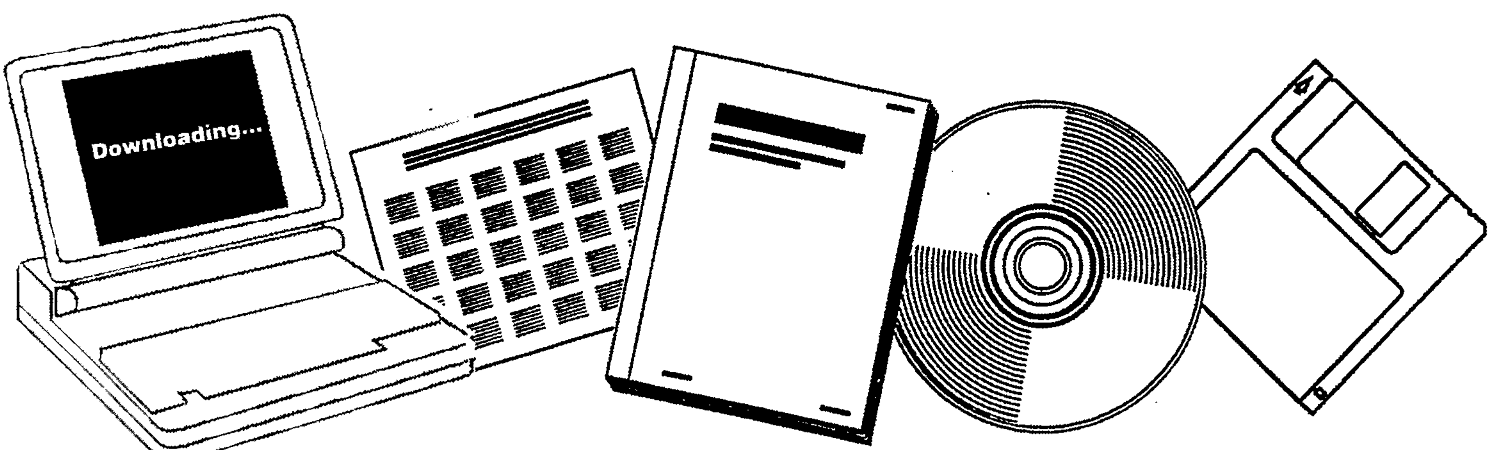
DETERMINATION OF OPERATING PARAMETERS AND DISSOLVED OXYGEN CONCENTRATION PROFILE IN A TAPERED, FLUIDIZED BED

MASSACHUSETTS INST. OF TECH., OAK RIDGE, TENN. SCHOOL OF CHEMICAL ENGINEERING PRACTICE

19 MAY 1977



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SUBJECT: Determination of Operating Parameters and Dissolved Oxygen Concentration Profile in a Tapered, Fluidized Bed

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ABSTRACT

Minimum and maximum operating flowrates, axial holdups, pressure and dissolved oxygen profiles were determined for a 4.5 m, 273 liter, tapered, fluidized bed. Coal particles, totaling 36, 50, 75 and 110 kg were fluidized with nitrogen and water. The solid and gas holdup profile was most uniform at the minimum liquid flowrate and a liquid to gas flowrate ratio of ten. Oxygen mass transfer, calculated for the 36 kg loading only, was greatest at the minimum gas and liquid flowrate with an overall mass transfer coefficient of $\sim$0.08 min^{-1}.

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Contents

1.0 SUMMARY

Operating parameters for a 273 liter, tapered, fluidized bed were obtained for 36, 50, 75 and 110 kg of coal particles fluidized with nitrogen and water. The parameters included the minimum and maximum operating flowrates, the axial and radial pressure and dissolved oxygen profile and the axial volume fraction (holdup) profile. The minimum operating flowrate was independent of coal loading and the solids holdup decreased with height for the two phase, water-coal system. The solids holdup was constant with height in the three-phase system at liquid-to-gas flowrate ratios of approximately ten. Oxygen profiles were obtained at four flowrates for the 36-kg loading. Oxygen transfer from the water to the nitrogen was greatest at the lowest gas and liquid flowrates (5.6 and 13.1 ℓ/min) with an overall mass transfer coefficient of ~0.08 min^{-1}. No radial oxygen of pressure variation could be detected at any axial position.

