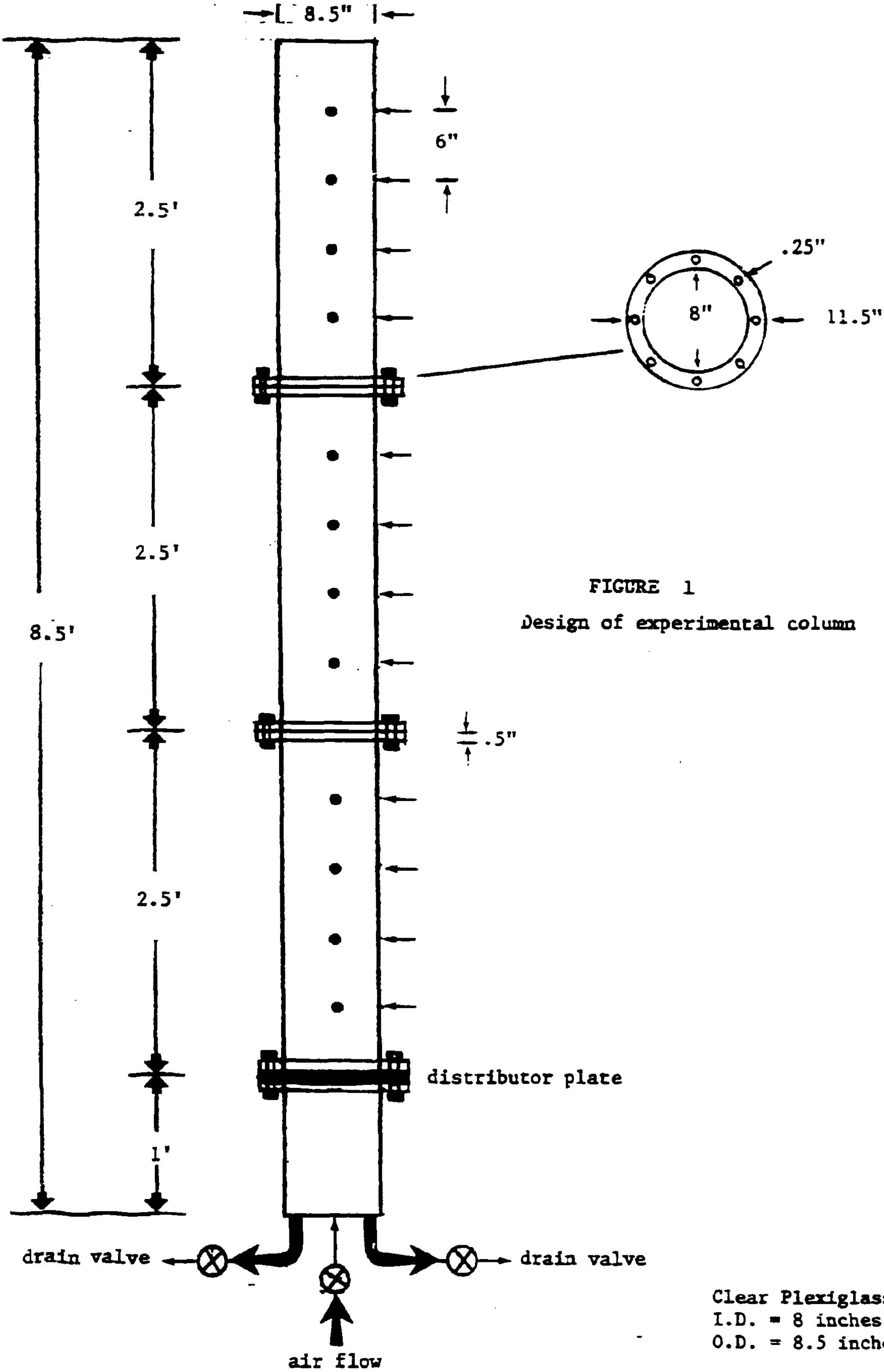


FIGURE 1

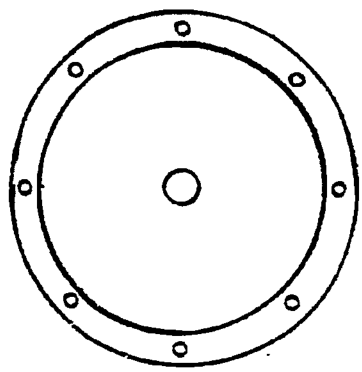
Design of experimental column

Clear Plexiglass Column
I.D. = 8 inches
O.D. = 8.5 inches

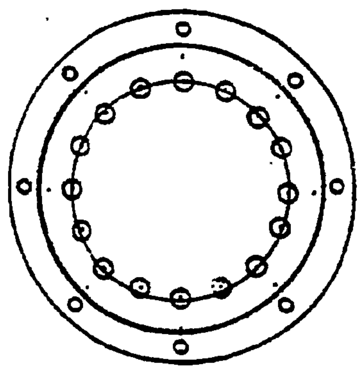
1 block approx. = 1.5"

● ← Probe Holes, 90° o

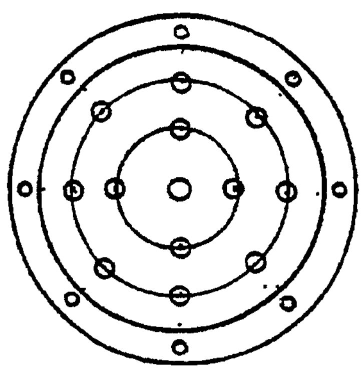
PROPOSED DISTRIBUTOR PLATE DESIGNS



One hole for central air introduction



Annular air introduction



Even air introduction

FIGURE 2: Proposed distributor plate designs

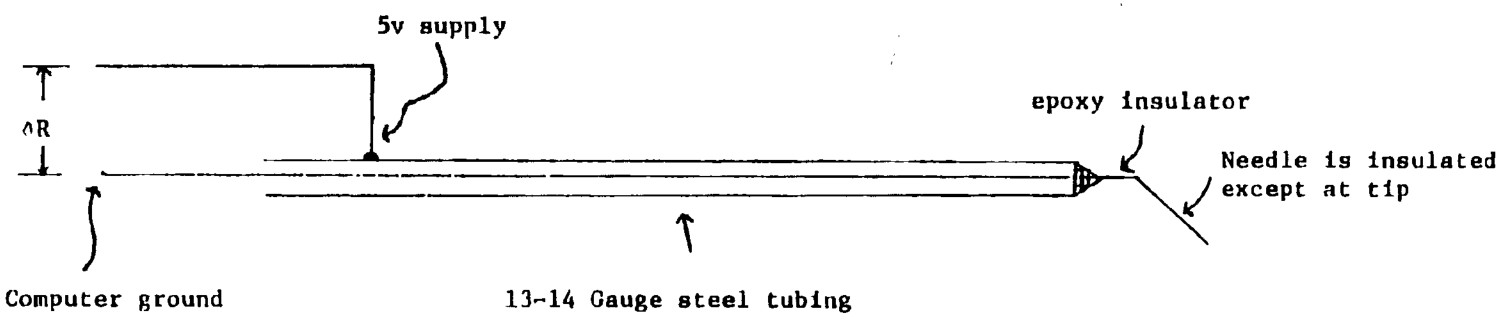


Figure 3: Resistance probes designed and built for experimental research

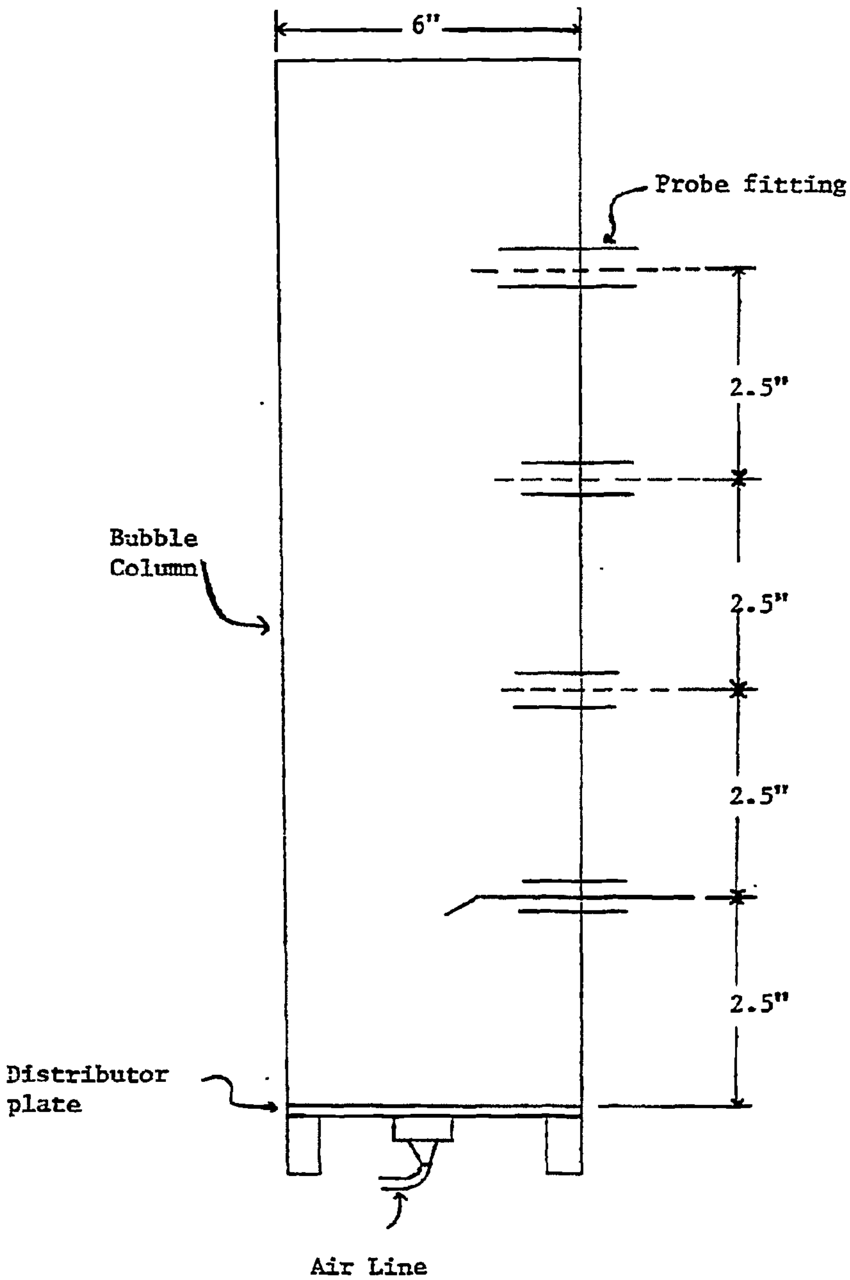
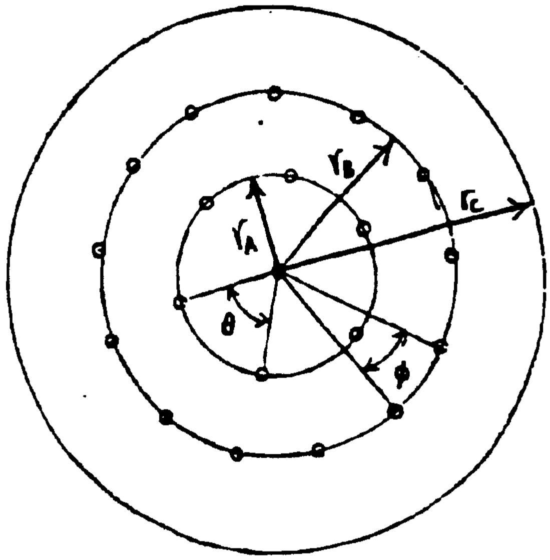


Figure 4: Schematic showing probe ports on small experimental column



D = 6 3/8 in.
D_{Holes} = 1/16 in.
#Holes = 20

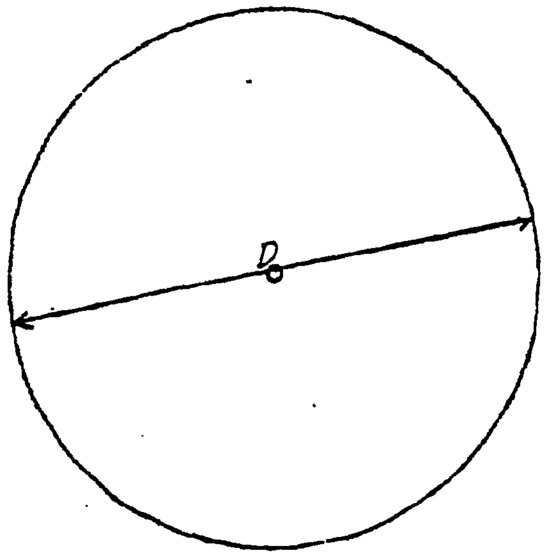
Pattern - Equal Distribution

r_A = .6875 in. $\theta = 60°$

r_B = 1.21875 in. $\phi = 27.7°$

r_C = 3.1875 in.

Figure 5a: Distributor plate used for even air distribution in small bubble column.



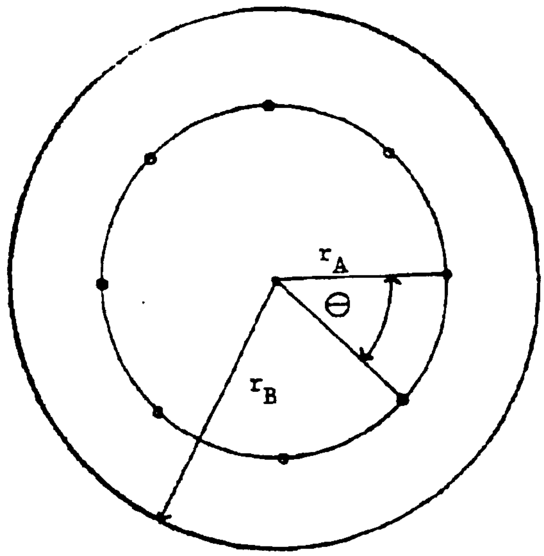
$D = 6\ 3/8$ in.

$D_{Hole} = 3/16$ in.

Holes = 1

Pattern - Single hole in center of plate.

Figure 5b: Distributor plate with central air introduction used in small column.



r_A = 2.25 in.

r_B = 3.1875 in.

θ = 45°

D = 6 3/8 in.

D_{Holes} = 1/16 in.

#Holes = 9

Pattern - One hole the center,
hole 15/16" from the
outer edge.

Figure 5c: Nine hole distributor used in small column.

