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ERL 87-95 (OPJ)
C12

EXIT DISCONTINUITY IN SLURRY BUBBLE COLUMNS

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01-7990517

November 1987

ENERGY RESEARCH LABORATORIES
DIVISION REPORT ERL 87-95(OPJ)

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EXIT DISCONTINUITY IN SLURRY BUBBLE COLUMNS

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SUMMARY

The exit discontinuity in slurry bubble columns, i.e., the difference in the apparent solids concentration at the very top of the column (C_t) and the concentration in the effluent (C_e), was studied in a 0.3 m ID bubble column, using air as the gas phase, water, a light hydrocarbon oil (Varsol) and trichloroethylene as liquids and glass beads of different sizes and density as solids.

The results showed that the drop in solids concentration occurs in a very small layer at the gas/liquid interface. By changing the column exit configuration and removing the gas/liquid interface the exit discontinuity disappeared. The extent of the exit discontinuity depended on the liquid properties and appeared to be related to the foaming tendency of the liquid. In addition, in those systems where the exit discontinuity was significant, it depended on the solids properties and the gas and liquid superficial velocities.

The magnitude of the exit discontinuity, expressed as C_t/C_e , decreased with increasing superficial gas velocity in the water and Varsol systems. In trichloroethylene no exit discontinuity was observed. The correlation

$$C_t/C_e = 1 + 0.5(U_g/V_t)^{-0.4}$$

derived by others from measurements in an air/water system, accurately predicted the exit discontinuity in water. Predictions for the other systems were not in agreement with our measurements. The exit discontinuity in Varsol was very much larger, particularly when foaming was not suppressed.

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DISCONTINUITÉ À LA SORTIE DES COLONNES DE BARBOTAGE À BULLES

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RÉSUMÉ

La discontinuité à la sortie des colonnes de barbotage à bulles, i.e., la différence entre la concentration apparente des solides au sommet de la colonne (C_t) et la concentration des effluents (C_e), a fait l'objet d'une étude. À ces fins, on a utilisé une colonne à bulles de 0,3 m ID, de l'air comme phase gazeuse ainsi que de l'eau et une huile d'hydrocarbure légère (Varsol) et du trichloro-éthane comme liquides, et des perles de verre de différentes dimensions et densités comme solides.

Les résultats indiquent que la chute de la concentration des solides se produit dans une petite couche à l'interface gaz/solide. En modifiant la configuration de la sortie de la colonne et en éliminant l'interface gaz/liquide, la discontinuité a disparu. Le degré d'importance de la discontinuité à la sortie dépendait des propriétés du liquide et semblait être relié à la tendance du liquide au moussage. De plus, dans les systèmes où la discontinuité était importante, elle dépendait des propriétés des solides et des vitesses superficielles du gaz et du liquide.

Le degré d'importance de la discontinuité à la sortie, exprimé en C_t/C_e , diminuait en fonction de l'augmentation de la vitesse superficielle du gaz dans les systèmes eau et Varsol. On n'a relevé aucune discontinuité à la sortie dans le trichloro-éthane. La corrélation

$$C_t/C_e = 1 + 0,5(U_g/V_t)^{-0,4}$$

dérivée par d'autres chercheurs au cours de l'analyse d'un système air/eau, prédisait de façon exacte la discontinuité à la sortie dans l'eau. Les prédictions concernant les autres systèmes ne correspondaient pas à nos mesures. La discontinuité à la sortie dans le Varsol était beaucoup plus importante, en particulier quand le moussage n'était pas supprimé.

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INTRODUCTION

Many investigators have successfully used an equation of the form

$$C/C_0 = \exp (-mLx) \quad [1]$$

to describe solids concentration distributions in bubble columns for the batch case, i.e., with no liquid flow (1-5). This equation is the steady state solution of the axial dispersion sedimentation model with no liquid flow where $m = V/E_s$. The concentration along the column is related here to the concentration at the bottom. If one takes the concentration at the top of the column as reference one should use:

$$C/C_t = \exp mL(1-x) \quad [2]$$

The steady state solution of the axial dispersion sedimentation model with liquid flow can be expressed as:

$$C/C_f = [C_0/C_f + U_1'/(V-U_1')] \exp [-(V-U_1')Lx/E_s] - U_1'/(V-U_1') \quad [3]$$

with C_0 as the known boundary value, or if expressed with C_t (3):

$$C/C_f = [C_t/C_f + U_1'/(V-U_1')] \exp [(V-U_1')(L-z)/E_s] - U_1'/(V-U_1') \quad [4]$$

Some investigators have assumed $C_t = C_f$ (2,6) but others state that C_t is not equal to C_f (3,5).

Equations 3 and 4 describe the effect of the liquid velocity on the solids concentration distribution. However, several investigators have found experimentally that the effect of liquid superficial velocity on the solids distribution, i.e., solids mixing is negligible for the low velocities normally employed in bubble columns (2,3). This can be easily understood if one realizes what happens in a bubble column. The main driving force for the mixing in a bubble column is the gas flow. At normal operating values the gas flow sets up liquid circulation cells and the liquid flow due to these circulation cells is an order of magnitude larger than the liquid superficial

velocity. Therefore, a change in the small superficial liquid velocity should have hardly any effect on the solids distribution.

Since the physical reality appears to be very different from the assumptions made in the derivation of the axial dispersion sedimentation model Eq. 1 can be considered a one-parameter empirical correlation that successfully describes the axial solids distributions. Substituting V/E_s for m makes it a two-parameter model, which should be applicable also.

The parameter m was found to be proportional to V_t^a with "a" varying from 0.65 to 1.0 (2-4). Kato et al. (3) and Smith and Ruether (5) used data from continuous flow runs with Eq. 3 and 4 to calculate V and E_s . Very similar results were obtained: E_s was somewhat smaller than the corresponding liquid dispersion coefficient and depended on the particle size (Re_p), column size and gas rate. At the same time both Kato et al. (3) and Smith and Ruether (5) reported very similar particle settling velocities that were greater than the particle terminal settling velocity. On the other hand Kojima et al. (7) used $V = V_t$ and obtained a much larger Pe_p ($U_g D/E_s$), or smaller E_s , than Kato et al. (3), and E_s in this case was significantly smaller than E_1 .

Independent measurements of the settling velocities of different solids in a bubble column showed good agreement with calculated free settling velocities, $V=V_t$ (8). Therefore, it appears, that the (empirical) parameter describing the solids mixing, E_s , can be smaller than the liquid dispersion coefficient in some cases, and separate correlations for the solids dispersion will have to be developed. In any case, after V_t and E_s are calculated one knows m and thus the shape of the solids concentration profile (Eq. 2; C/C_t vs x). If $C_t \neq C_e$ then knowing the exit discontinuity (C_t/C_e) is required to solve for the actual solids concentrations. Smith and Ruether (5) give the relation $C_t = 1.27 C_f$ for the exit discontinuity, whereas Kato et al. (3) give the relation $C_t/C_f = 1 + 0.5 (U_g/V_t)^{-0.4}$ ($C_e = C_f$ for a steady state and C_f is known). Both studies found a negligible effect of liquid velocity on solids mixing. Only Smith and Ruether (5) performed

measurements in a liquid other than water, i.e., ethanol. Both investigators used a column with a gas/liquid interface at the top of the column, i.e., gas left the column at the top, whereas liquid overflowed through the side.

EXPERIMENTAL

A schematic diagram of the glass column (0.30 m diam and 5.26 m long) and accessory equipment is shown in Fig. 1. Slurry feed was mixed with a small amount of gas and entered the column bottom through a central inlet. The remainder of the gas was equally distributed between five peripheral spargers located at the half radial position. For some experiments gas and slurry entered together through a single orifice sparger.