It is recommended that oxygen mass transfer be investigated at liquid-to-gas flowrate ratios less than one for several bed loadings. Decreasing the inlet bubble size and installing redistributor plates within the column are also suggested to improve the mass transfer.

2. INTRODUCTION

2.1 Background

A tapered, cocurrent, fluidized bed has advantages as a reactor vessel for biological processes. Fluidization prevents biomass from plugging the reactor, and the increase in column cross sectional area with height reduces the superficial velocity and therefore instabilities such as slugging. In previous studies, degradation of phenol and nitrates and gas-liquid mass transfer as a function of flow rates, particle size and solids loading, have been studied with a bench-scale, tapered, fluidized bed (10, 11). A 273-liter, tapered, fluidized bed reactor has recently been installed at the Chemical Technology Division of ORNL to investigate scale-up parameters associated with these processes.

Basic operating parameters for this reactor such as the minimum fluidization velocity, maximum fluid flow rates, phase volume fractions (holdups) and oxygen and pressure profiles along the bed are needed as a function of solids loading and liquid-gas flow rates prior to starting up the reaction.

The minimum fluidization velocity is the lowest liquid and gas superficial velocity necessary to fluidize the bed, and the maximum operating velocity is defined as the superficial velocities that will place the height of the fluidized bed at the top of the column. This velocity is less than terminal velocity or maximum fluidization velocity. The phase holdups or volume fractions are the relative amounts of solid, liquid, and gas in a given volume. Since the microorganisms grow on the solid phase (coal particles), the solids holdup is a measure of the amount of biomass per unit volume. Thus, the phase holdups are needed to predict optimum coal loadings and nutrient and oxygen concentrations in the inlet streams. The pressure profile is used to calculate the bed height and the volume fraction profiles.

For this investigation, coal particles (-30 to +60 mesh) were fluidized with water and nitrogen. Since the inlet water was saturated with oxygen, the oxygen mass transfer was from the liquid to the gas. When operating as a bioreactor, the oxygen transfer will be from the gas to the liquid.