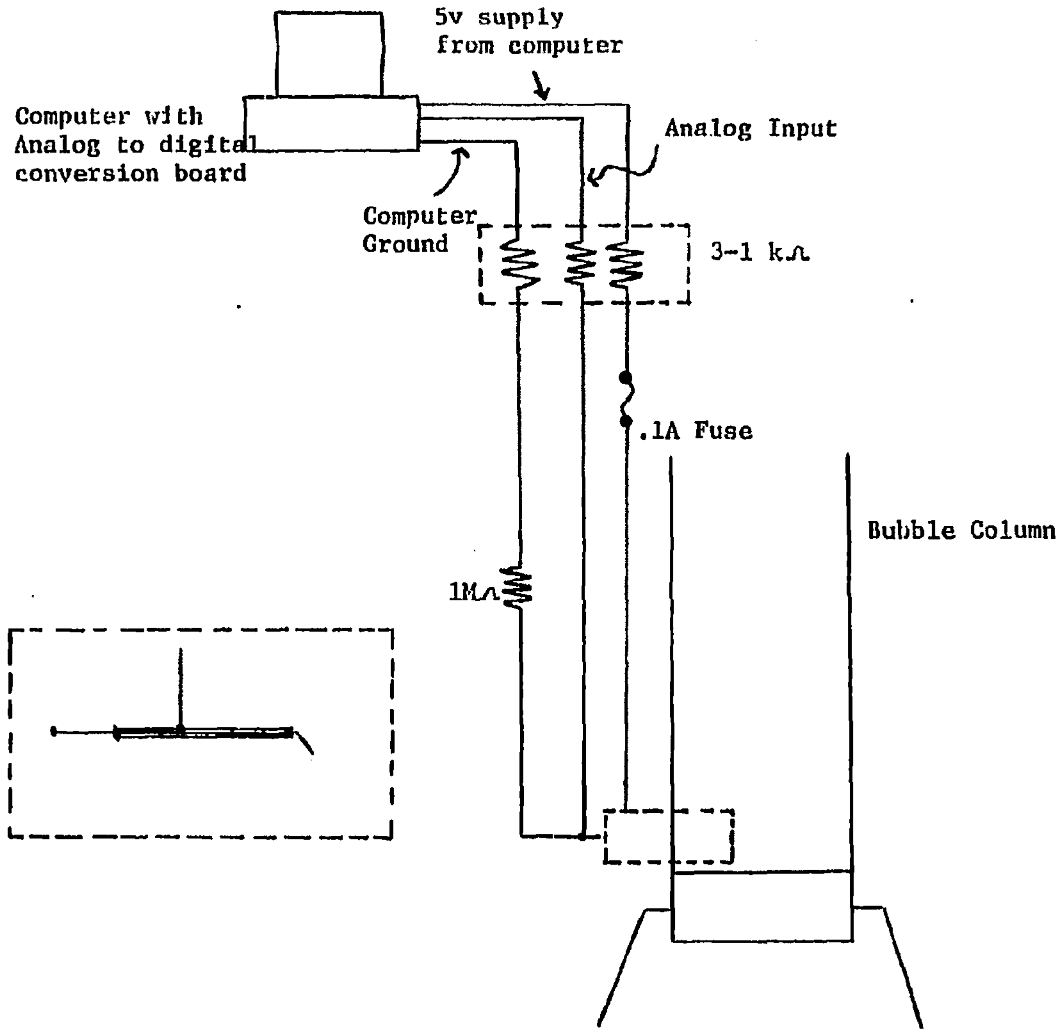


Figure 6: Circuit used with resistance probe.

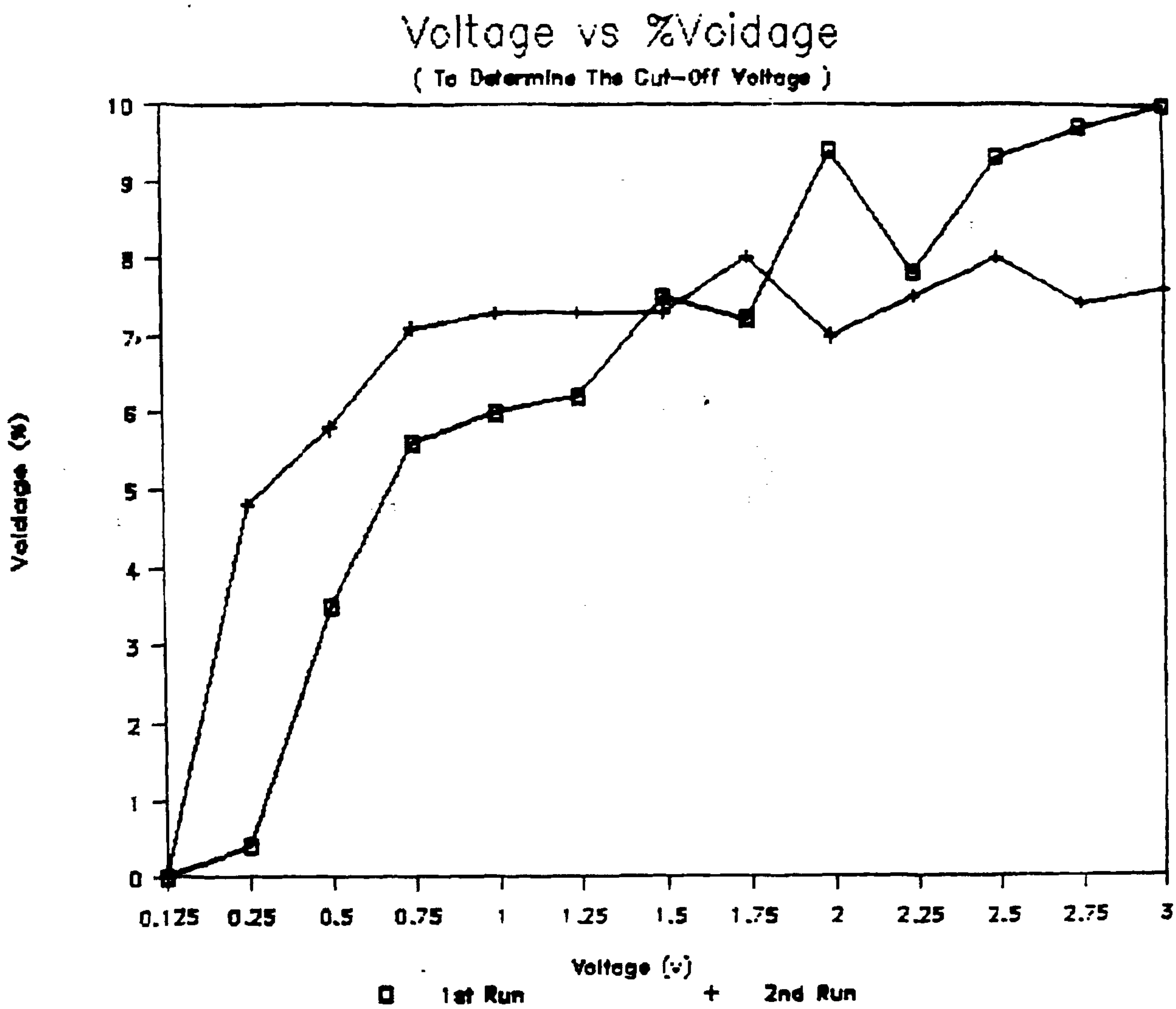


Figure 7: Time averaged voidage of flow versus voltage to determine cut off voltages.

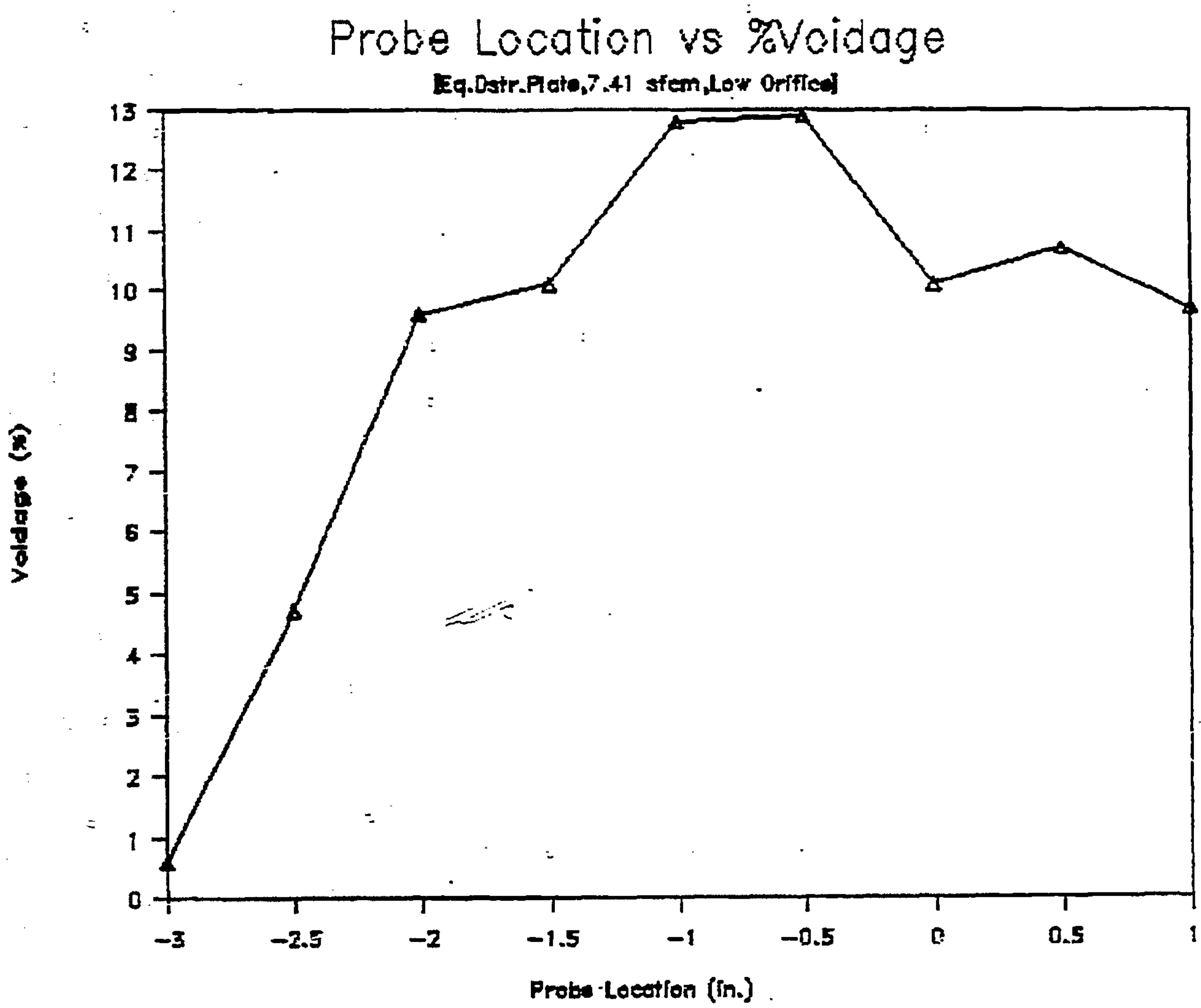


Figure 8: Distributor plate, even, fig. 5a,

Air flow, 7.41 scfm., traverse 5" above plate.

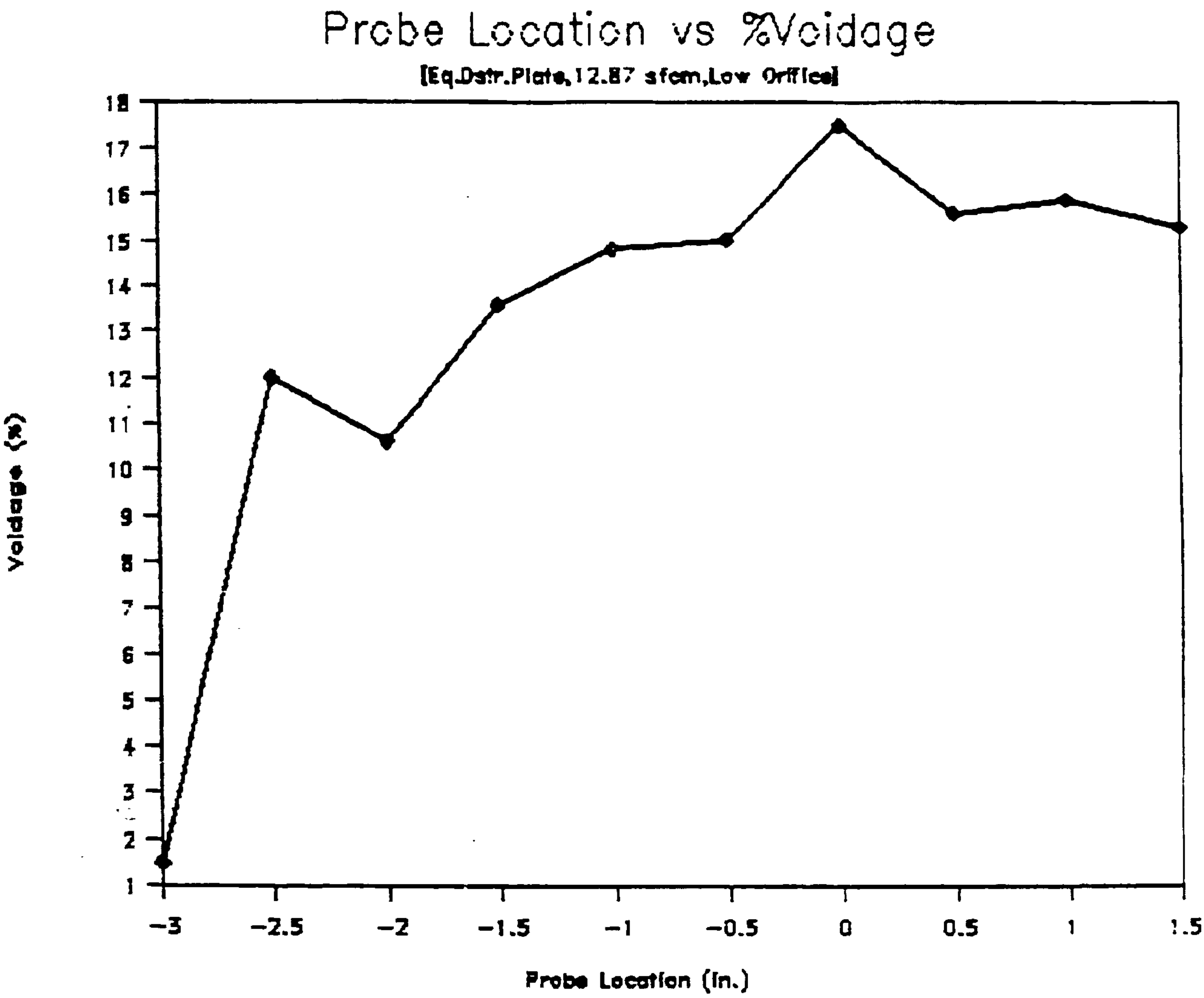


Figure 9: Distributor plate, even, fig. 5a,

Air flow 12.87 scfm., traverse 5" above plate.