In most experiments slurry effluent was removed through a side outlet at position 11 and fed to a settling tank to remove solids. Clear liquid was recycled to the slurry tank, along with a regulated amount of fresh solids to maintain a constant slurry feed concentration and size distribution. Solids concentrations were measured in the feed, effluent and at 10 axial positions in the column. For some experiments with slurry flow an additional sample port was located 2 cm below the exit. Steady state concentration profiles were measured when the exit concentration was the same as the feed concentration. Materials and experimental conditions are summarized in Tables 1 to 3. Further details can be found in an earlier publication (9). A 0.1 diam glass column was used to investigate the nature of the free interface at the top of the column in water, Varsol and trichloroethylene. Photographs were taken of the interface at 2 gas rates (1.3 and 2.3 cm/s) and 3 liquid rates (0, 0.1 and 0.2 cm/s).

RESULTS

Sparger design was found to have little influence on gas holdup (9) or solids mixing (10).

Solids concentration profiles were plotted versus axial position on a semilogarithmic basis and extrapolated to position 11 to obtain the apparent top concentration, C_t . For the air-water system the solids concentration was measured experimentally 2 cm below the exit and found to be in good agreement with the extrapolated value. However, in most cases C_t was found to be higher than C_e .

Some results from the air-water system are shown in Fig. 2 to 5. Figure 2 shows that when the slurry feed concentration was set close to the extrapolated value of C_t from a batch concentration profile, the concentration profile under continuous liquid and gas flow shifted to higher concentration levels until the exit discontinuity of $C_t/C_e = 1.26$ was satisfied. Note that the slope (m) of the two profiles was identical. Figure 3 shows that the batch solids concentration profile was exactly reproduced by setting the feed solids concentration somewhat lower than the batch value of the top concentration. Figures 2 and 3 also show that the C_t/C_e ratio decreased slightly as the gas velocity was increased.

The magnitude of the exit discontinuities shown in Fig. 2 and 3 indicated that a large solids concentration gradient existed in the 2 cm between the overflow (C_e) and the sample position 2 cm lower.

For two experiments the column exit configuration was changed. In the first, the column was operated in the batch mode and the solids concentration profile extrapolated to position 11; C_t (extr) = 12.4 kg/m³. Then slurry was fed to the column at this concentration and the gas/liquid interface was maintained 0.1 m above the liquid exit (position 11). Figure 4 shows the results. The concentration in the effluent at position 11 was 12.7 kg/m³ whereas 2 cm below the liquid exit it was 12.8 kg/m³ and at position 11 the extrapolated concentration was 12.4 kg/m³.

All three are very similar indicating the absence of an exit discontinuity. Note again the identical slopes of the two experiments indicate that the effect of liquid velocity on solids mixing is negligible.

In the second experiment the side exit was closed and both gas and liquid left at the top of the column. At position 11 the concentration was 13.3 kg/m^3 . The extrapolated concentration at the top of the column was 12.6 kg/m^3 whereas the measured concentration in the effluent was 12.7 kg/m^3 (Fig. 5). Thus, with this exit configuration the exit discontinuity also was absent.

The magnitude of the exit discontinuity, expressed as C_t/C_e , is plotted versus the gas superficial velocity in Fig. 6 for the air-water system. Also shown is the prediction from the relation given by Kato et al. (3), $C_t/C_e = 1 + 0.5(U_g/V_t)^{-0.4}$, for the conditions used in these experiments. Good agreement is observed. Changing the liquid superficial velocity from 0.0012 to 0.0024 m/s (at $U_g = 0.04 \text{ m/s}$) did not result in a change in the exit discontinuity.

Solids concentration profiles were measured in a Varsol/air system with an anti-foam agent added to prevent the formation of foam. The exit discontinuity (C_t/C_e) is plotted versus the gas superficial velocity in Fig. 7. Two bands of data can be distinguished depending on the liquid superficial velocity. A further refinement has been made by drawing a third line through the high density, high liquid flow data which indicates a possible effect of the solids density at the higher liquid flowrate (the low liquid flowrate data show too much scatter to make this distinction). The predictions from the relation of Kato et al. (3) also show the effect of particle density, however, generally the predictions are much too low.

Thus, although the liquid superficial velocity does not influence the solids concentration distribution, i.e., the solids mixing or solids dispersion coefficient, it does appear to influence the solids concentration level by influencing the exit discontinuity. Finally, it should be noted that the exit discontinuity even at the high liquid flow rate is larger than that in the air/water system.

Experiments in the air/Varsol system without anti-foam were carried out by using three sizes of glass beads at only one liquid flowrate of 0.0013 m/s. From Fig. 8, it appears that larger particles exhibit a somewhat larger exit discontinuity. The exit discontinuity in this system is much larger than those in the two previously discussed systems. The relation of Kato et al.(3) again results in values that are much too low.

Figure 9 shows the results of an experiment in which the exit discontinuity has been greatly increased by adding a foaming agent to the Varsol. The upper sections of the column were filled with foam which overflowed the top of the column at a rate equal to the liquid feed rate, however, solids continually accumulated during the run. Three profiles taken at 1-h intervals are shown. The solids concentrations show a dramatic drop in the top four sections of the column. If the solids profile for the lower part of the column is now extrapolated to the top position, exit discontinuities (C_t/C_e) of about 3-4 result.

Several experiments were performed with air/trichloroethylene and solids 2 at gas superficial velocities from 0.10 to 0.19 m/s. This liquid having half the viscosity and twice the density of Varsol exhibited no significant exit discontinuity; $C_t/C_e = 0.97 \pm 0.07$. The gas holdup in this liquid was the lowest of the systems studied (9). The relation of Kato et al. predicts exit discontinuities similar to those for Varsol.

Photographs of the free interface at the top of the column were taken in a 0.1 m diam column (e.g. Fig. 10-12). Fig. 10 and 11 show the distinct difference in appearance of the bulk of the column and of the area close to the interface. It appears that bubbles reaching the interface remain there for a short time resulting in a thin unstable layer with a much higher gas holdup. Since it takes time for the liquid to drain from an exiting bubble and for the bubble to burst, a densely packed stagnant layer of bubbles several bubble diameters thick exists on the surface. In trichloroethylene the layer was very thin or non-existent (Fig. 12). The bubble layer thickness corresponds qualitatively with the measured exit discontinuities, i.e., the layer was thickest in Varsol and almost absent in trichloroethylene. The effect of gas and liquid superficial velocities on the thickness of the bubble layer could not be clearly distinguished for the conditions used.

DISCUSSION

The above results clearly indicate that Eq. 2, which is universally used to describe solids concentration profiles in slurry bubble columns operating in a batch mode, also provides an excellent description of the solids gradient in continuous bubble columns where the superficial liquid velocity is reasonably low. In continuous columns where a free surface exists at the overflow level there is a large change in solids concentration across a thin slurry layer immediately below the free surface. Photographs of the interface at the top of a bubble column revealed that the gas holdup at the interface is much higher than that in the bulk of the column. This discontinuity near the interface may be viewed as an additional resistance to the transport of solids. The large solids gradient observed across this layer is then seen as the driving force required to overcome this resistance and maintain steady state. The magnitude of this resistance and thus of the solids gradient is reflected by the observed exit discontinuity. When liquid is withdrawn below the interface, or when gas and liquid are forced out of the system together, no free interface exists at the liquid exit and the exit discontinuity disappears.

In systems that have a gas/liquid interface at which the gas disengages from the liquid the extent of the exit discontinuity depends on the liquid properties, particularly on the foaming tendencies of the liquid. The stability of a foam layer is related to the bubble stability which depends on the bubble film elasticity (11). Surface elasticity results from surface tension differences between the surface and the bulk (the result of concentration gradients). Note that pure liquids do not foam. The stability of the foam is further affected by the liquid viscosity, the density difference between gas and liquid, and the bubble size. These factors affect the liquid drainage between bubbles (11). They might cause trichloroethylene not to exhibit an exit discontinuity; it is a one component liquid having low viscosity and high density. On the other hand, Varsol is a multi-component liquid having a higher viscosity and a lower density.

For a given system the exit discontinuity also depends on the particle properties and gas and liquid superficial velocities. However, the variation of the exit discontinuity with these variables appears to be larger for systems in which the exit discontinuity is large.