2.2 Objectives

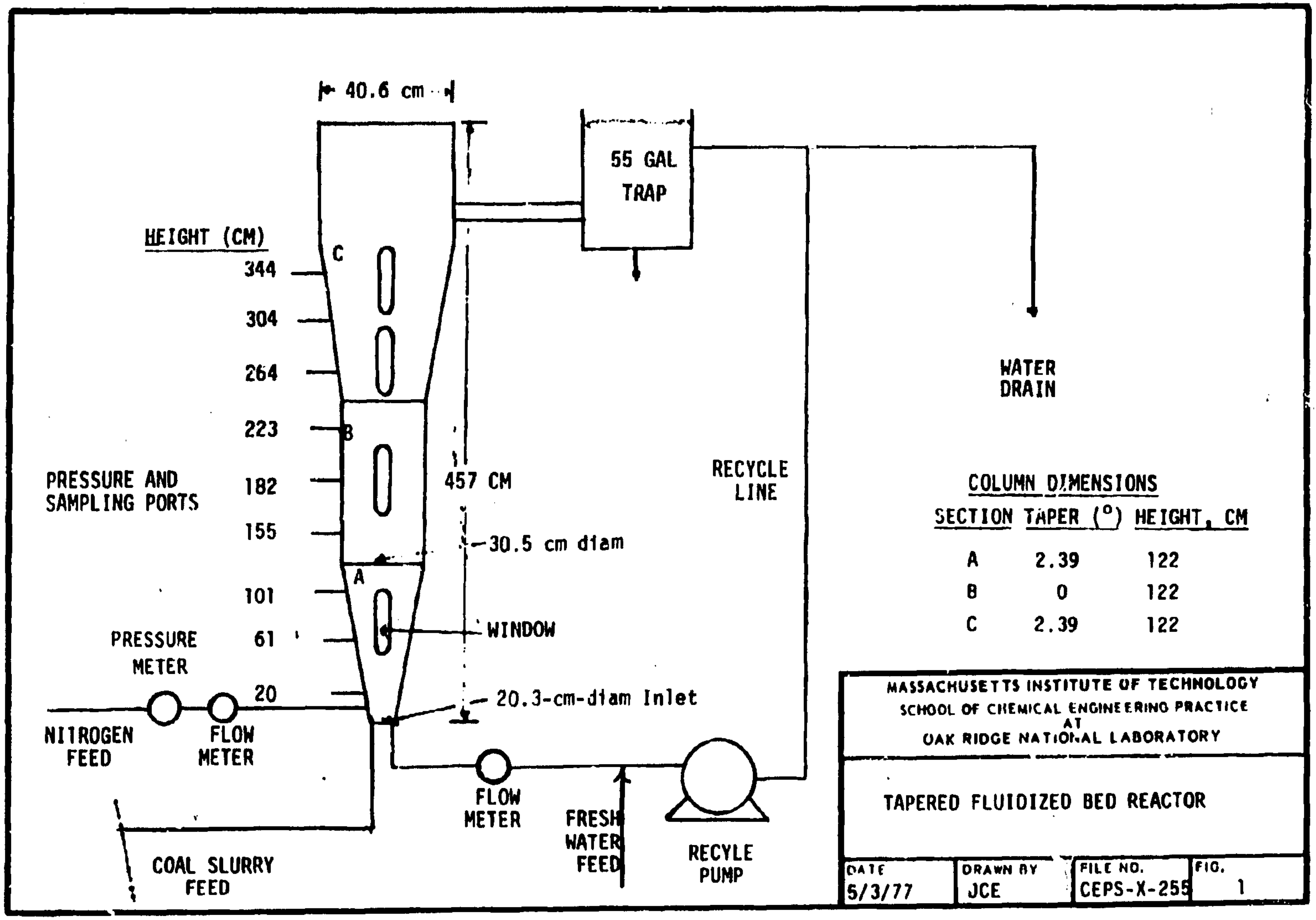
The objectives were to determine: (1) maximum and minimum operating liquid and gas flow rates as a function of solids loading, (2) axial and radial pressure and oxygen concentration variation through the reactor, (3) axial phase holdup variation, and (4) estimation of the gas-liquid mass transfer coefficient.

2.3 Method of Attack

Minimum fluidization and maximum operating velocity for the two-phase, solid-liquid system were determined at coal loadings of 36, 50, 75, and 110 kg. Gas and liquid flow rates that fluidized the bed near intermediate and minimum fluidization levels were also determined at these loadings. Oxygen concentrations and pressure were determined with probes inserted into nine ports along the column and samples of the bed composition were also obtained from these ports to determine the phase holdups. A summary of the operating conditions for each experiment is presented in Table 1 of Section 3.

3. APPARATUS AND PROCEDURE

As shown in Fig. 1, the 4.57-m (15-ft) column consists of two 1.22 m, tapered sections separated by a straight section of equal length. A top section and the adjacent 0.21 m^3 (55-gal) drum allows entrained solids to



COLUMN DIMENSIONS

SECTION	TAPER (°)	HEIGHT, CM
A	2.39	122
B	0	122
C	2.39	122

settle. A recycle pump supplements the inlet water flow rate. However, the fresh water feed was used for all flow rates below 76 liter/min. Nitrogen flow rates were measured with an orifice meter.

The axial pressure profile was measured by connecting nine manometers to the ports on the side of the column. A tube, with several small holes near its end, could be inserted into the column through the ports to measure the radial variation in pressure. The oxygen concentration was obtained by attaching a 40 ml-chamber containing a YSI dissolved oxygen probe to this tube. Water flow through the sample chamber was controlled with a valve so that a constant residence time could be maintained for different positions along the column.

To determine the volume fractions, 500 ml of coal slurry was taken from each sample port. The sample was weighed then dried to determine the mass of the coal particles. The dried coal was then mixed with a known volume of water and the final volume of the coal-water slurry was measured to determine the density of the coal. With this density and the density of water, the solid and liquid volume fractions for the sample were calculated from the initial sample weight. It was necessary to determine the coal density at each port since there was an apparent stratification of coal particle size with bed height. It was assumed that the ratio of solid-to-liquid volume fraction in the bed was the same as that in the sample. The volume fractions in the bed were then determined with this ratio and the pressure drop across that section of the bed. Details of the calculation are presented in Appendix 9.1.