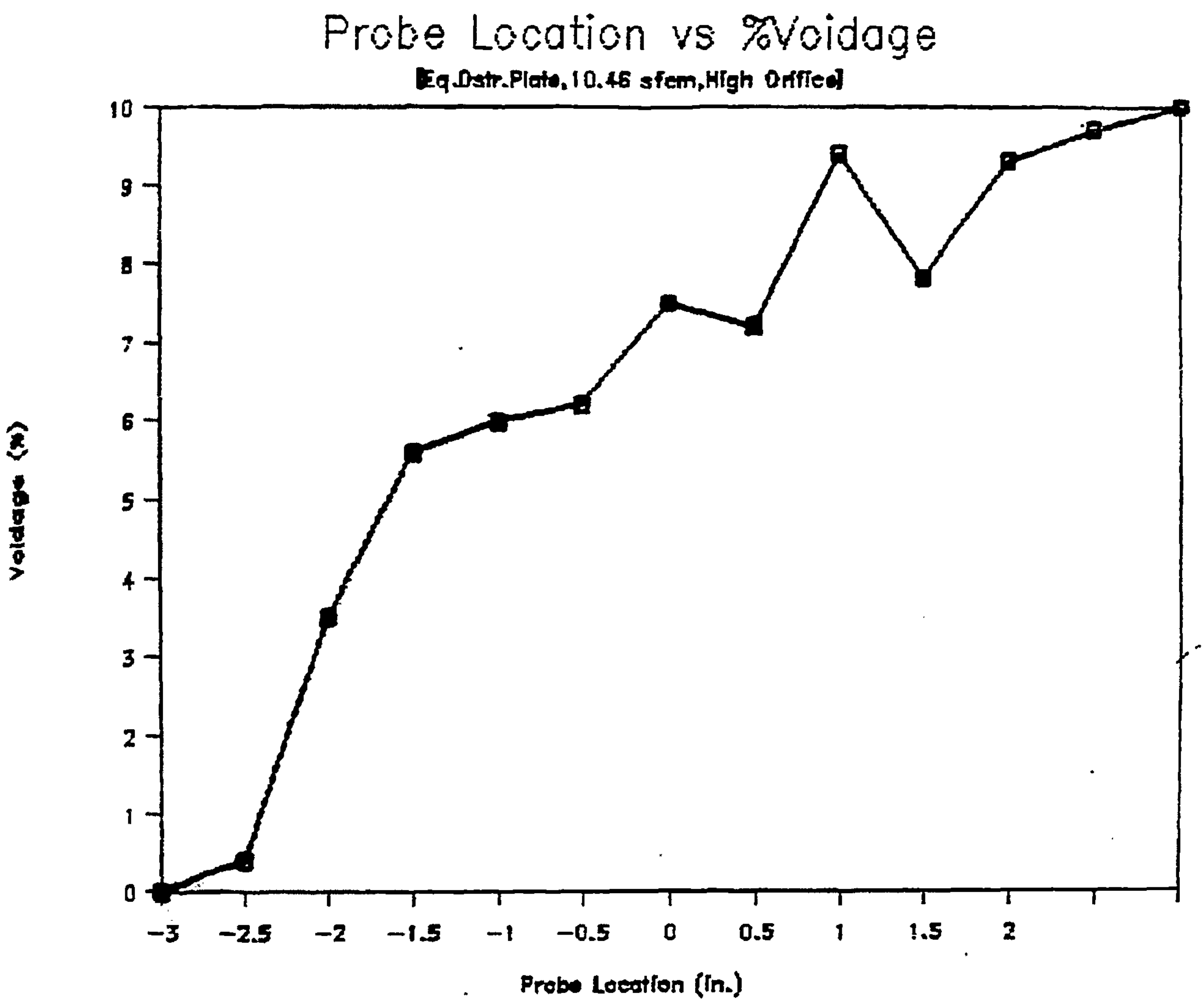


Figure 10: Distributor plate, even, fig. 5a,

Air Flow 10.46 scfm, traverse 10.5" above plate.

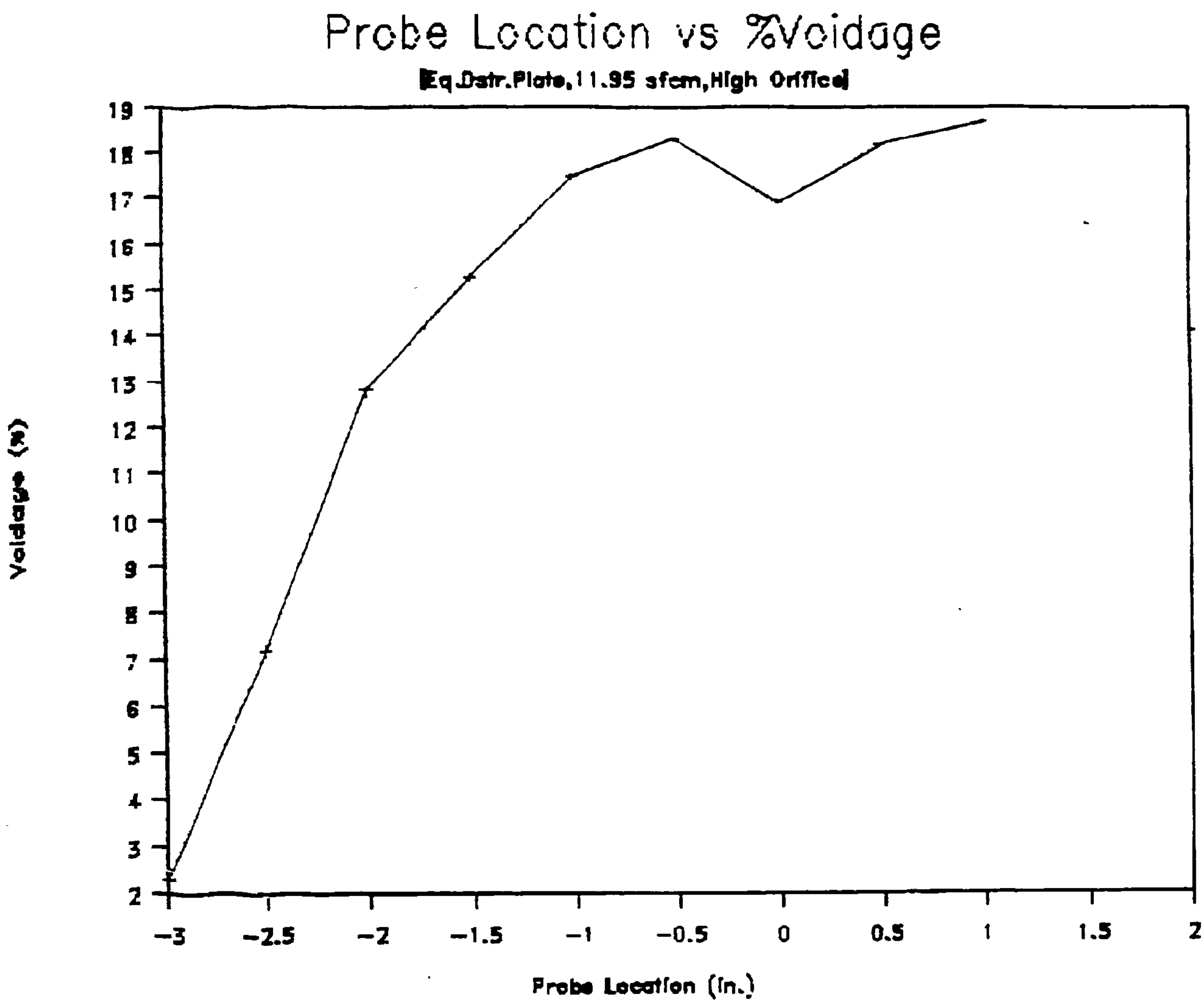


Figure 11: Distributor plate, even, fig. 5a,

Air flow 11.95 scfm, traverse 10.5" above plate.

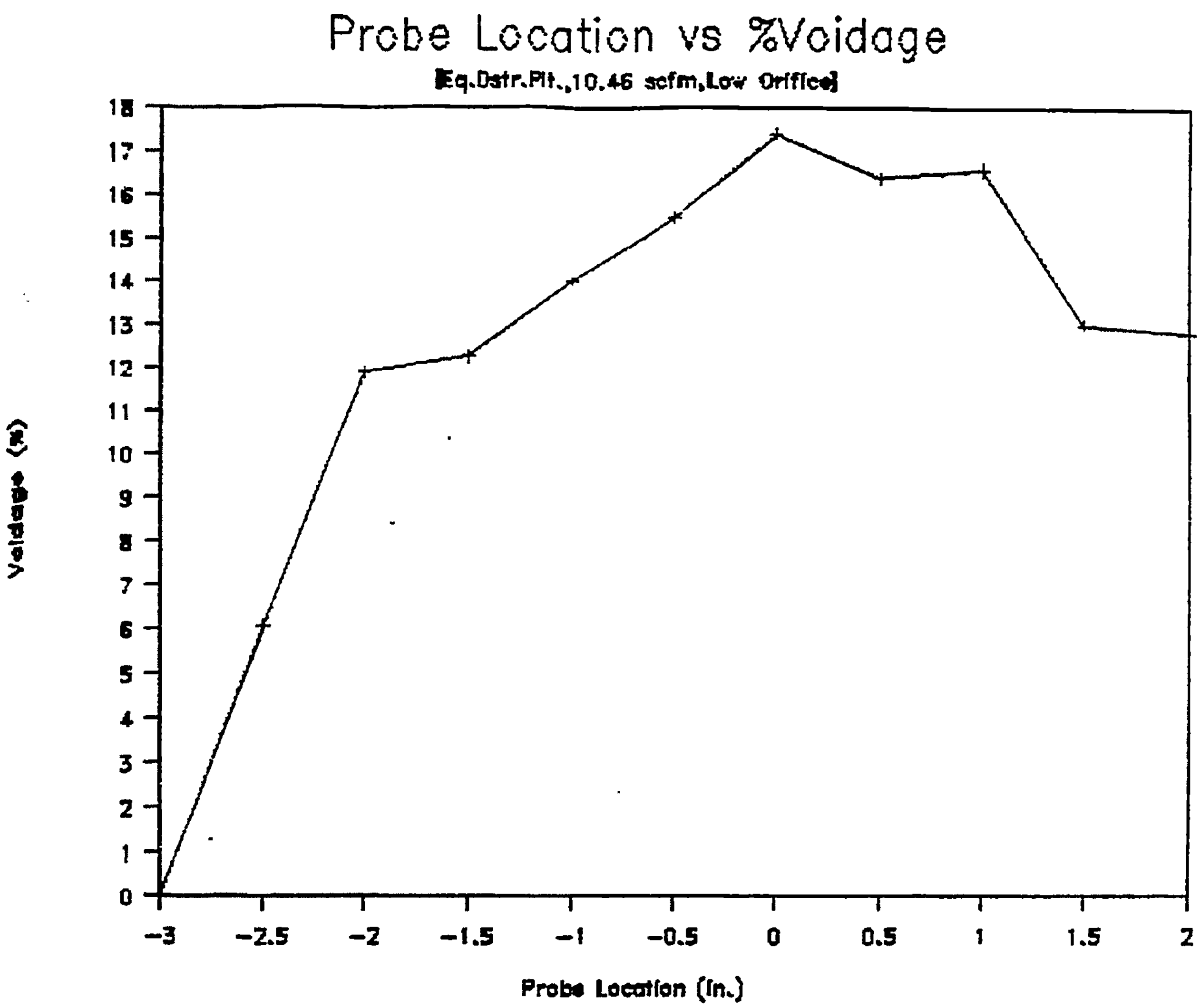


Figure 12: Distributor plate, even, fig. 5a,

Air flow 10.46 scfm, traverse 5" above plate.