The relation given by Kato et al. (3) to predict the exit discontinuity was derived solely from measurements in an air/water/glass beads system. Its predictions agree with our measurements in water. However, the predictions for the other systems differ significantly from our measured values.

The above results show that in order to predict the solids concentration levels in bubble columns one needs to know: the parameter describing the extent of mixing in the column (m parameter or E_s) which can be determined from batch studies, and the exit discontinuity (C_t/C_e).

A correlation for m is currently being developed. Knowledge of m only will allow prediction of the shape of the solids concentration profile, but to predict absolute levels knowledge of the exit discontinuity is also required. This discontinuity depends on liquid and solid properties on which further study is required.

NOTATION

- C = concentration of solid particles in slurry, kg/m^3
- C_0 = concentration of solid particles in slurry at $z = 0$, kg/m^3
- C_e = concentration of solid particles in effluent, kg/m^3
- C_f = concentration of solid particles in feed, kg/m^3
- C_t = concentration of solid particles in slurry at $z = L$, kg/m^3
- d = particle diameter, m
- D = column diameter, m
- E_l = liquid dispersion coefficient based on liquid, m^2/s
- E_s = solids dispersion coefficient based on slurry, m^2/s
- L = column length, m
- m = parameter defined in eq 1, 2 and 5
- Pe_p = $U_g D / E_s$, Peclet number
- Re_p = $d V_t / \nu$, Reynolds number
- U_g = superficial gas velocity, m/s
- U_l = superficial liquid velocity, m/s
- U_l' = actual mean velocity of slurry = $U_l / (1 - \epsilon_g)$, m/s
- V = mean particle settling velocity, m/s
- V_t = terminal settling velocity of single average sized particle, m/s
- x = z/L , dimensionless column height
- z = axial height from the bottom of the column, m
-
- ϵ_g = gas holdup, fraction
- ν = kinematic viscosity, m^2/s

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Table 1 - Properties of liquids used in 0.30 m diam bubble column at 25°C

	Water*	Varsol**	Trichlorethylene***
Liquid density, kg/m ³	997	788	1452
Liquid viscosity, Pa.s x 10 ³	0.890	1.236	0.552
Vapour pressure, kPa	3.17	0.5 at 38°C	10.00
Surface tension, N/m	0.0720	0.0283	0.029 at 30°C

* Deionized

** Esso Chemicals Varsol Solvent DX 3641, low aromatics 185-209°C B.P.

*** Canada Colours and Chemicals Ltd., Neu-Tri Trichloroethylene (Dow Chemical Co.)

Table 2 - Properties of solids used in 0.3 m diameter bubble column

Solids	1	2	3	4	5	6
Solids density, kg/m ³	2450	2450	2450	2450	4470	2450
Particle diam ave, μm	58	71	91	122	75.5	66
Particle diam range, μm	-45-75	45-106	68-150	63-150	-45-106	-45-75
Particle diam range*, mesh	170-325	170-230	140-170	120-140	170-230	140/270
Terminal settling velocity, m/s						
Water, 25°C	0.00300	0.00443	0.00690	0.01119	0.01103	0.00394
Varsol, 25°C	0.00247	0.00369	0.00599	0.01009	0.00901	0.00325
Trichloroethylene, 25°C	0.00322	0.00456	0.00684	0.01085	0.01328	0.00409

* Designation of manufacturer

Table 3 - Experimental conditions

Liquid	U_g m/s	U_l m/s x 10 ²	Solids no
Water	0.04-0.2	0.0-0.24	1
Varsol	0.04-0.2	0.13	2, 3, 4
Varsol (anti-foam)	0.04-0.2	0.13-0.24	2, 5
Varsol (foamer)	0.07	0.12	6
Trichloroethylene	0.10-0.19	0.13-0.19	2