Minimum fluidization velocities were obtained by monitoring the pressure drop through the bed as the gas and liquid flow was increased, until the pressure difference between the bottom and top pressure tap was constant. The maximum operating flow rates were determined by adjusting the liquid and gas flow rate until the bed could be seen in the top window. Liquid and gas flowrates and the fluidized bed height for all experiments are presented in Table 1.

At high gas velocities, entrainment of solids beomces a problem. A centrifugal pump was connected to the bottom of the collection drum to recycle solids back to the column.

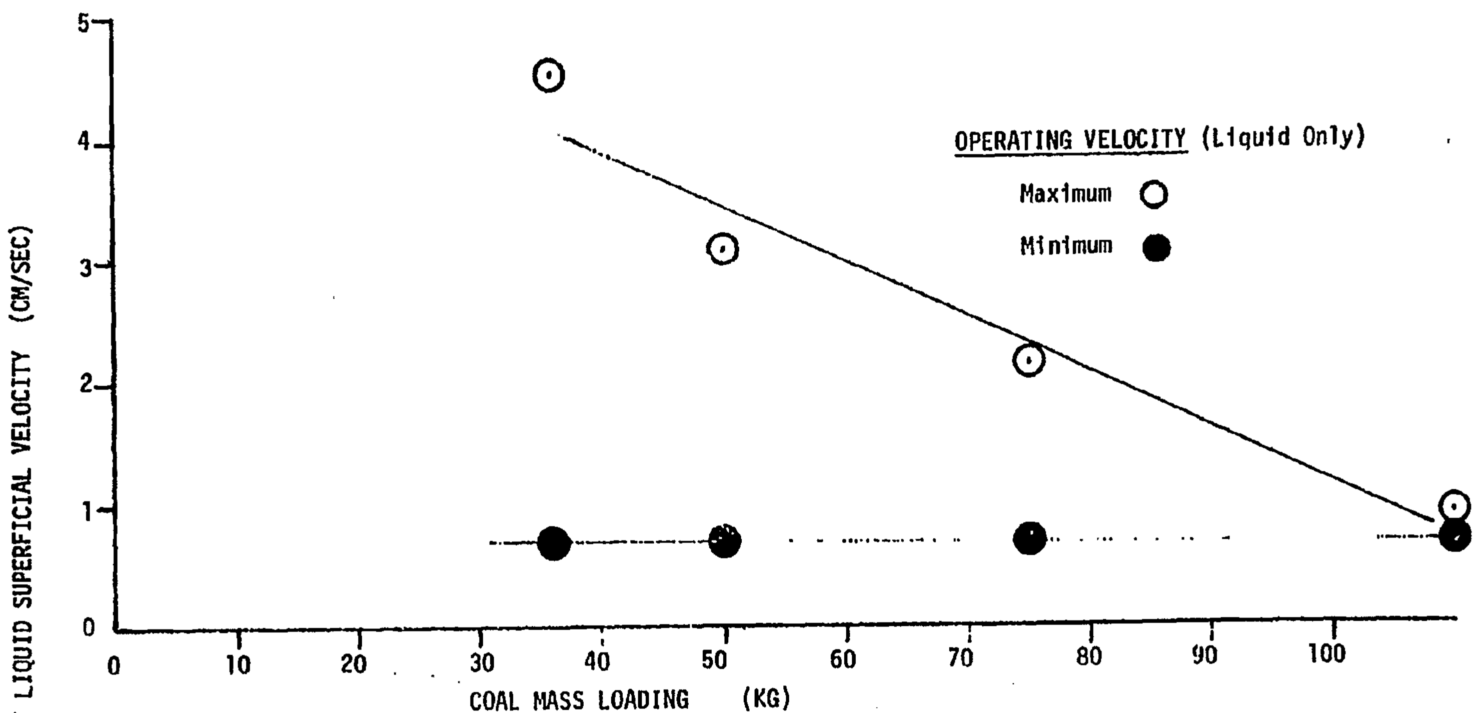
4. RESULTS AND DISCUSSION OF EXPERIMENTAL CONDITIONS

4.1 Minimum and Maximum Operating Conditions

In Fig. 2 the maximum and minimum liquid superficial operating velocity (no gas flow) is plotted against coal loading. The velocity is calculated from the liquid flowrate and in the cross-sectional area at the bottom of the reactor. The minimum operating velocity is seen to be independent of