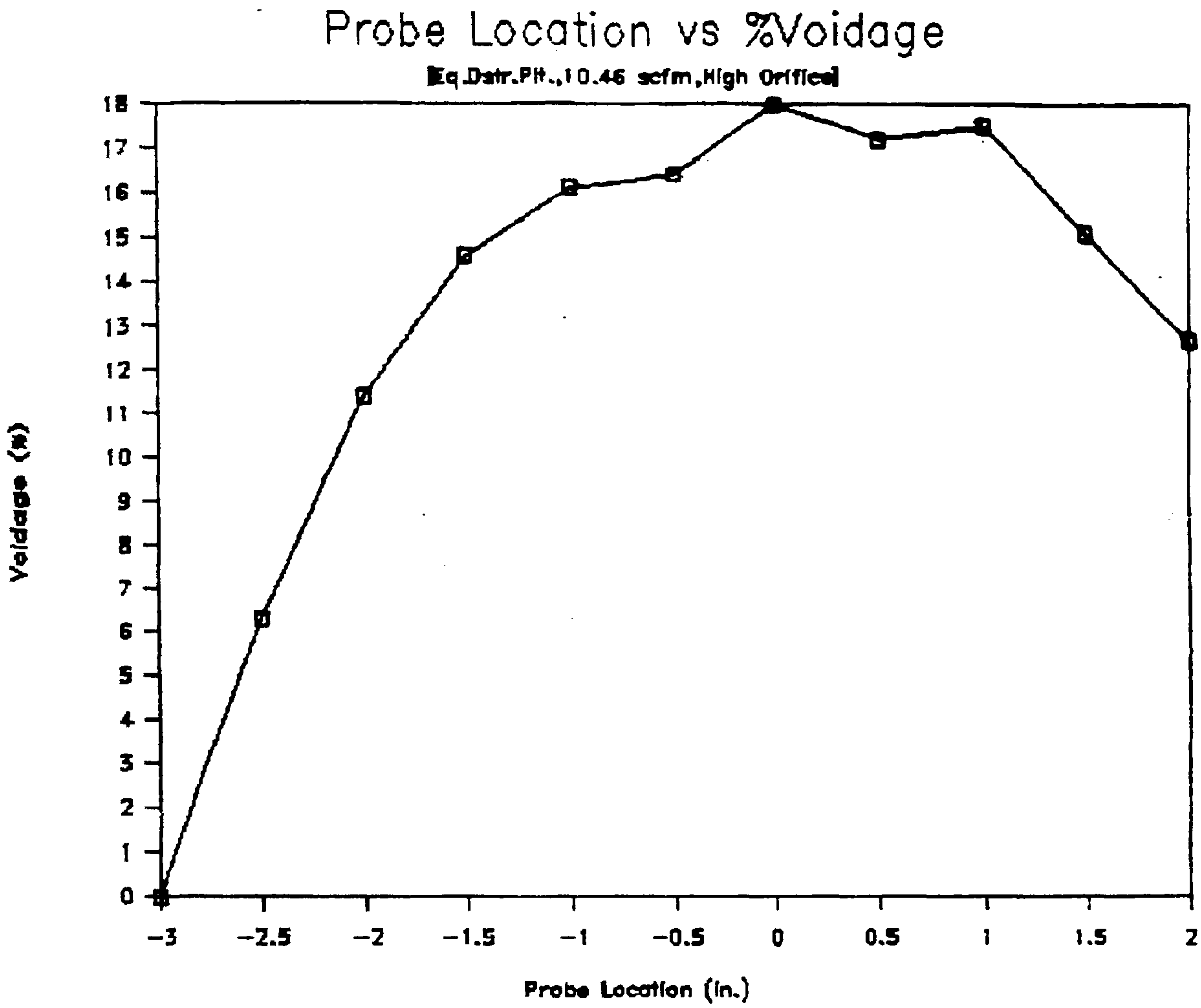


Figure 13: Distributor plate, even, fig. 5a,

Air flow 10.46 scfm, traverse 10.5" above plate

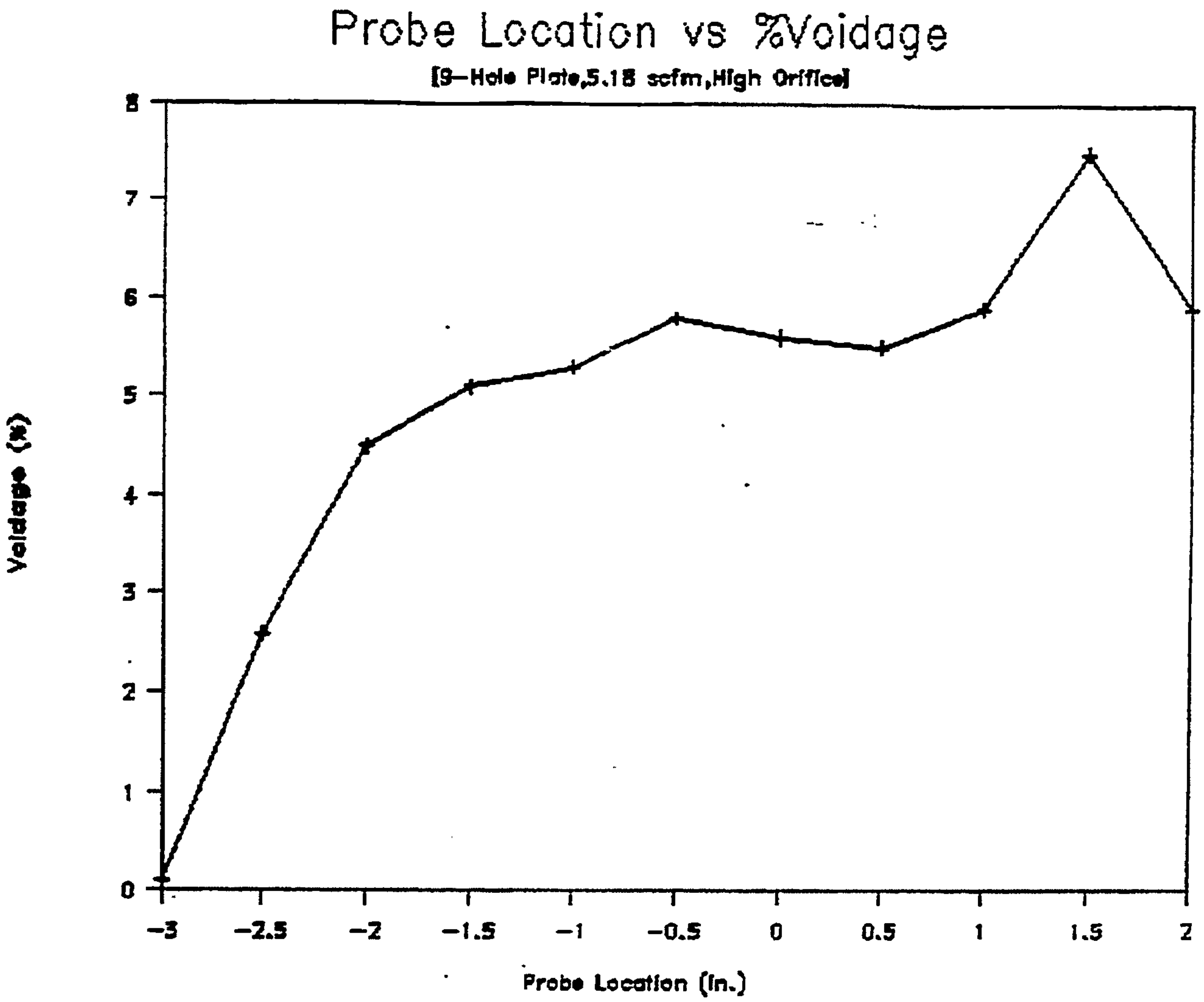


Figure 14: Distributor plate, 9 hole, fig. 5b,

Air flow 5.18 scfm, traverse 10.5" above plate

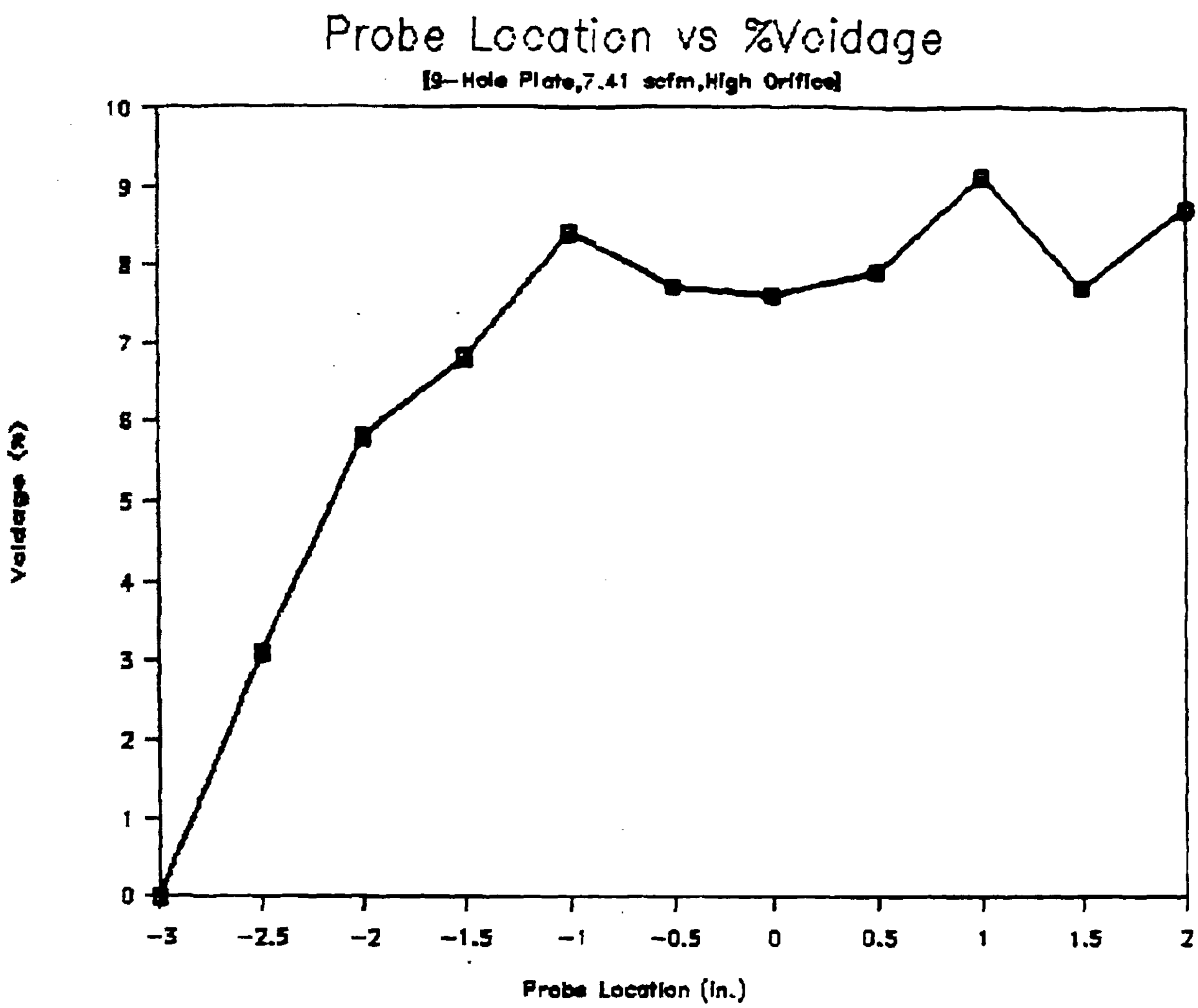


Figure 15: Distributor plate, 9 hole, fig. 5b,

Air flow 7.41 scfm, traverse 10.5" above plate

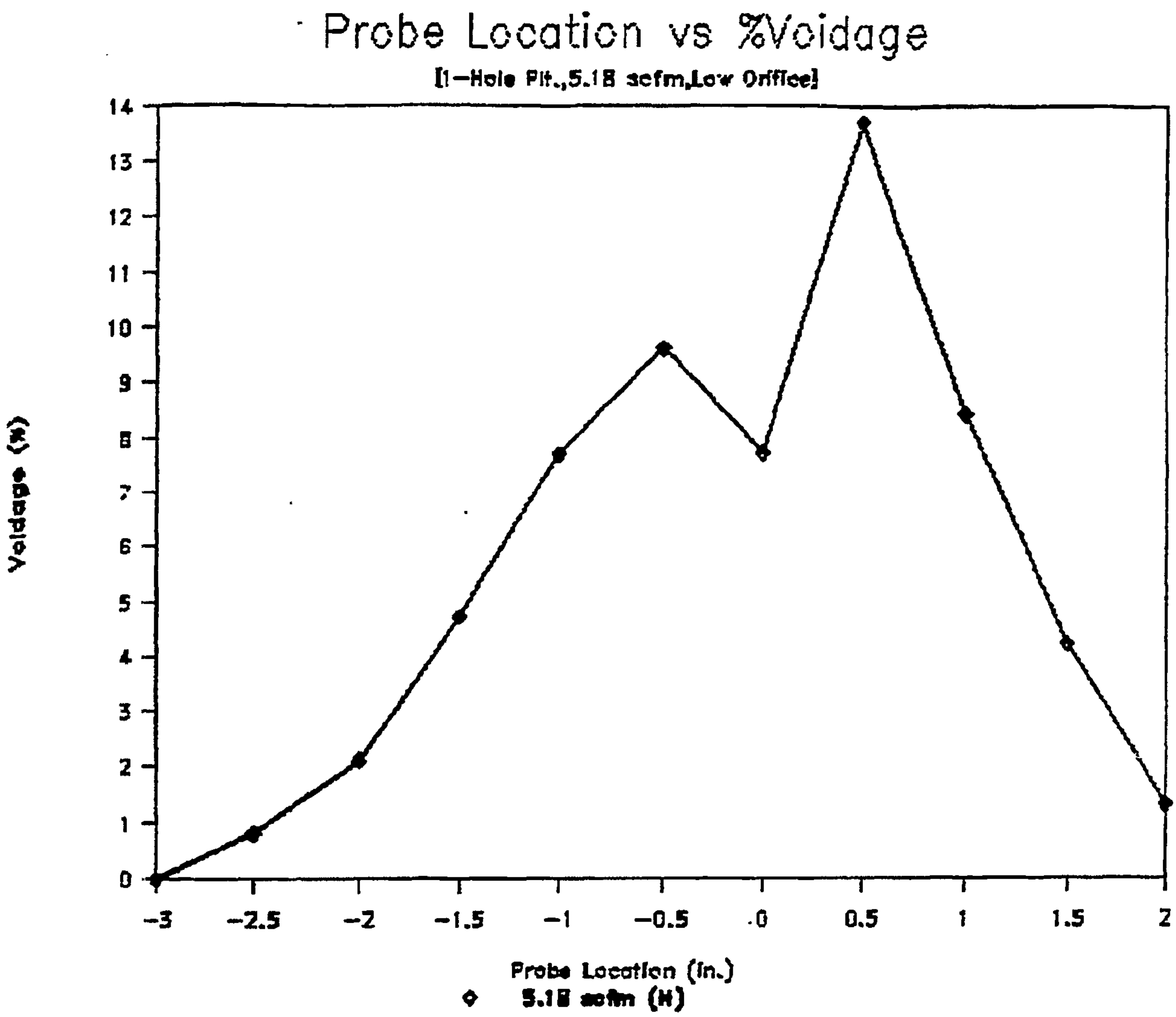


Figure 16: Distributor plate, center hole, fig. 5c,

Air flow 5.18 scfm, traverse 5" above plate

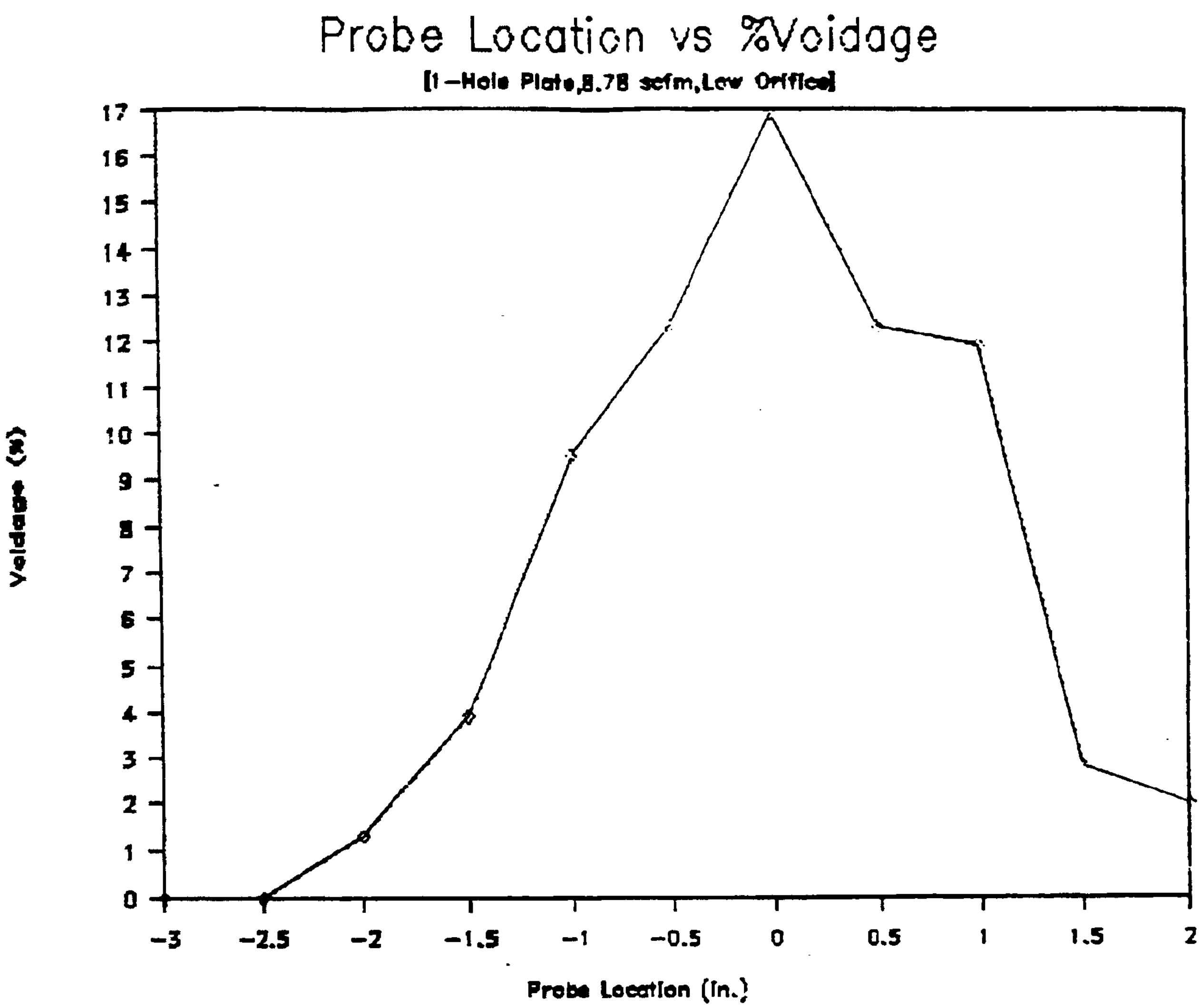