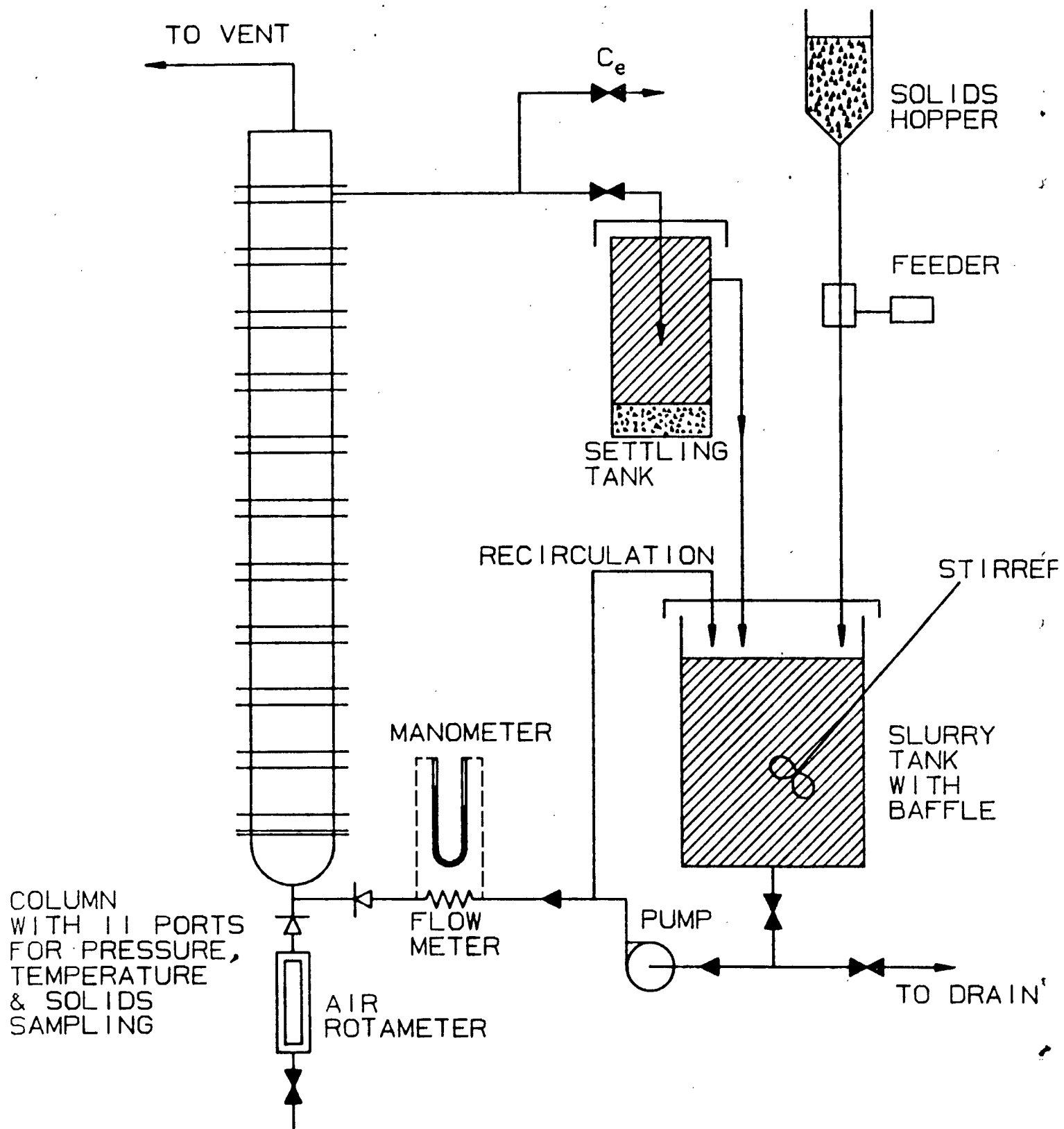


Fig. 1 - Schematic of experimental apparatus

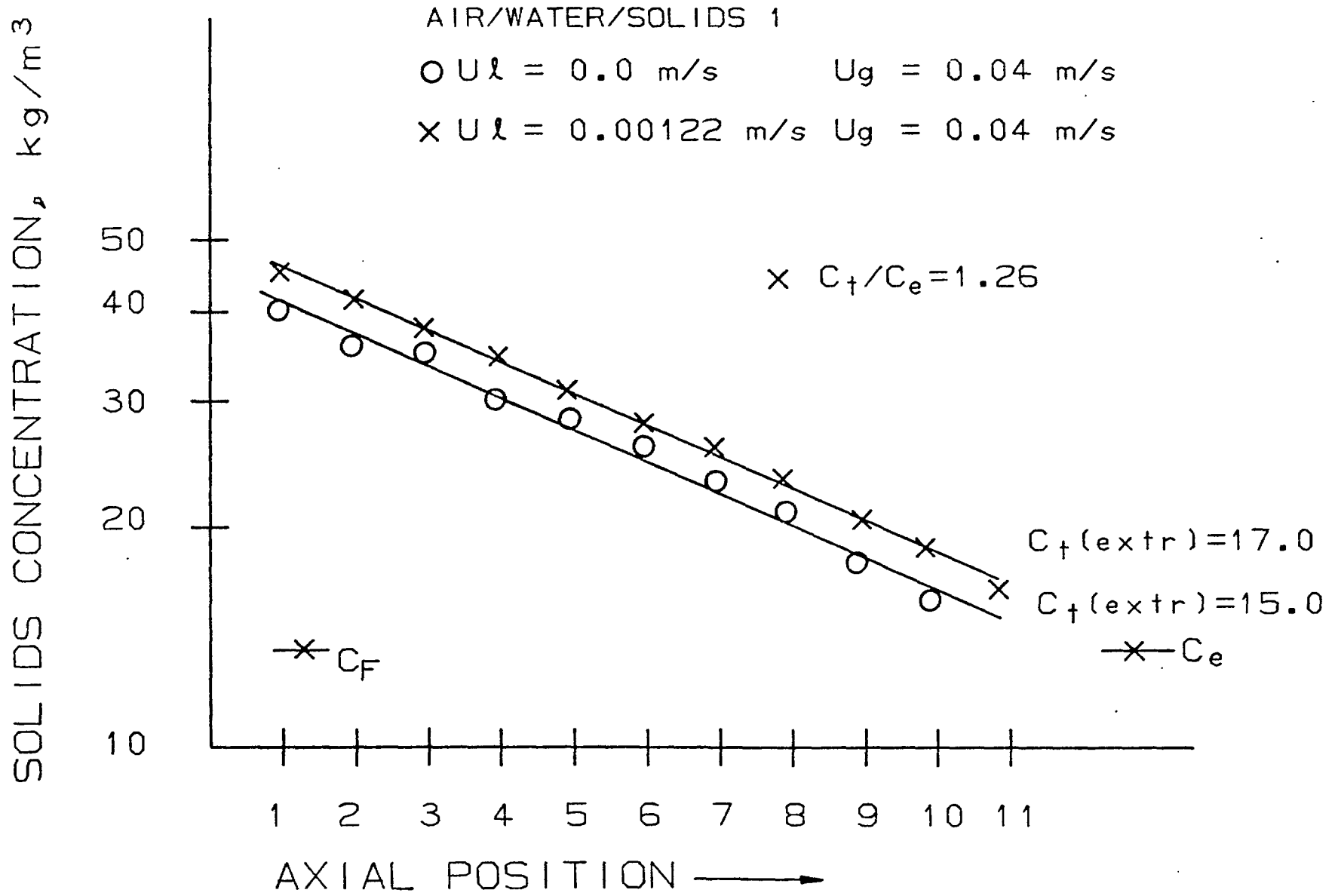


Fig. 2 - Effect of exit discontinuity

SOLIDS CONCENTRATION, kg/m^3

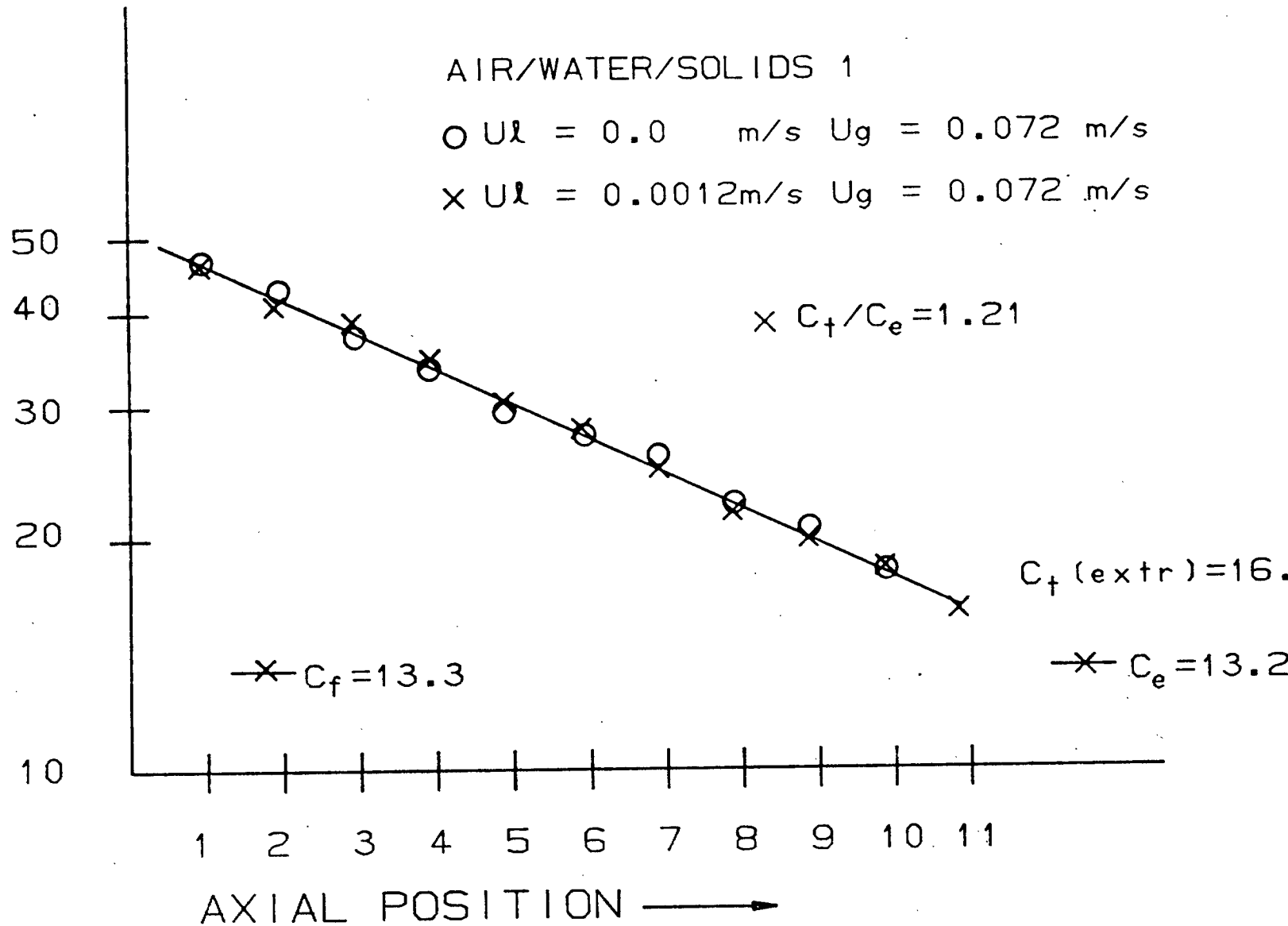


Fig. 3-- Reproduction of batch profile by feeding lower solids concentration