TABLE I: OPERATING CONDITIONS FOR EXPERIMENTS

Solids Loading, M_S (Kg)	Flow Rates (ℓ/min)		Bed Height (cm)		Degree of Fluidization Hb/Hbs	Axial Profiles Obtained	
	L	G	Static, Hbs	Fluidized, Hb		O_2	ϵ_s
36	13.6	0	104	140	1.3	X	X
	52.3	0		270	2.6	X	X
	60.7	0		330	3.2	✓	✓
	88.4	0		360	3.5	X	X
	13.1	5.6		141	1.3	✓	X
	48.3	5.6		217	2.1	✓	✓
	62.1	8.2		280	2.7	✓	X
50	13.8	0	132	181	1.4	X	✓
	60.5	0		339	2.6	X	✓
	20.6	20.2		231	1.8	X	✓
	54.5	5.4		289	2.2	X	✓
75	13.7	0	182	213	1.2	X	✓
	28.7	0		291	1.6	X	✓
	42.2	0		335	1.8	X	✓
	13.4	1.4		230	1.3	X	✓
	12.3	3.2		234	1.3	X	✓
	31.9	3.2		319	1.8	X	✓
110	13.9	0	242	305	1.3	X	✓
	14.7	0		309	1.3	X	✓
	18.1	0		321	1.3	X	✓
	10.0	11.1		279	1.2	X	✓
	13.8	6.7		292	1.2	X	✓
	14.6	11.0		289	1.2	X	✓



INLET AREA = 314.2 cm^2
NO GAS FLOW

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MINIMUM AND MAXIMUM OPERATING VELOCITIES AS A FUNCTION OF MASS LOADING

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coal loading as is expected, since this velocity corresponds to the minimum fluidization velocity which is independent of the number of particles according to Wen and Yu (12). The maximum operating velocity, defined as the liquid flow rate at which the solid bed was at the top of the column, shows a decrease with increasing coal loading. The maximum operating velocity does not correspond to the terminal velocity, or the liquid velocity at which the particles leave the bed. The maximum operating velocity decreases with increasing coal loading since there are a larger number of particles in the bed as the solids loading increases.