Figure 17: Distributor plate, center hole, fig. 5c,

Air flow 8.78 scfm, traverse 5" above plate

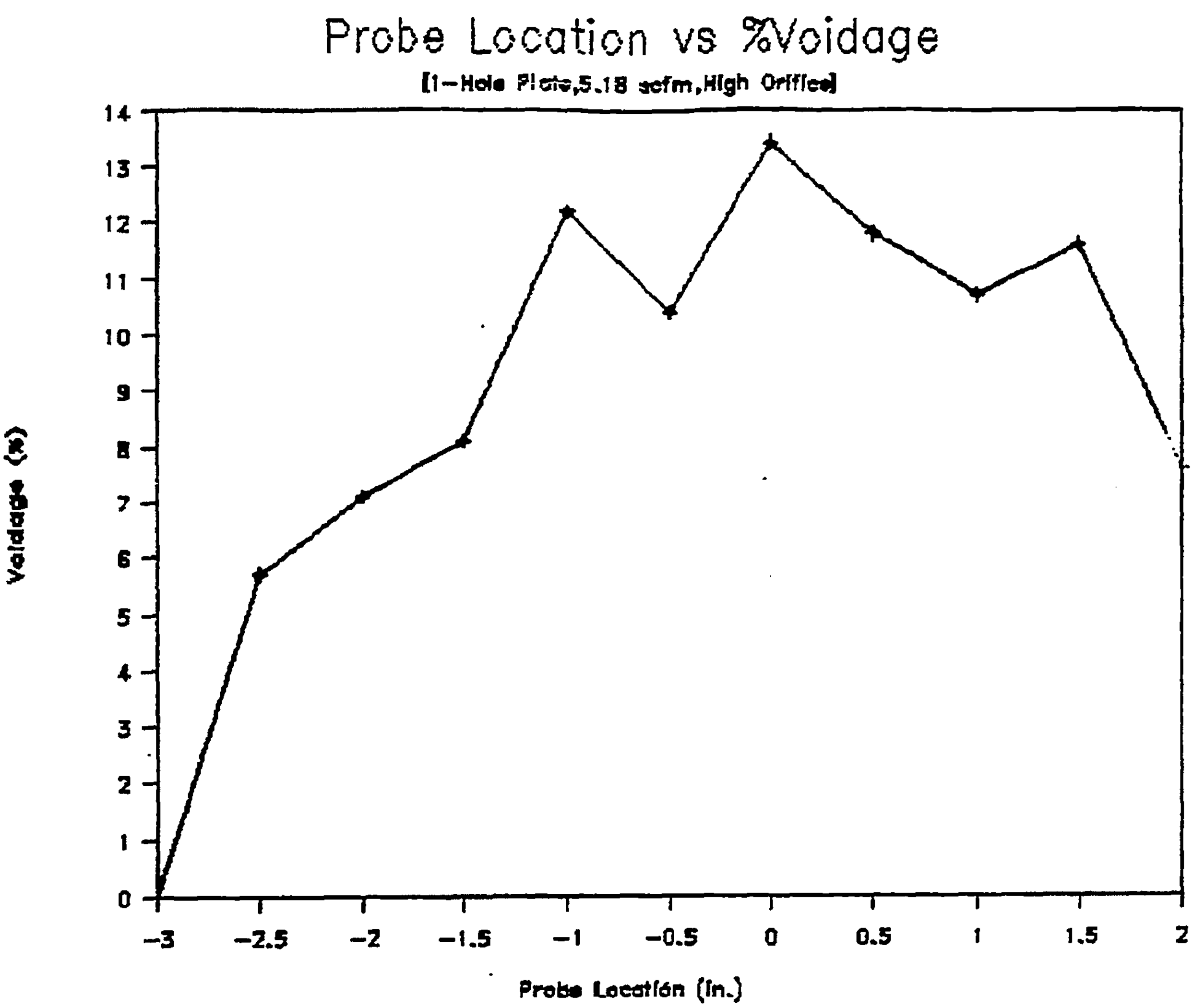


Figure 18: Distributor plate, center hole, fig. 5c,

Air flow 5.18 scfm, traverse 10.5" above plate

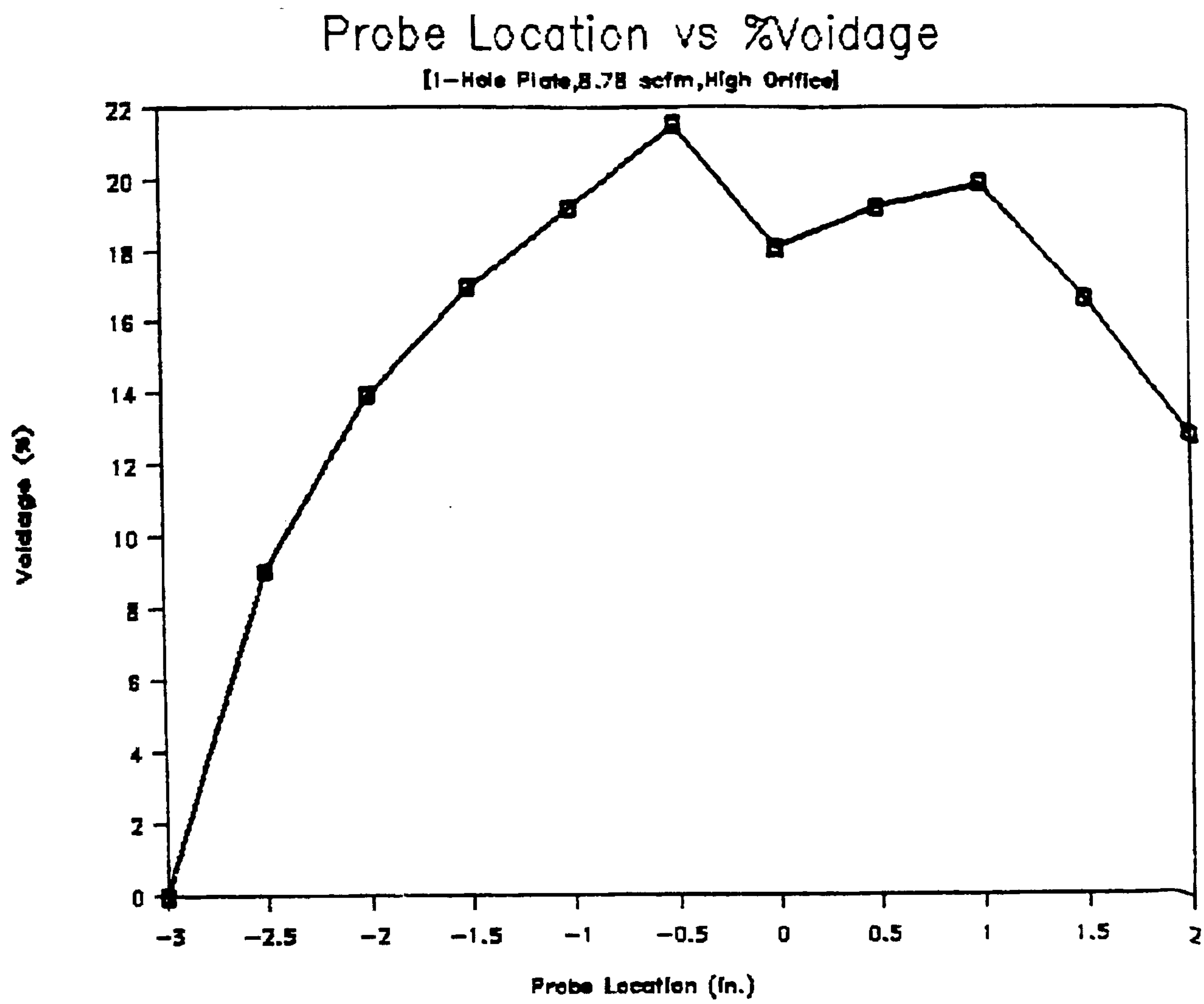


Figure 19: Distributor plate, center hole, fig. 5c,

Air flow 8.78 scfm, traverse 10.5" above plate

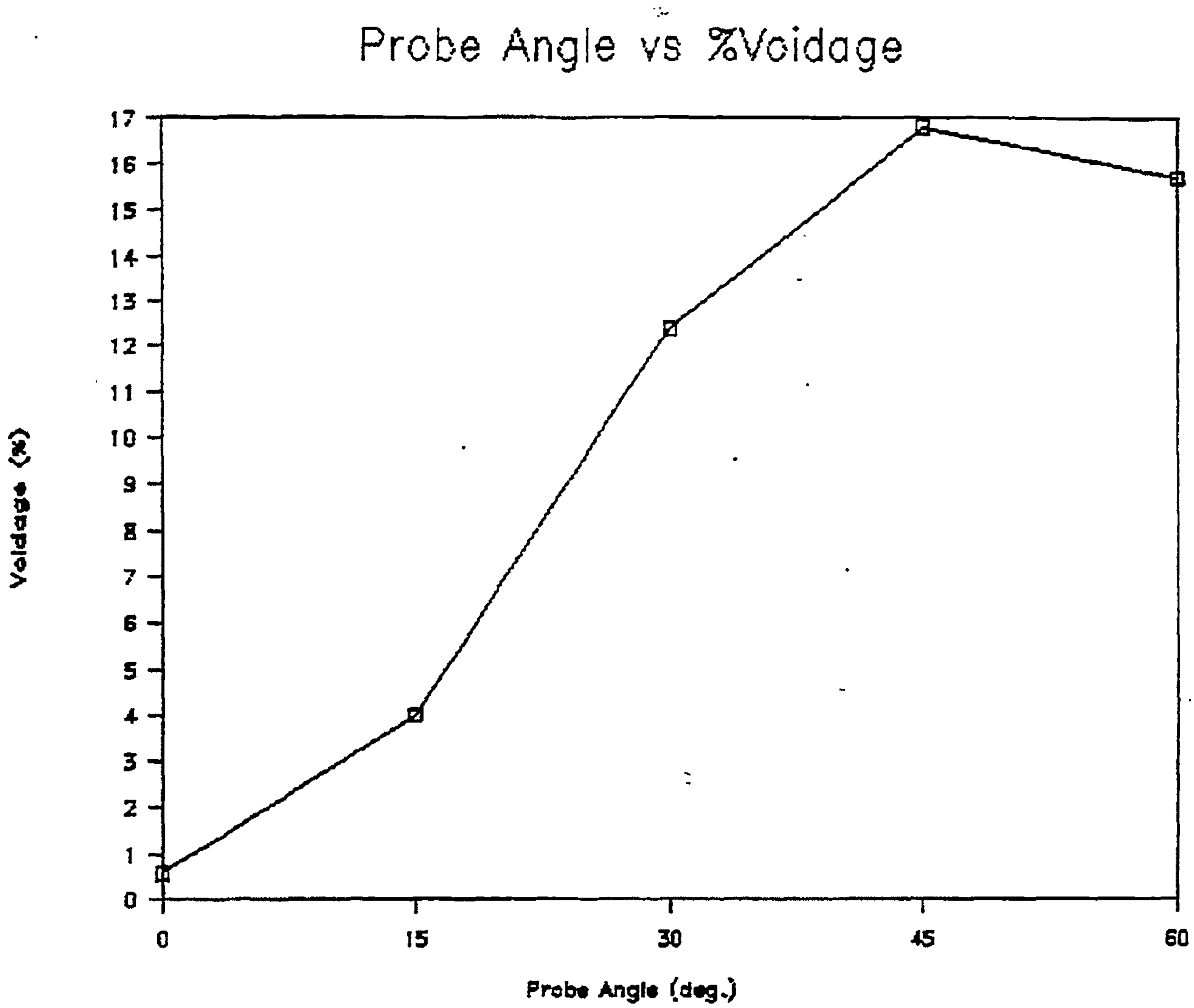


Figure 20. Effect of the probe tip angle on the measured voltage at one point in the column.

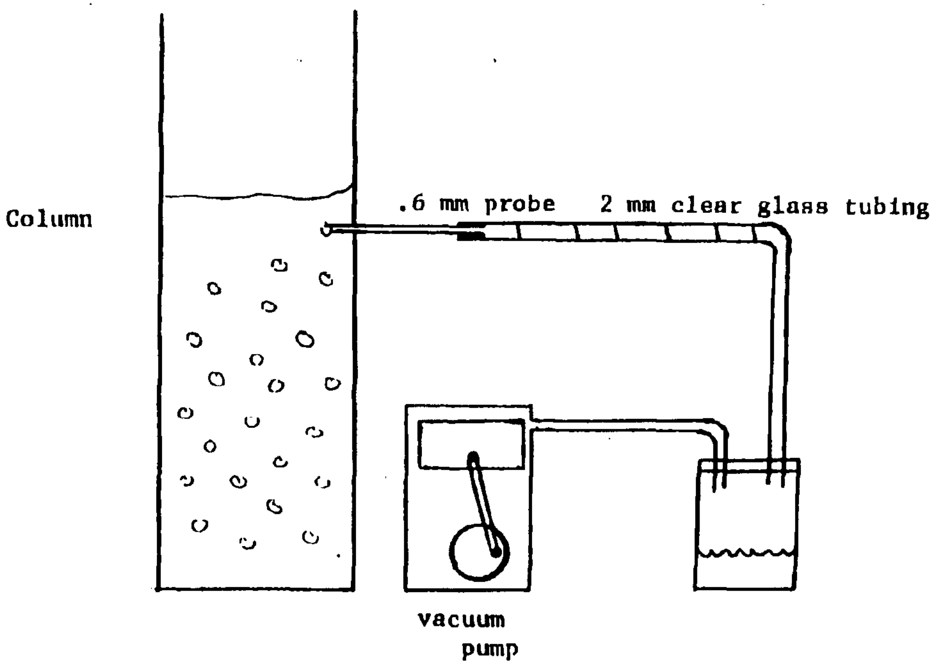


Figure 21. Proposed new probe.