SOLIDS CONCENTRATION, kg/m^3

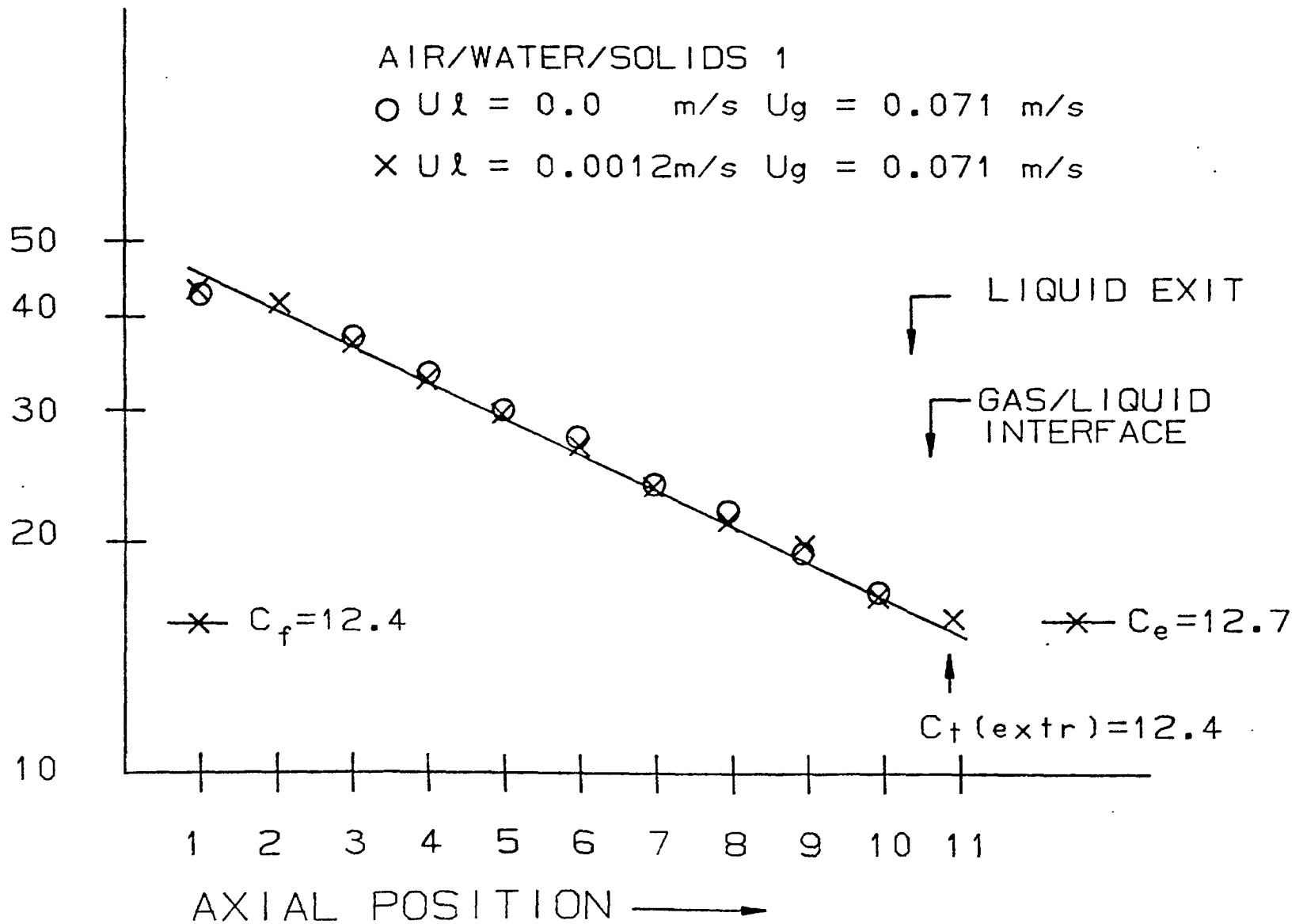


Fig. 4. Solids concentration profile with liquid exit below gas/liquid interface

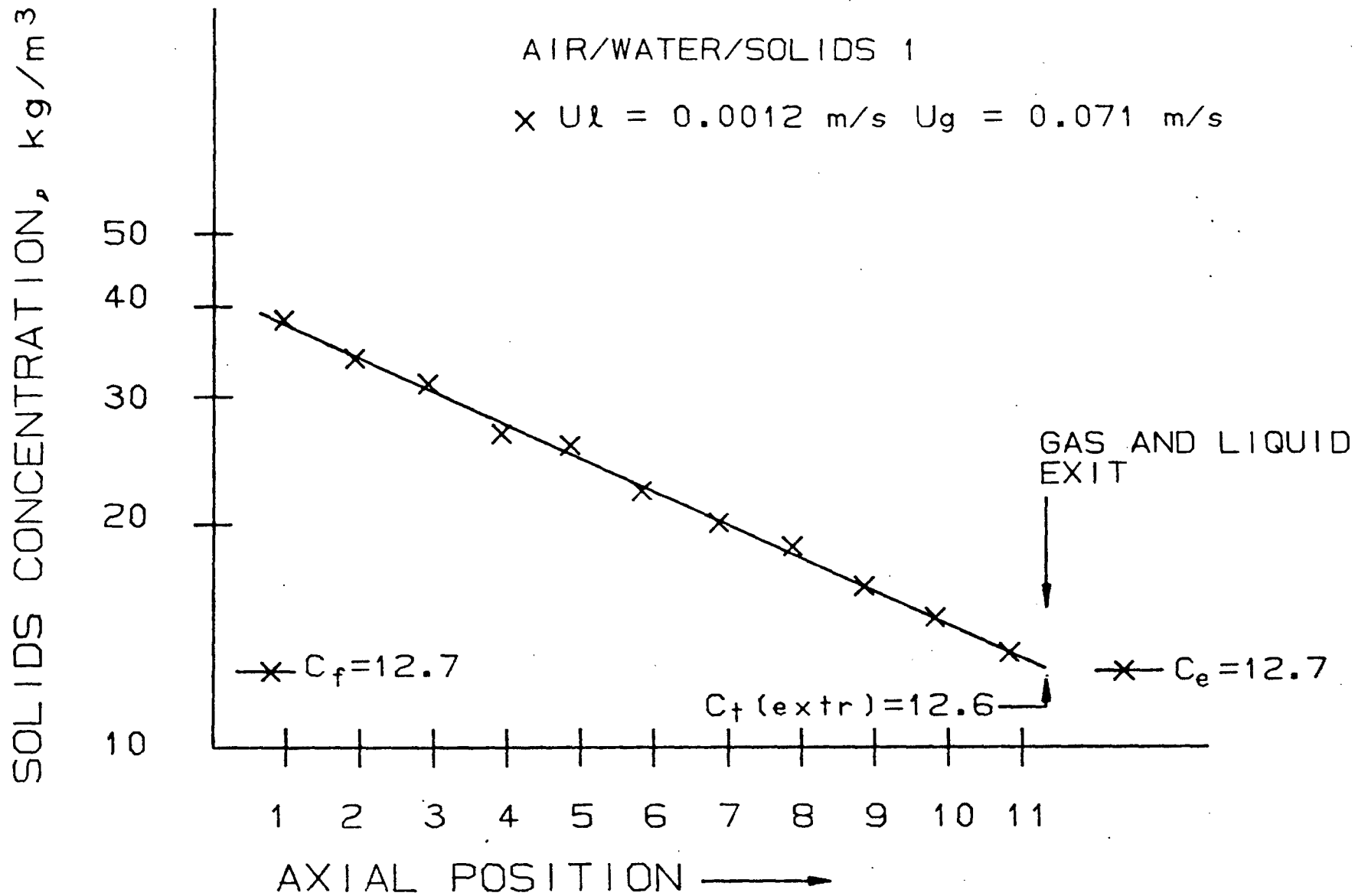


Fig. 5 - Solids concentration profile with gas and liquid exit both at the top of the column