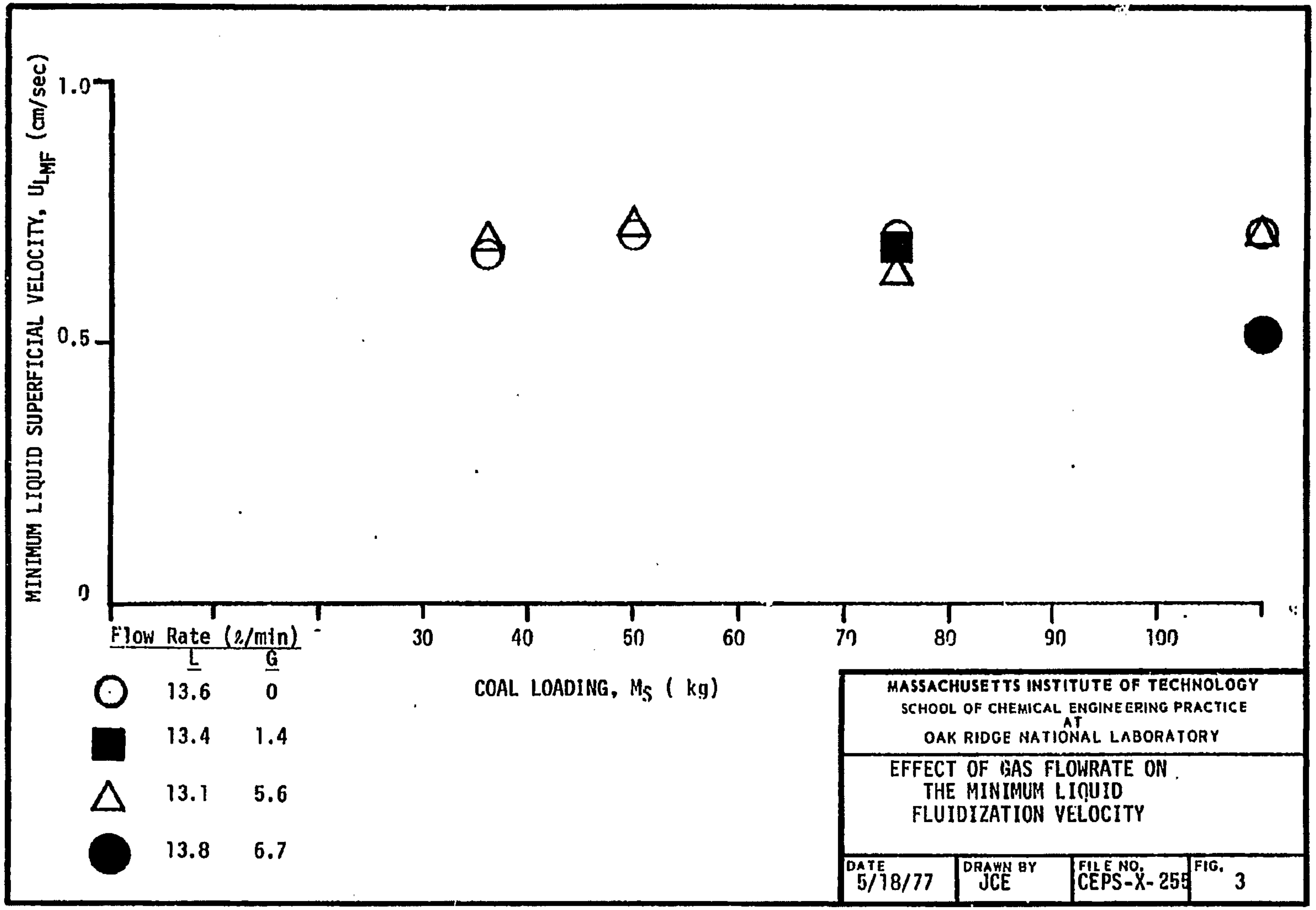
The effect of gas flowrate on the minimum liquid fluidization velocity is presented in Fig. 3. Unfortunately, the influence of the gas flowrate at liquid flowrates much less than the minimum liquid fluidization rates (Fig. 2) was not determined. Thus the data in Fig. 3 only indicate the solids are chiefly fluidized by the liquid flowrate.

4.2 Pressure Profiles

The pressure drop across the bed increases until the fluid velocity is sufficient to suspend the particles. At this minimum fluidization point, the pressure drop across the bed is equal to the weight of the suspended particles. In Fig. 4 the pressure at each port minus its static bed pressure is plotted against column height at minimum fluidization for the four coal loadings. For each loading there is a distinct change in slope in the axial pressure profile. This change in slope corresponds to the solid bed height. The bed height at minimum fluidization increases with coal loading. This is expected since the static bed height also increases with coal loading.

At constant solids loading and no gas flow, increasing the liquid flow rate produces the pressure profile shown in Fig. 5. Once again, the change in slope of the profile corresponds to the height of the bed. Ideally, the pressure above the solid bed should be the same for all flow rates. However, limitations in the column draining capacity caused the water level above the bed to rise slightly with liquid flow rate.

The radial pressure variation at a constant liquid and gas flow rate and coal loading is shown in Fig. 6. The radial pressure readings are plotted against reduced radius (radial distance from center divided by the column radius at that height). Readings were taken with the probe at the bottom two ports (20 and 61 cm) and the port at the top of the middle section (223 cm). The vertical bars through the points represent the oscillation of the manometer reading during measurement. There was no measurable radial pressure variation at any of the probe positions.