APPENDIX A: Basic Program

BASICA PROGRAM TO COLLECT DATA

```
LIST
5   RE = 0
10  DIM X1(1000),X2(1000),X3(1000)
20  PRINT "How Many Data Samples Do You Wish To Take?"
30  INPUT N
40  BASADR% = &H300
50  FOR I = 1 TO N
60  OUT BASADR% + 1,0
70  XH% = INP(BASADR% + 1)
75  X% = XH%*16
80  V = X%*10/4096
90  X1(I) = V - 5
110 X3(I) = X1(I)
130 IF X3(I)<1.625  THEN X2(I)=1
140 IF X3(I)>1.625  THEN  X2(I)=0
150 IF X2(I) = 1 THEN RE = RE + 1
160 ELSE GOTO 170
170 NEXT  I
240 PRINT "The Voidage is";RE/N*100 ; "Percent"
500 STOP
999 END
Ok

1LIST   2RUN   3LOAD"   4SAVE"   5CONT 6,"LPT1 7TRON 8TROFF9KEY    0SCREEN
```

Line #05 ------- sets the counter to 0

Line #10 ------- dimensions and arrays X1,X2,X3

Line #20-30 ---- input number of samples to take

Line #40-------- sets the base address of the DASH-8

Line #50,170 --- loop that controls # of samples taken

Line #60 ------- tells DASH-8 to take a sample

Line #70 ------- inputs the value into the computer

Line #75,80,90 - converts reading to -5 to +5 volts

Line #110-150 -- determines if its a bubble or not

Line #240 ------ prints out the percent voidage

APPENDIX B: Non-Newtonian Model

NON-NEWTONIAN TWO-PHASE CIRCULATION IN BUBBLE COLUMNS

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ABSTRACT

Gas-liquid and gas-slurry bubble columns are widely used in the mineral and engineering industries, particularly for aeration (oxidation), synthesis of oil and flotation of mineral fines. Even though gas may be introduced into a bubble column evenly through a distributor plate over the whole column floor, circulation patterns generally develop in the column. These circulation patterns reduce gas holdup and residence time in the column and must therefore be predicted for accurate column design. This paper extends a force balance approach (originally used for turbulent systems) to predict circulation in non-Newtonian gas-liquid mixtures and demonstrates how the rheological properties will affect a single circulation pattern in a column. Wall shear stress need not be known in advance and is in fact available to the user of the model upon solution of the velocity profile.

INTRODUCTION

A bubble column consists of a large tank filled with liquid or slurry through which a gas is bubbled, usually to achieve interphase mass transfer. These columns are used widely throughout the engineering industries (Sharma et al., 1982), particularly for the aeration of sludges. They also offer advantages over fixed beds for Fischer-Tropsch synthesis (Stern et al., 1985). A similar device, the Pachuca tank (Lamont, 1958; Clark, 1984) is used for oxidation and mixing of slurries in the mineral processing industries. Bubble columns are also used for flotation to separate minerals or coal from gangue material (Young, 1982; Harris, 1976).

Although gas may be introduced evenly over the floor of a bubble column, at all but very low gas throughputs with carfully designed distributors (Siemes, 1958) bubbles coalesce and circulation patterns evolve in the mixture. Although very complex patterns are observed in large ponds (Otero et al., 1985) a simple circulation pattern, with the mixture rising at the center and flowing down at the column walls, is often observed in bubble columns. This pattern has been termed "gulfstreaming" by Freedman and Davidson (1969). Clearly, where gas is introduced centrally, as in Pachucu tanks, circulation also takes place and is often accentuated.

Explanation of the evolution of gulfstreaming when gas is evenly introduced is lacking in the literature but an heuristic argument for the development of the pattern can be presented; consider a column with bubbles distributed evenly throughout its volume. The axial hydrostatic head over the height of the column is identical at any radius from the column center provided that all wall effects are neglected. Let one bubble, due to some mixing or perturbation, move inward away from the wall to near the column center. Since the gas void fraction in the column center is now slightly greater than near the wall the axial hydrostatic head is now greater near the wall than in the center. Since the mixture upper surface is at the same pressure over the whole cross-section, there must be an inward radial pressure gradient at the bottom of the column. The movement of mixture resulting from this gradient carries more bubbles toward the center, further increasing the radial gradient so that a stable circulation pattern rapidly develops.

It may be argued that a bubble moving from the center toward the wall could initiate a reverse pattern and indeed such patterns have been observed in fluidized beds (Lin et al., 1985; Surma, 1985) and appear to be related to saddle shaped void profiles observed in some low velocity gas-liquid flows (Galaup, 1975; Serizawa et al., 1975). However, the gulfstreaming observed by Freedman and Davidson (up at the center, down at the wall) usually prevails at high gas superficial velocities, perhaps due to wall effects.

Prediction of circulation velocity is very important since it has a profound effect on gas holdup, liquid mixing heat transfer and reaction in the column (Shah et al., 1982). However, the velocity is generally difficult to measure, requiring the use of anemometry (which can be complicated in two phase systems) or the use of probe pairs with cross-correlation of their signals. In contrast, the local void fraction is quite readily measured using optical or resistance probes (Galaup, 1975). The analysis presented below shows that the velocity distribution across a column can be found from a combination of void fraction measurements and a rheological relationship.

LITERATURE SURVEY

Bubble columns have been reviewed in detail by Shah et al. (1982).

Specific work on the prediction or modelling of mixture circulation is reported by Rietema (1982), Hills (1974), Freedman and Davidson (1969) and Miyauchi et al. (1981). Recently Molerus and Kurtin (1986) have developed a model for circulation by considering concentric upflow and downflow zones. These authors have all considered either turbulent or Newtonian viscous systems. The basic approach used in this paper to model non-Newtonian systems follows closely the recent turbulent mixing length model of Clark et al. (1987).

GENERAL MODEL

Let us consider the case where a gas is bubbled through a column free of baffles or draft tubes containing a liquid or non-settling slurry and let us assume that we have access to the gas void distribution as a function of the radius, $\varepsilon(r)$, at some height in the column. The analysis developed below cannot be applied to columns with a very shallow aspect ratio since radial velocity components characteristic of the top and bottom of the column will be neglected.

The time-average density, $\rho(r)$, of the mixture at some radius is given by

$$\rho(r) = \rho_L\ (1 - \varepsilon(r)) + \rho_G\ \varepsilon(r) \qquad (1)$$

where ρ_L is the liquid or slurry density and where the gas density, ρ_G, is often set to zero. Let us assume a wall axial shear stress T_W (we shall show later that it need not be known a priori) in which case we can predict the axial shear stress at any radius (Clark et al., 1987; Levy, 1963) using a force balance

$$T\ (r) = T_W[1 + Rg(\bar{\rho} - \rho_i(r))/(2\ T_W)](r/R) \qquad (2)$$

where R is the column radius, g is acceleration due to gravity $\bar{\rho}$ is the average density over the cross section

$$\bar{\rho} = \frac{1}{R^2} \int_0^R 2 \rho (r) r \, dr \qquad (3)$$

and ρ_i is an average density within a radius r

$$\rho_i (r) = \frac{1}{r^2} \int_0^r 2\rho (r) r \, dr \qquad (4)$$

Let us also assume that we have a rheological model for the fluid in the column, which as a first approximation will not account for the presence of the gas in the liquid or slurry.

$$T (r) = f \left[\frac{du}{dr} \right] \qquad (5)$$

If this model can be inverted so as to yield du/dr as a function of T(r) (it cannot be inverted reliably for Bingham plastics, for example) then it can be used in conjunction with equation 2 to yield du/dr. Integrating from the known boundary condition U = 0 at r = R, the velocity U(r) can then be found. Integrating U(r) over the column cross-section yields a flowrate Q.

$$Q = 2\pi \int_0^R U (r) r \, dr \qquad (6)$$

We will have found U(r) using an assumed value for T_W. If the correct value for T_W had been assumed, then Q = 0 because there is no <u>net</u> flow across a cross-section of the column, else we have assumed a T_W corresponding to a net up or down flow in the column. In this case the correct T_W must be found by trial and error. Experience has taught the authors that velocity distribution can be <u>very</u> sensitive to T_W.

SPECIFIC CASES

The general theory presented above has been applied previously to turbulent flow (Clark et al., 1987) and verified using air-water data of Hills (1974). No closed solution was found, so that U(r) and Q had to be determined by numerical integration. An analytic, yet not very tractable, solution can be found for the viscous Newtonian case, where

$$T\ (r) = \mu \frac{du}{dr} \tag{7}$$

do that

$$\frac{du}{dr} = \frac{r}{\mu} \left[\frac{T_\omega}{R} + g \frac{(\bar{\rho} - \rho_i)}{2} \right] \tag{8}$$

Since void fraction in the most common gulfstreaming pattern is a maximum at the center and a minimum at the wall, it can be described with reasonable accuracy (Zuber and Findlay, 1964) by an equation of the form

$$\varepsilon = \varepsilon_c \left[1 - \left(\frac{r}{R} \right)^p \right] \tag{9}$$

where ε_c is the void fraction at the column center. Hence one finds that

$$\rho\ (r) = \rho_L - \rho_L \varepsilon_c + \rho_L \varepsilon_c \left(\frac{r}{R} \right)^p \tag{10}$$

or

$$\rho_i = \rho_L (1 - \varepsilon_c) + \frac{2\rho_L}{2 + p} \left(\frac{r}{R} \right)^p \tag{10a}$$

Combining equations 8, 9 and 10

$$du/dr = Ar + Br^{(p+1)} \tag{11}$$

where

$$A = \frac{T_w}{R\mu} + \frac{g\bar{\rho}}{2\mu} - \frac{g\rho_L (1 - \varepsilon_c)}{2\mu} \tag{11a}$$

and

$$B = \frac{g\rho_L}{\mu(2+p)R^p} \tag{11b}$$

so that

$$U(r) = \frac{Ar^2}{2} + \frac{Br^{p+2}}{1+p} + C \qquad (12)$$

where C can be found from the no-slip condition at the column wall. The two different powers of r in eqn. 12 permit the description of a reversing velocity profile.

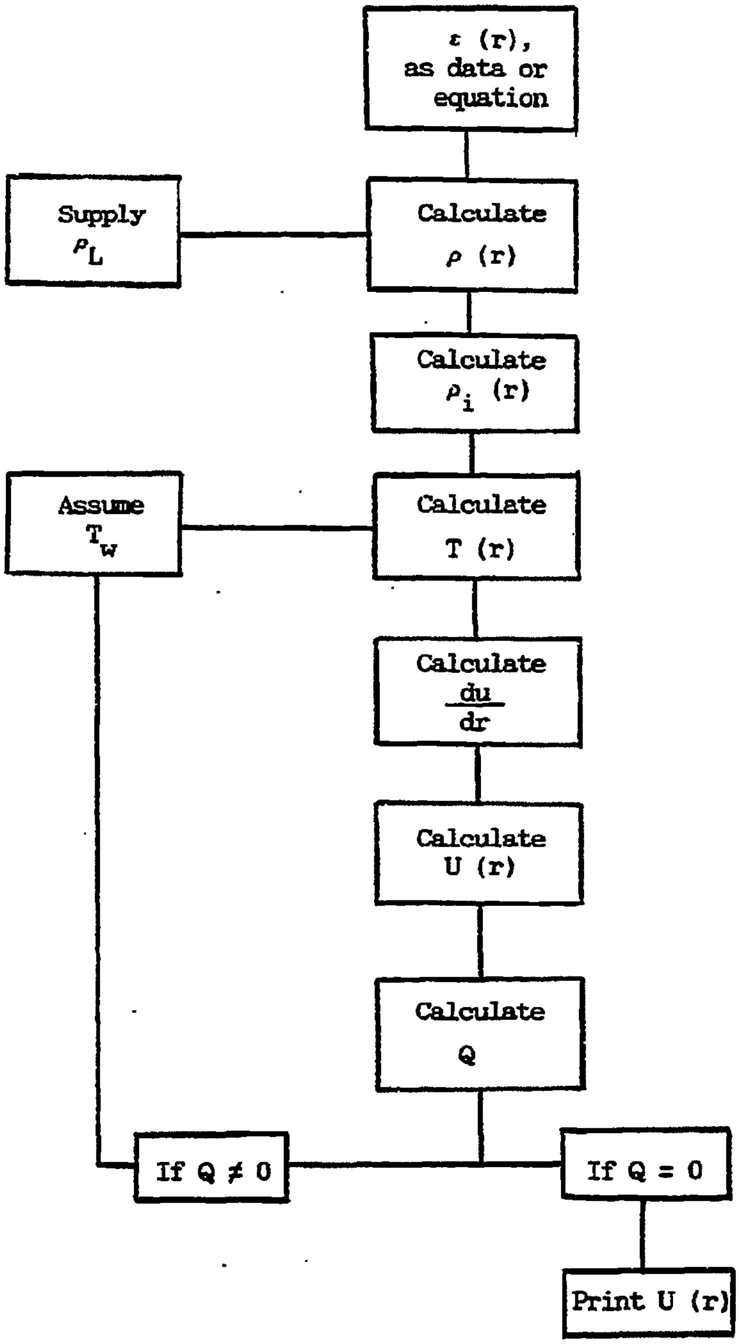

Figure 1: Scheme for calculating velocity profile.

For the non-Newtonian case a closed solution becomes cumbersome or impossible, so that computer solution is favored. The scheme shown in Figure 1 is readily employed.

RESULTS

A computer program was written in QUICKBASIC to describe circulation of a power law fluid, where

$$T = k\left(\frac{du}{dr}\right)^n \tag{13}$$

In each rheological case considered below, holdup in the center of the column, ε_C, was taken as 20% (the maximum value) and equation 9 was chosen to represent the voidage distribution with the exponent p = 3. This corresponded to an average gas void fraction of 9.6%. A 1m diameter column was considered.

The effect of varying both k and n for power law fluids was determined. For n = 1 (a Newtonian fluid) k was varied to produce the velocity distributions shown in figure 2. These distributions are all of similar shape but vary in their magnitude of velocity. The radii at which zero velocity occurs remains constant and the wall shear stress remains the same. This is reasonable since that shear stress is really balancing the unequal distribution of density, which is the same in each case.

For lower viscosities the velocities calculated are very high. In reality turbulent momentum transfer would serve to restrict these velocities so that the presence of turbulence in part of or throughout the whole of the column must be considered.