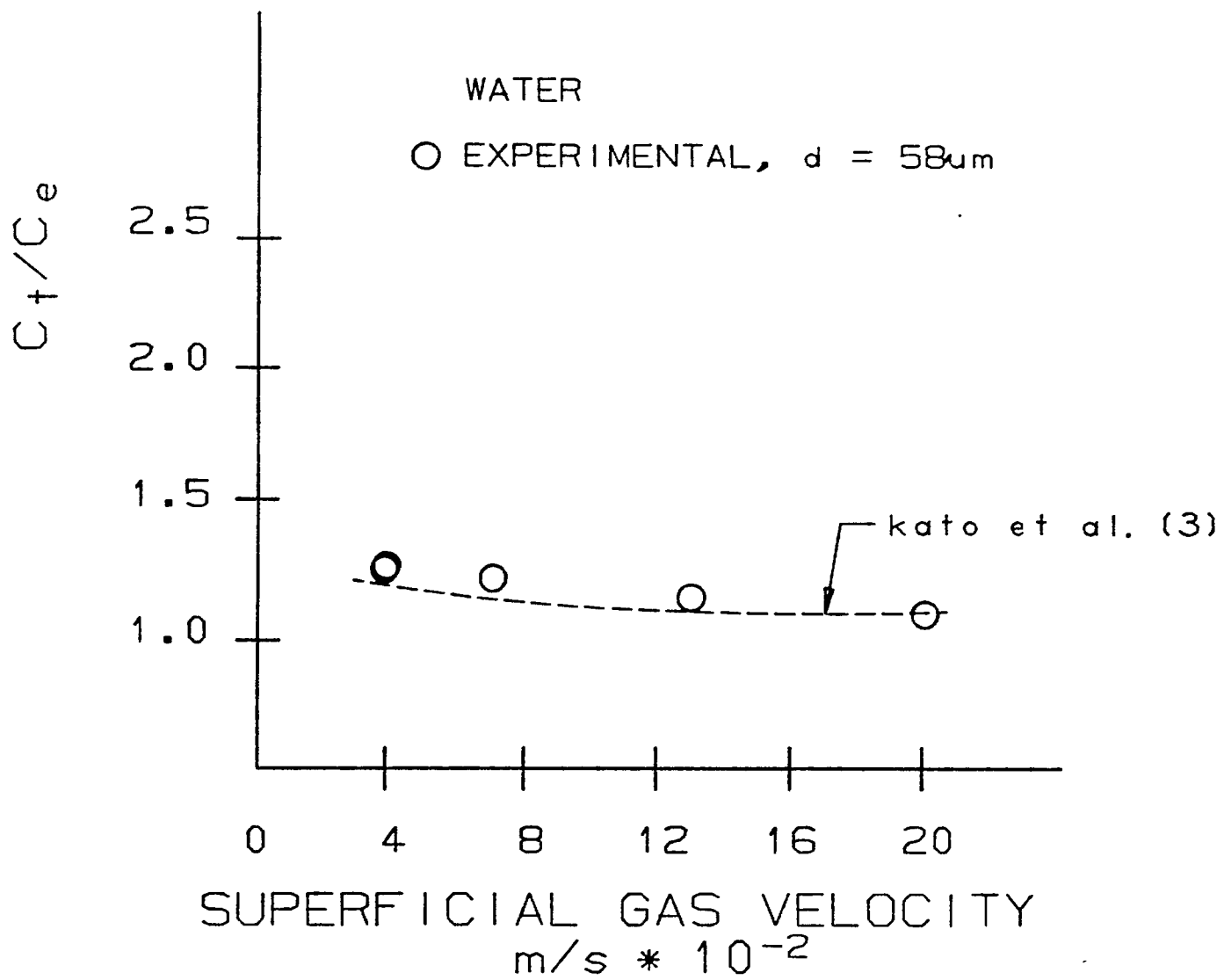


Fig. 6. - Exit discontinuity (C_t/C_e) vs superficial gas velocity for water

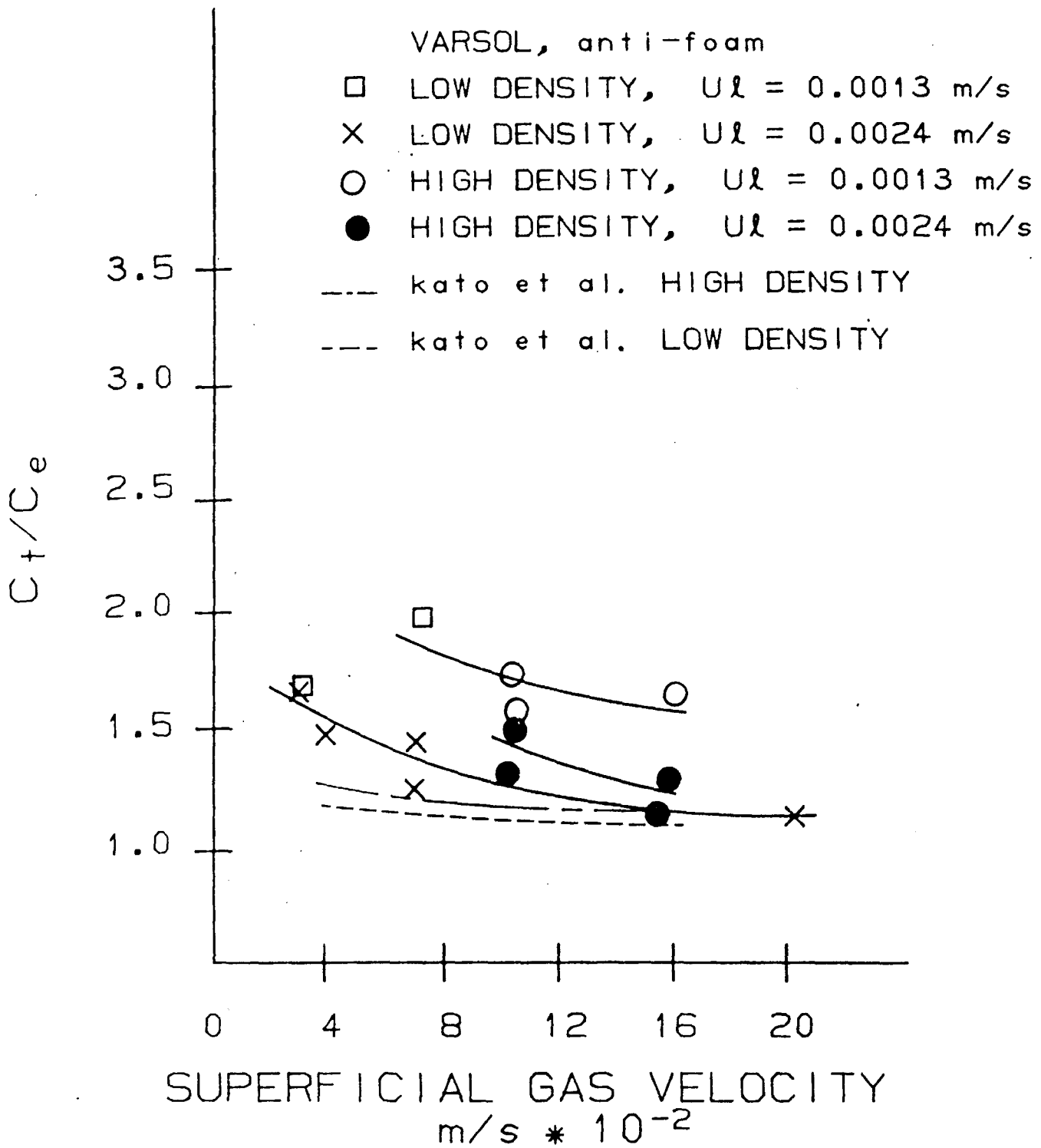


Fig. 7 - Exit discontinuity (C_t/C_e) vs. superficial gas velocity for Varsol with anti-foam