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EFFECT OF GAS FLOWRATE ON THE MINIMUM LIQUID FLUIDIZATION VELOCITY

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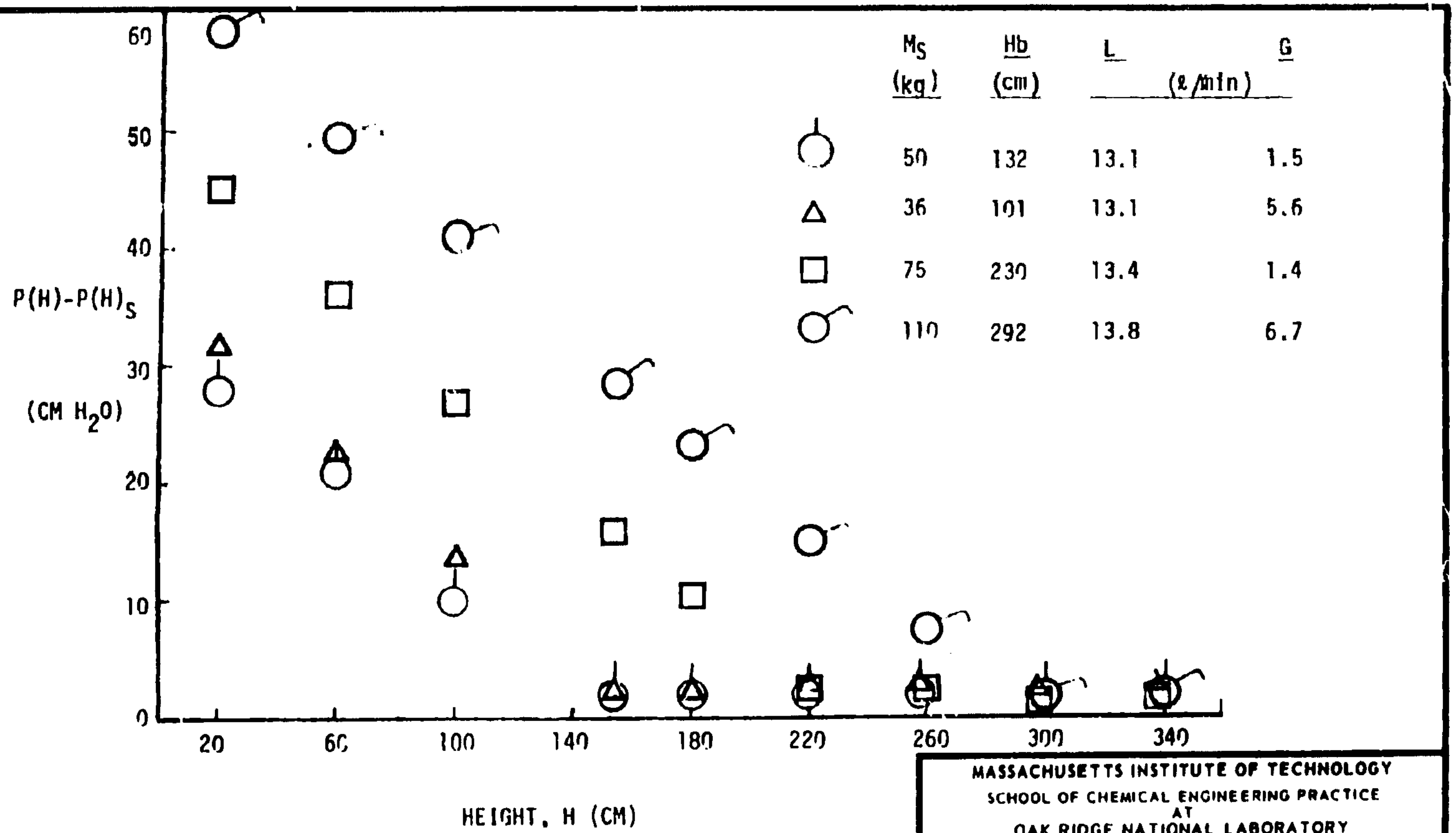