A simple way of dealing with the possibility of turbulence is to use a rheological model which takes into account momentum transfer by both viscous and turbulent mechanisms. For a turbulent model, mixing length

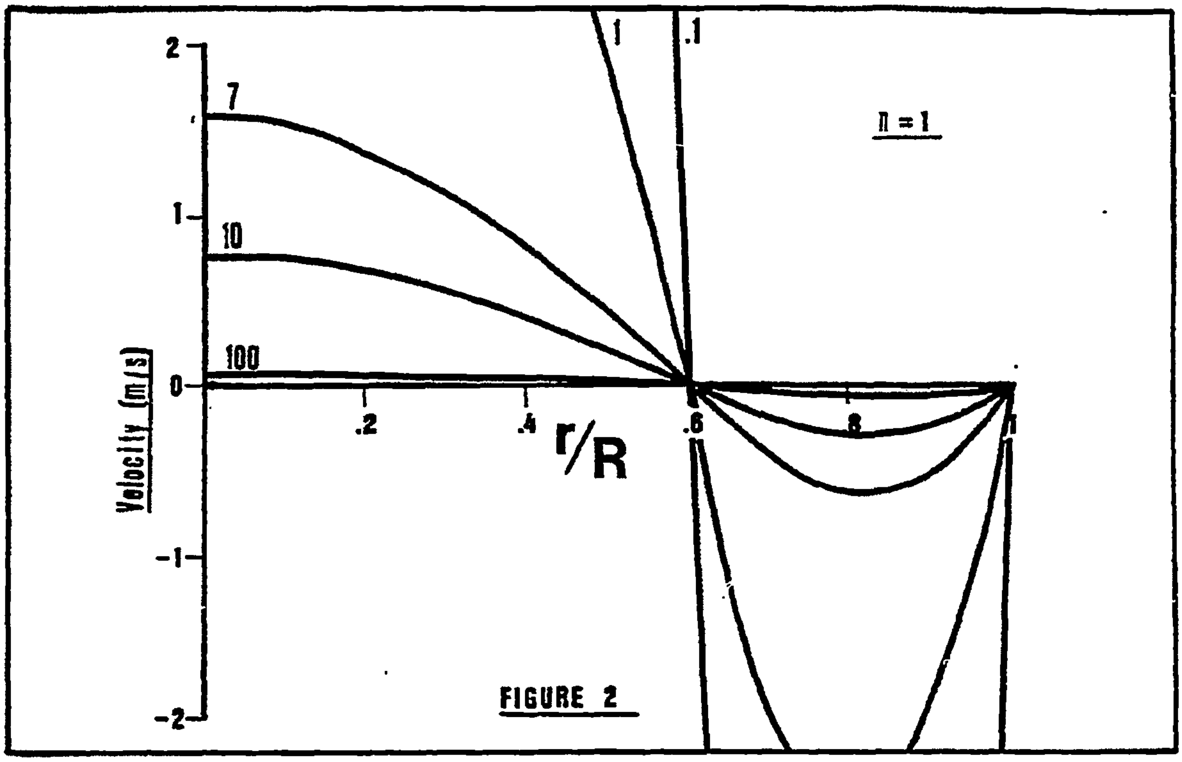

Figure 2: Effect of viscosity (for Newtonian liquids, n = 1) on the circulation velocity. Turbulent effects were neglected.

theory is proposed, since it has found good agreement with data for turbulent water circulation as demonstrated by Clark et al. (1987). Shear stress was accordingly taken as

$$T(r) = k\left(\frac{du}{dr}\right)^n + \ell^2\rho\left|\frac{du}{dr}\right|\left(\frac{du}{dr}\right) \qquad (14)$$

where ℓ^2 is the mixing length used by Clark et al., (1987)

$$\ell/R = 0.14 - 0.08\left(\frac{r}{R}\right)^2 - 0.06\left(\frac{r}{R}\right)^4 \qquad (15)$$

and $\rho = \rho_L(1-\varepsilon)$, the local mean fluid density.

Figure 3 shows distributions generated using the combined viscous and turbulent model for the same conditions as figure 3. Velocities of the less viscid fluids are considerably reduced demonstrating that turbulent momentum transport was significantly larger than viscous effects in those cases.

Equation 14 provided some difficulty in the analysis since du/dr was required as a function of T(r) rather than vice versa. In practice a Newton-Raphson method was used to find du/dr, taking care to preserve the appropriate sign of the differential.

The value of n was also varied, from 0.375 (shear-thinning) to n = 2 (dilatant fluid) for constant k. Resulting profiles are shown in figure 4. For low values of n both the central (upward) and annular (downward) velocity distributions become flatter and tend towards the plug flow distribution (an upward plug in the center with a downward annular plug) which would be found when n tends to zero. It was evident that shear-thinning fluids would permit very high velocities in the column and that transition to a turbulent mode was possible.

Figure 5 shows the effect of accounting for turbulence using equation

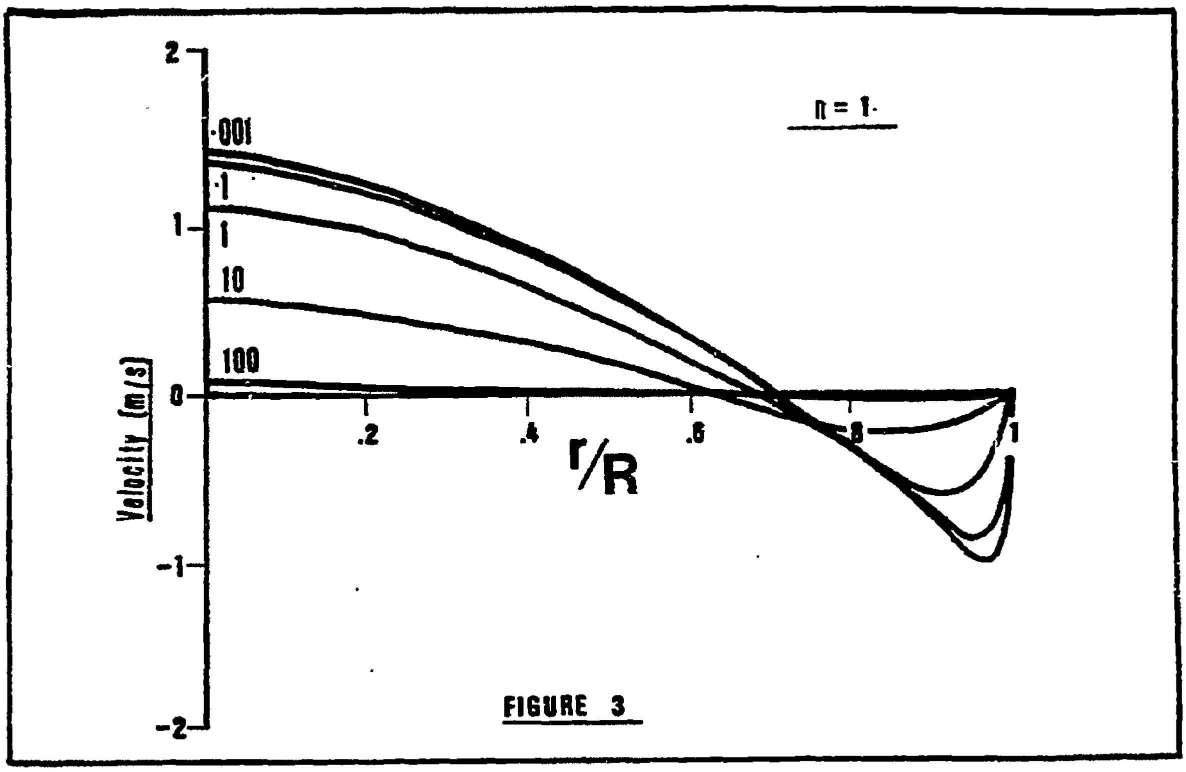

Figure 3: Velocity profiles for the same liquids considered in Figure 2, but with turbulent effects included.

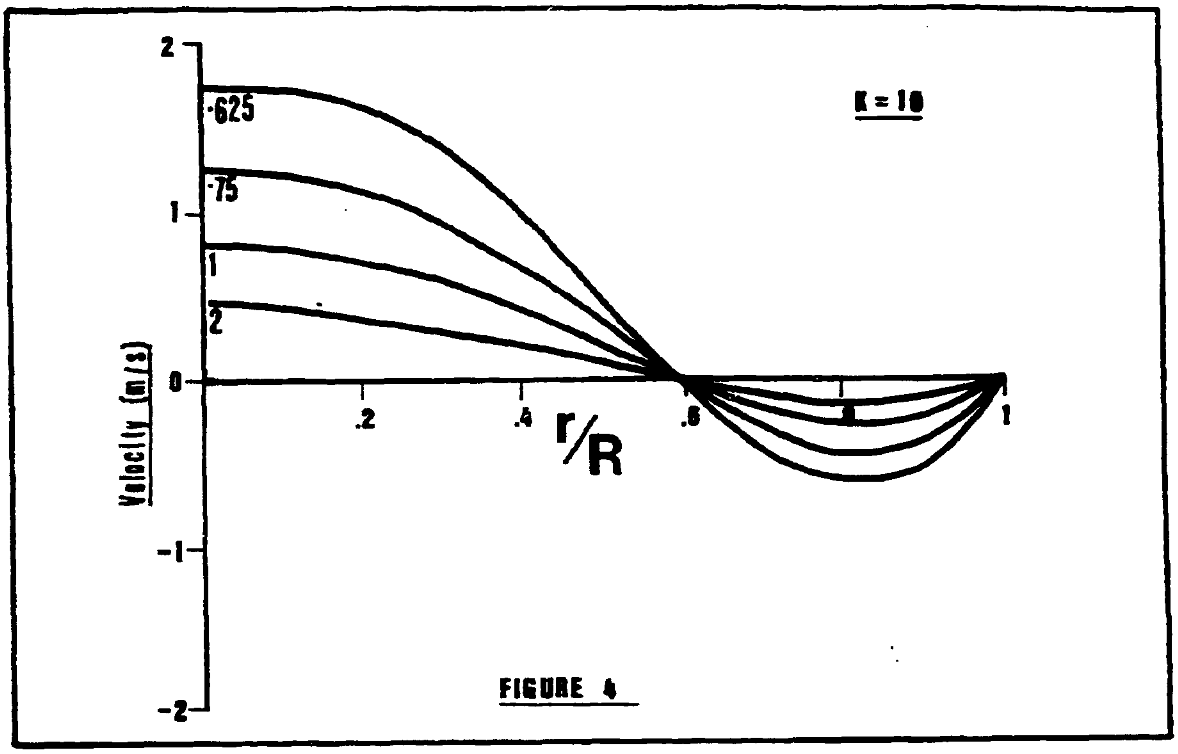

Figure 4: Velocity profiles for power law liquids (k = 10, n = 0.375 to 2) neglecting turbulent effects.

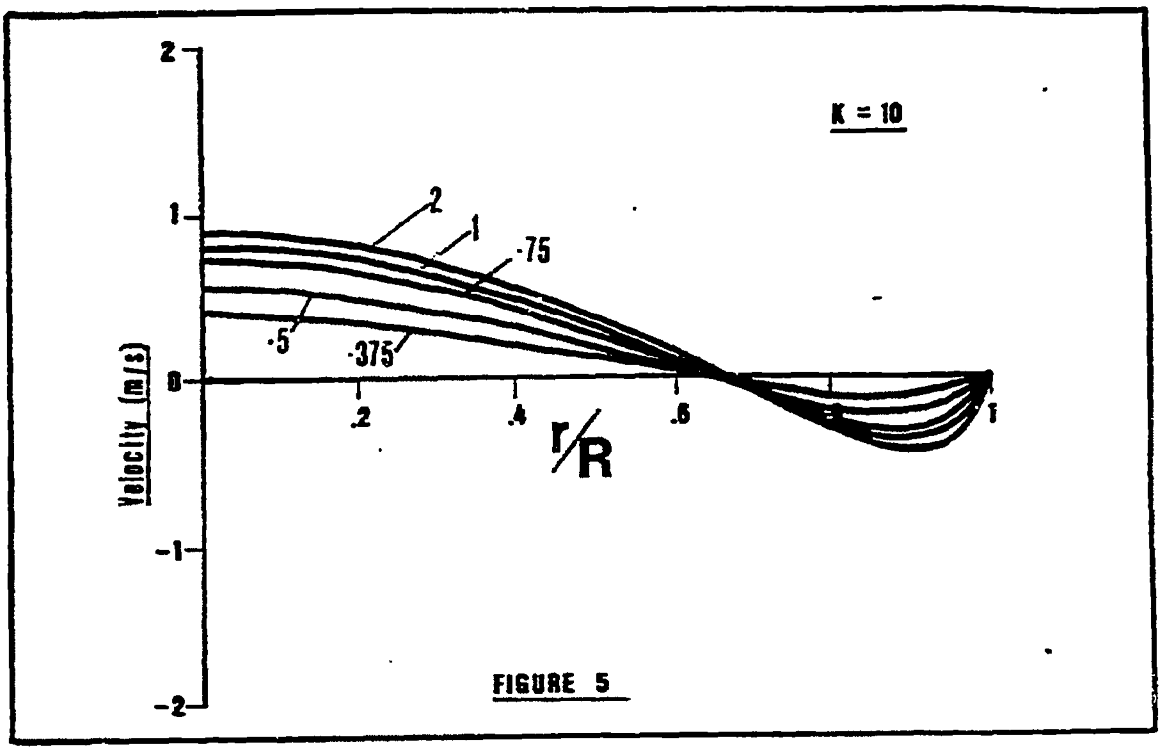

Figure 5: Velocity profiles for the same liquids considered in Figure 4, but with turbulent effects included.

14 rather than equation 13. Velocities of shear thinning fluids are considerably reduced by the added turbulent momentum transport. The ratio between turbulent and viscous transport is demonstrated further by a calculation for the circulation of banana puree, with $n = 0.46$ and $k = 6.5$ (Levenspiel, 1984) and with the same void distribution used in previous calculations. Figure 6 shows the computed velocity profile together with the ratio between eddy and molecular contributions to the momentum transport. Although the eddy contribution dominates over much of the radius, they are both the same order of magnitude.

All of the above calculations have been for the same void distribution, given by equation 9 with $\varepsilon_C = 20\%$ and $p = 3$. Figures 7 and 8 show the effect of changing ε_C to 25%, 10% and 5% while maintaining the same distribution shape. As expected, circulation velocities are reduced by decreasing the net void fraction in the column. Distributions retain a similar shape.

DISCUSSION

There can be no doubt that the proposed model has several practical limitations as discussed below, although to the authors' knowledge there is no more accurate method of prediction currently available.

Firstly, in being two dimensional, the model cannot be applied to shallow ponds or columns. However, most columns have an acceptable depth to diameter ratio so that the model can be applied with radial velocities neglected. In very large columns multiple circulation cells may develop so that the single cell prediction used above may be invalid.