VAR SOL

X $d = 71\mu\text{m}$, $U_l = 0.0013 \text{ m/s}$

□ $d = 91\mu\text{m}$, $U_l = 0.0013 \text{ m/s}$

○ $d = 122\mu\text{m}$, $U_l = 0.0013 \text{ m/s}$

--- kato et al., $d = 122\mu\text{m}$

--- kato et al., $d = 71\mu\text{m}$

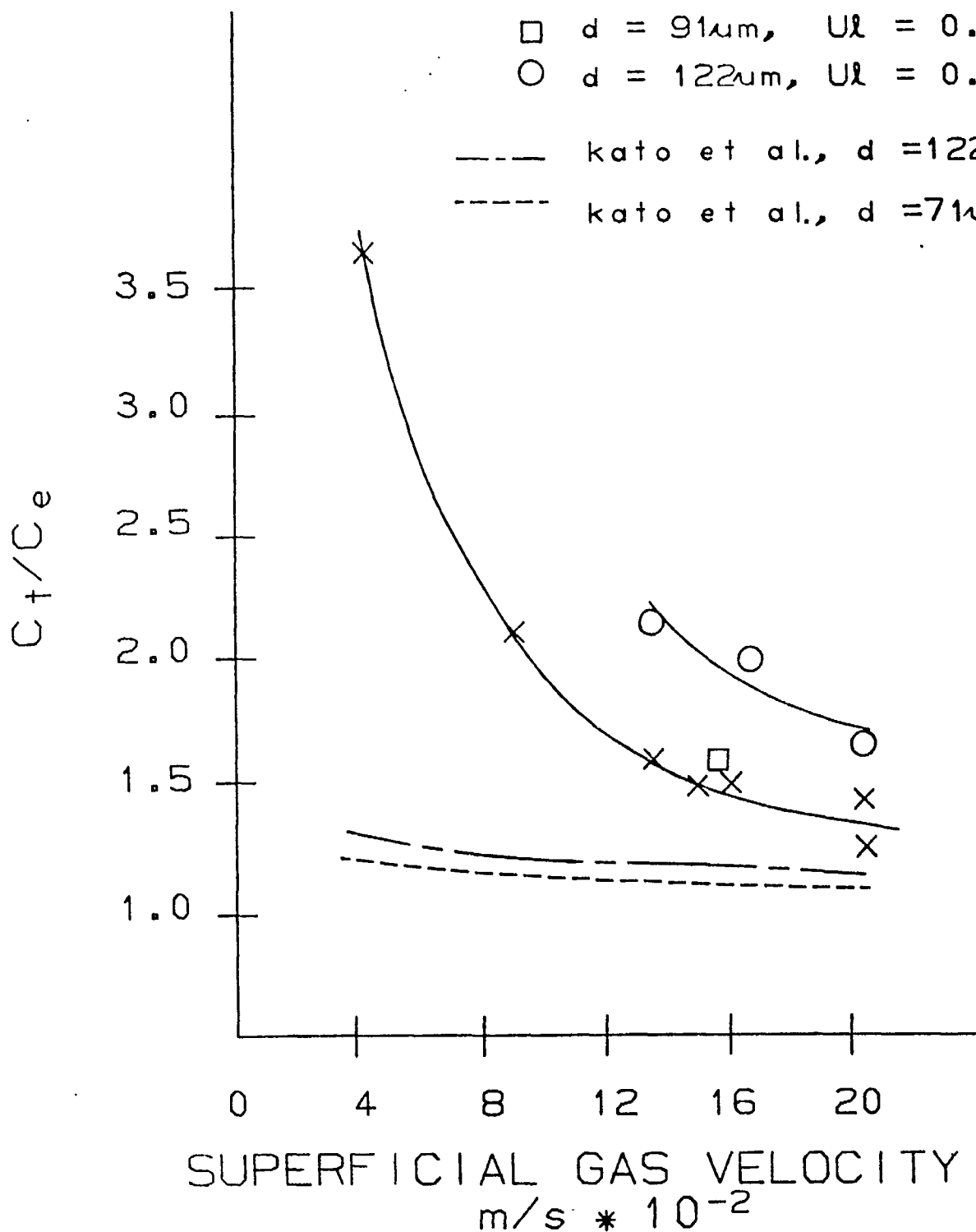


Fig. 8 - Exit discontinuity (C_t/C_e) vs. superficial gas velocity for Varsol without anti-foam