Secondly, the gas void distribution was assumed to vary from a maximum at the center of a minimum at the wall and an equation to describe

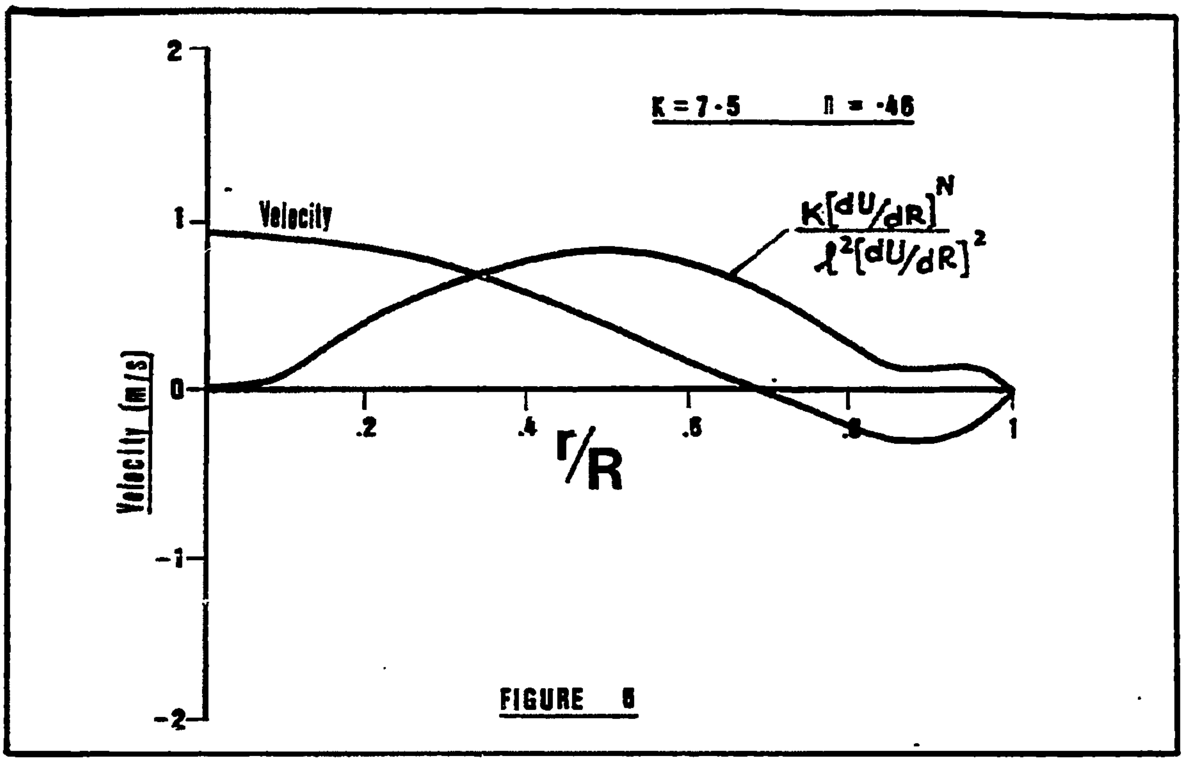

Figure 6: Velocity profile and ratio of viscous to turbulent effects for circulation of banana puree.

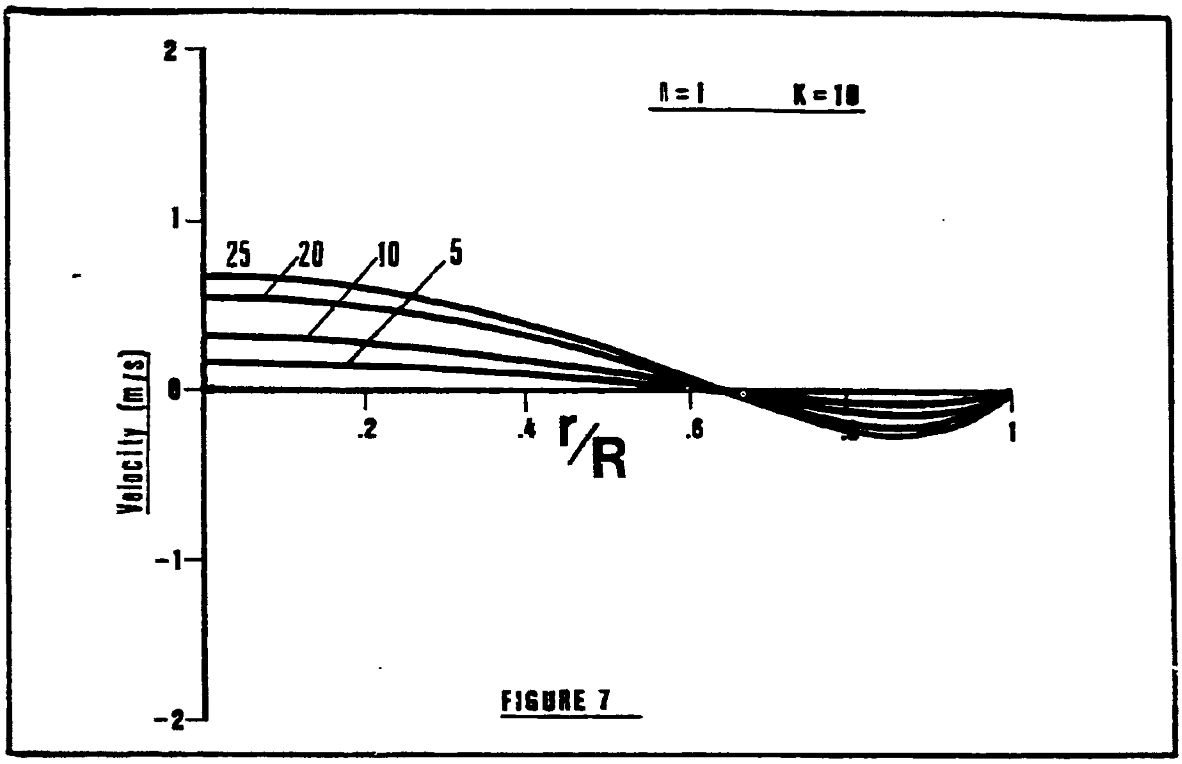

Figure 7: Effect of void fraction on circulation of a Newtonian liquid in a column. Centerline void fractions are shown.

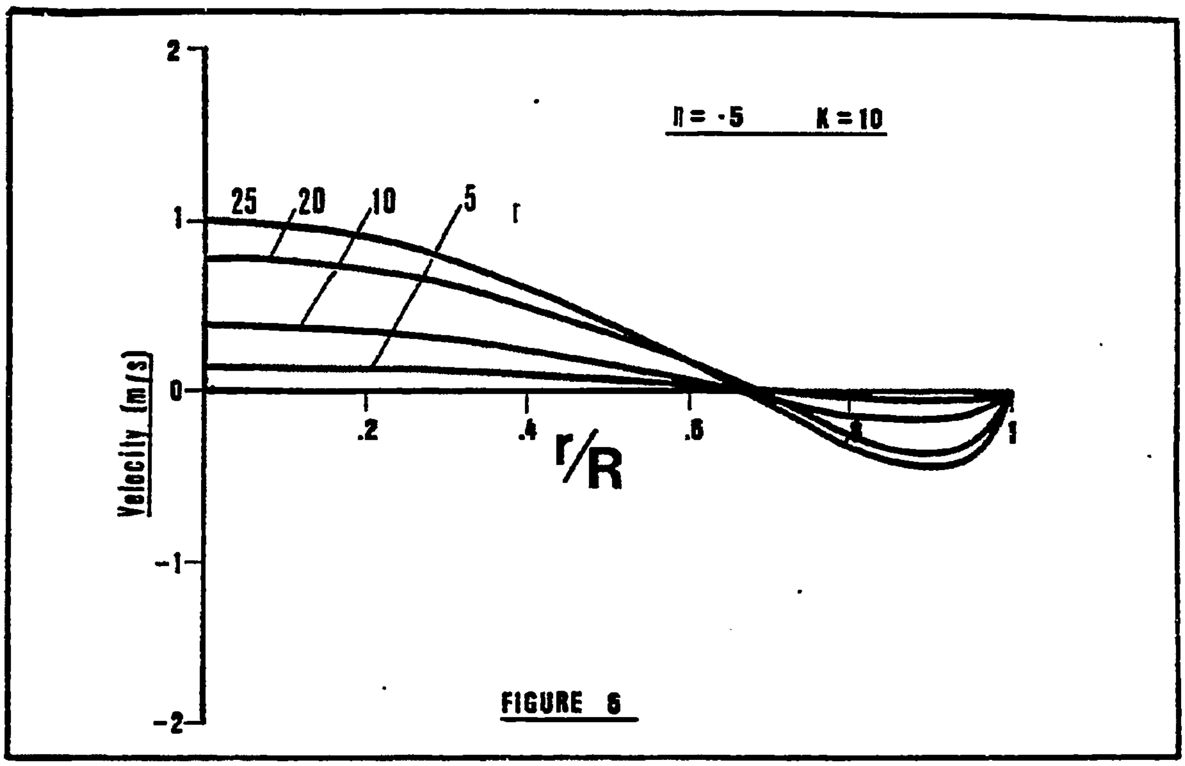

Figure 8: Effect of void fraction on circulation of a shear thinning liquid in a column. Centerline void fractions are shown.

the typical form was proposed. Flatter void profiles than the one proposed will reduce circulation and saddle shaped profiles will cause a reverse circulation pattern (Clark et al., 1987). Distributions can vary widely: for example, Rietema and Ottengraf (1970) have observed a central bubble "street" in a column of viscous liquid with a bubble free annulus. It would be wise to measure the actual void profile for a more precise velocity prediction. Void fraction is far more readily measured than local velocity (for example, with resistance probes), so that the model is still of great benefit.

Thirdly, the presence of the air bubbles in the liquid will affect the system rheology. One is tempted to argue that the bubbles can transmit no shear, so that a revised shear stress relationship

$$T(r) = (1 - \varepsilon(r))\, k \left(\frac{du}{dr}\right)^n \qquad (16)$$

would be employed, but lateral movement of bubbles can enhance momentum transfer, as can the flow of liquid around the rising bubble (Clark and Flemmer, 1985a, 1985b). Small bubbles can also cause viscosity changes in the liquid.

Despite these limitations, the model offered above provides a reasonable, simple estimate of velocity distribution in a bubble column.

A final interesting observation is that the radius at which maximum downward velocity occurs, r_{max}, is fixed by the wall shear and void profile. At this radius the change in velocity du/dr is zero and hence the shear stress must be zero. Since there is no radial pressure variation, dP/dz (z = axial height) must be the same for the cylinder bounded by r_{max} and for the whole column cross-section. The value of r_{max} can be found from a force balance using the cross-sectional average density $\bar{\rho}$, the average density within the cylinder bounded by r_{max}, $\rho_l(r_{max})$, and the wall shear, T_w. No other radius is pre-determined in this fashion, but it would appear that the radius at which liquid velocity is zero does not vary over a wide range. Typically from our calculations the liquid velocity was zero at a radius of 0.65R for viscous cases with r tending to 0.7R as turbulent effects dominated. Experimental work on viscous glycerol–water solution in a 22cm diameter column by Rietema and Ottengraf (1970) to be showed/approximately 0.58R for U = 0, while the data of Hills (1974) for turbulent systems show closer to 0.7R. This supports our conclusions.

REFERENCES

Clark, N.N. "Predicting the Circulation Rate in Pachuca Tanks with Full Height Draft Tubes" Mineral and Metallurgical Processing, November 1984, pp. 226-232. Also in Trans AIME, 1984.

Clark, N.N., Flemmer, R.L.C. and Atkinson, C.M. "Turbulent Circulation in Bubble Columns" A.I.Ch.E. Journal, Vol. 33, 1987, pp. 515-518.

Clark, N.N. and Flemmer, R.L.C. "Two Phase Pressure Loss on Terms of Mixing Length Theory" (2 parts) Ind. and Eng. Chem. Fundamentals, Vol. 24, 1985a, pp. 412-418, 1985b, pp. 418-422.

Freedman, W. and Davidson, J.F. "Holdup and Liquid Circulation in Bubble Columns" Trans. I. Chem. E. Vol. 47, 1969, pp. T251-T262.

Galaup, J.P. "Contribution to the Study of Methods for Measuring Two Phase Flow" Ph.D. Thesis, University of Grenoble, 1975.

Harris, C.C. "Flotation Machines", in Flotation, M.C. Fuerstenau, ed., AIME, New York, 1976.

Hills, J.H. "Radial Non-Uniformity of Velocity and Voidage in a Bubble Column" Trans I. Chem. E., Vol. 52, 1974, pp. 1-9.

Lamont, A.G.W. "Air Agitation and Pachuca Tanks" Can. Jour. Chem. Eng., August 1958, pp. 153-160.

Levenspiel, O. Engineering Flow and Heat Exchange, Plenum Press, New York 1984.

Levy, S. "Prediction of Two Phase Pressure Drop and Density Distribution from Mixing Length Theory" Jour. Heat Transfer (ASME), May 1963, pp. 137-152.

Lin, J.S., Chen, M.M. and Chao, B.T. " A Novel Radioactive Particle Tracking Facility for Measurement of Solids Motion in Gas Fluidized Beds" A.I.Ch.E. Journal Vol. 31, pp. 465-473 (1985).

Miyauchi, T., Furusaki, S., Morooka, S. and Ikeda, Y. "Transport Phenomena and Reaction in Catalyst Beds" Advances in Chemical Eng. (Pub. by Academic Press, T.B. Drew et al., eds.) Vol. 11, 1981, pp. 275-448.

Molerus, O. and Kurtin, M. "Hydrodynamics of Bubble Columns in the Liquid Circulation Regime" Chemical Engineering Sci. Vol. 41, 1986, pp. 2685-2692.

Otero, Z., Tilton, J.N. and Russel, T.W.F. "Some Observations on Flow Patterns in Tank-Type Systems" Int. Jour. Multiphase Flow Vol. 11, 1985, pp. 583-589.

Rietema, K. "Science and Technology of Dispersed Two Phase Systems" Chem. Eng. Sci., Vol. 37, 1982, pp. 1125-1150.

Rietema, K. and Ottengraf, S.P.P. "Laminar Liquid circulation and bubble street formation in a gas-liquid system" Trans. Inst. Chem. Engrs. vol.48, 1970, pp. T54-T62.

Serizawa, A., Kataoka, I. and Michiyoshi, I. "Turbulence Structure of Air-Water Bubbly Flow" Int. Jour. Multiphase Flow, Vol. 2, 1975, pp. 235-259.

Shah, Y.T., Kelkar, B.G., Godbole, S.P. and Deckwer, W.D. "Design parameters estimations for bubble column reactors" A.I.Ch.E. Journal Vol. 28, 1982, pp. 353-379.

Siemes, W. "Gasblasen in Flussigkeiten" Chem. Ing. Tech. Vol. 26, 1954, pp. 614-630.

Stern, D., Bell, A.T. and Heinemann, H. "A Theoretical Model for the Performance of Bubble Column Reactors used for Fischer Tropsch Synthesis" Chem. Eng. Sci. Vol. 40, 1985, pp. 1665-1667.

Surma, J.E. "The Determination of Bubble Velocity of Fluidized Beds" M.S. Thesis, Montana State University, 1985.

Young, P. "Flotation Machines", Mining Magazine, January 1982, pp. 35-59.

Zuber, N. and Findlay, J.A. General Electric Company Report GEAP 4592, 1964.

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