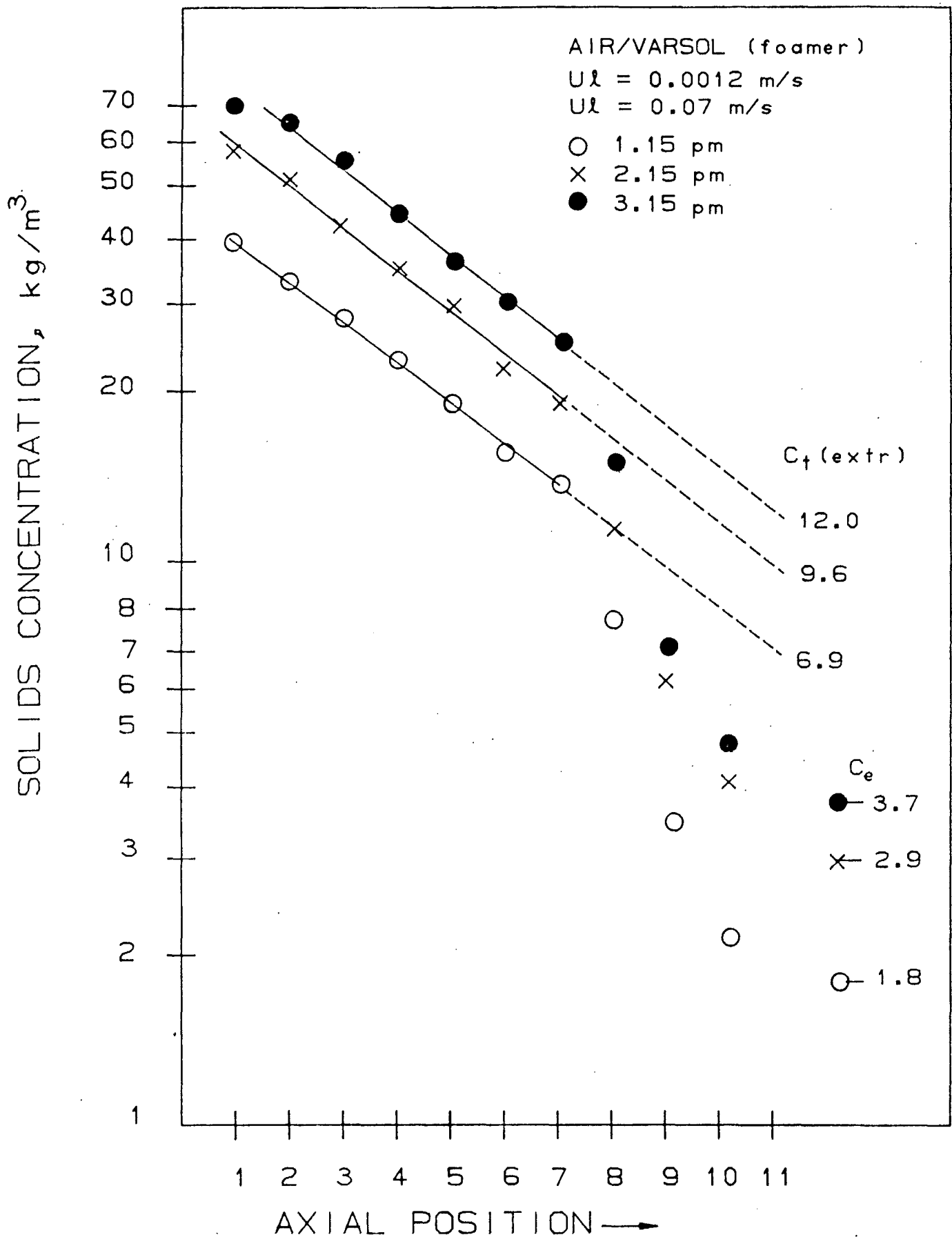


Fig. 9 - Solids concentration profile in Varsol with foamer

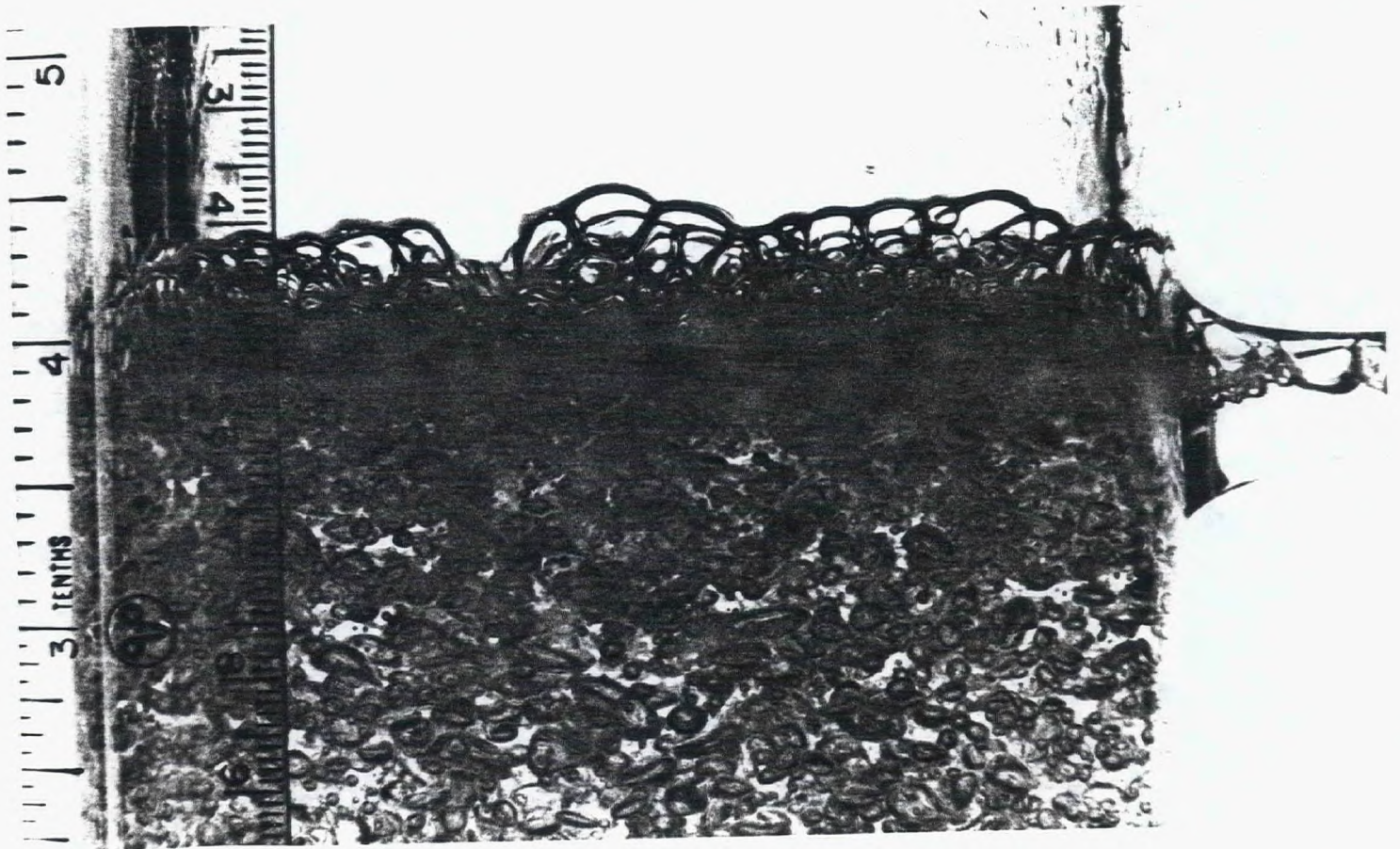


Fig. 10 - Free interface in Varsol at $U_g = 0.023$ m/s and $U_l = 0.001$ m/s



Fig. 11 - Free interface in water at $U_g = 0.023$ m/s and $U_l = 0.001$ m/s

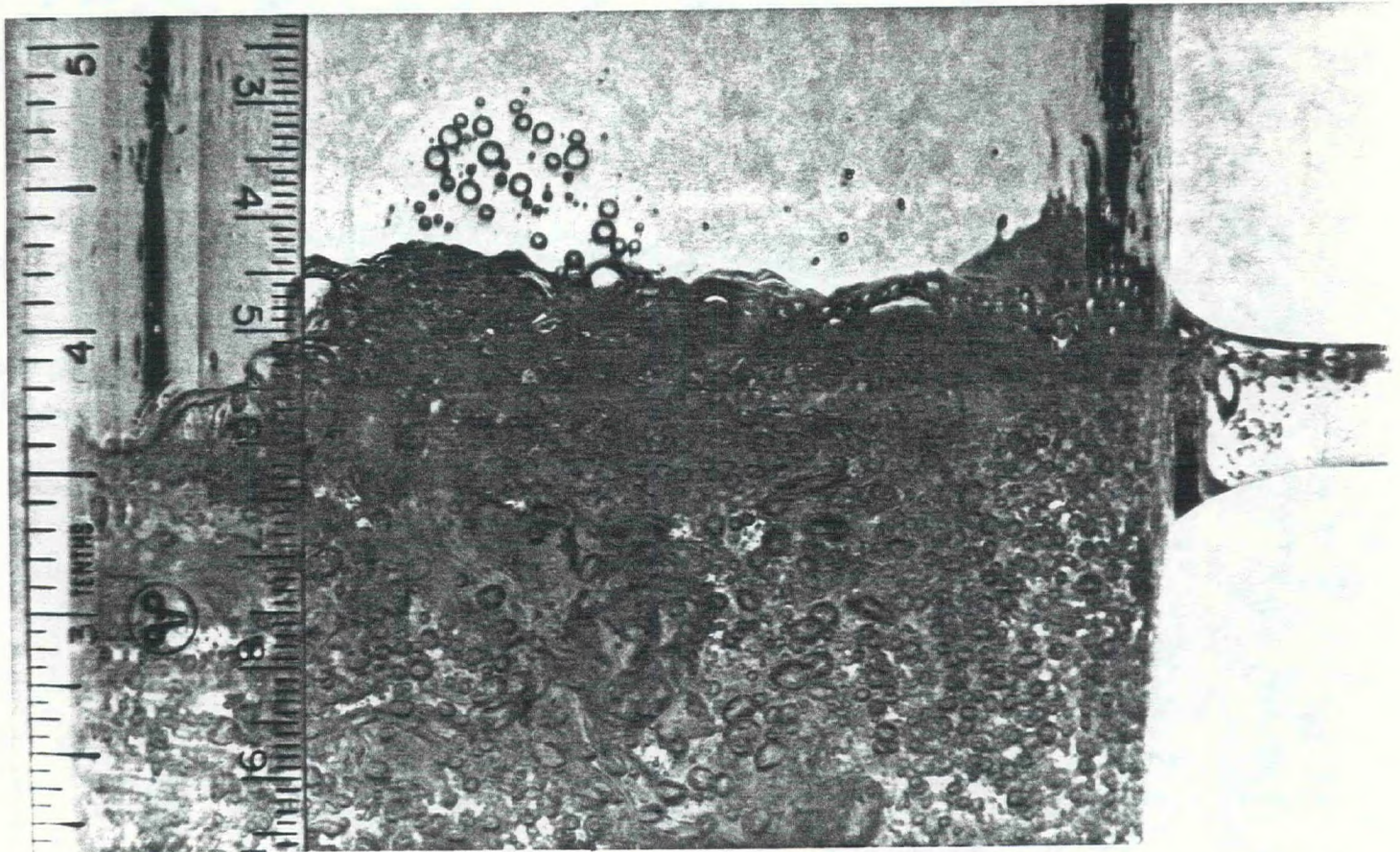


Fig. 12 - Free interface in trichloroethylene at $U_g = 0.023$ m/s and $U_l = 0.001$ m/s