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AXIAL PRESSURE GRADIENT
AT MINIMUM FLUIDIZATION

DATE	DRAWN BY	FILE NO.	FIG.
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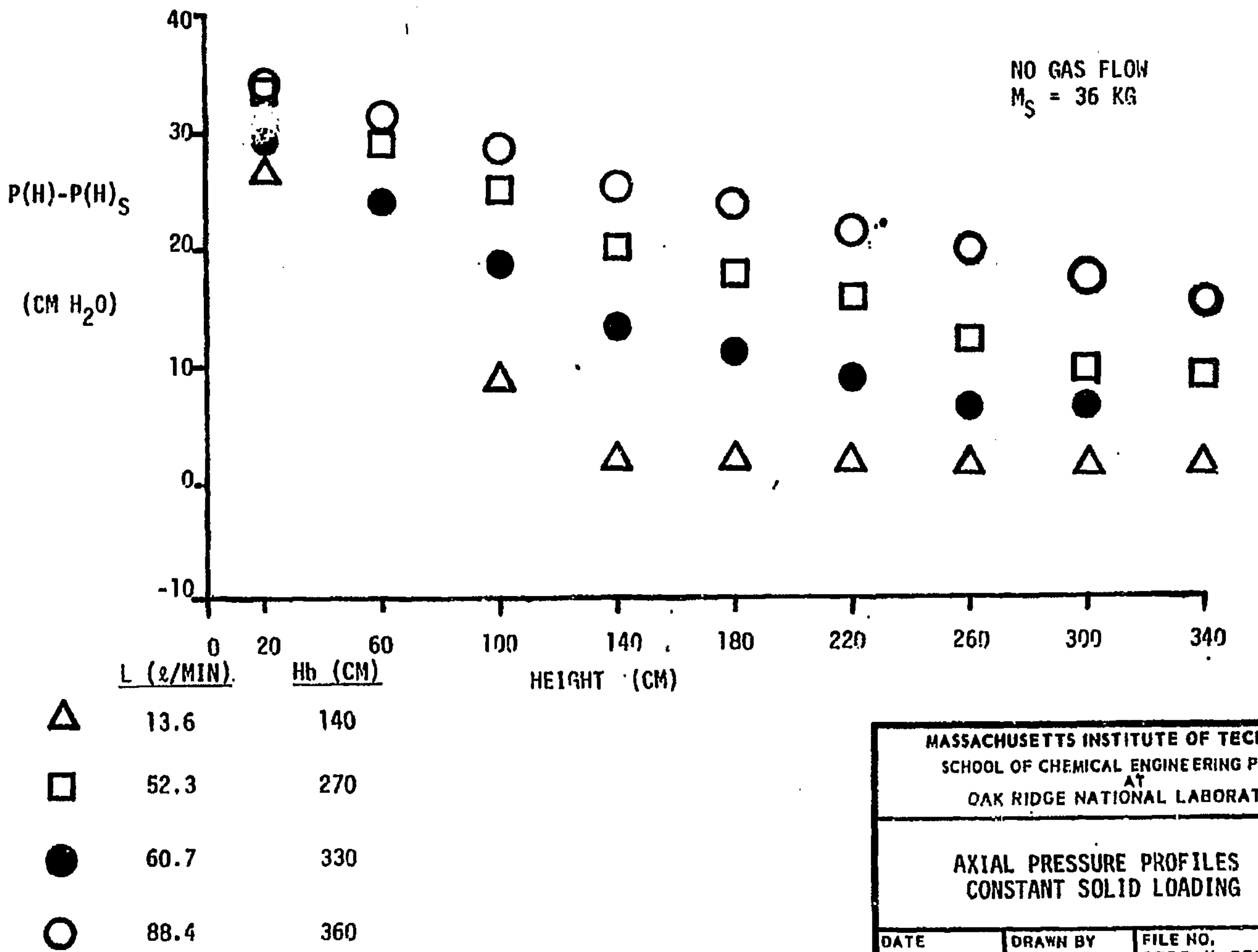

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AXIAL PRESSURE PROFILES
CONSTANT SOLID LOADING

DATE	DRAWN BY	FILE NO.	FIG.
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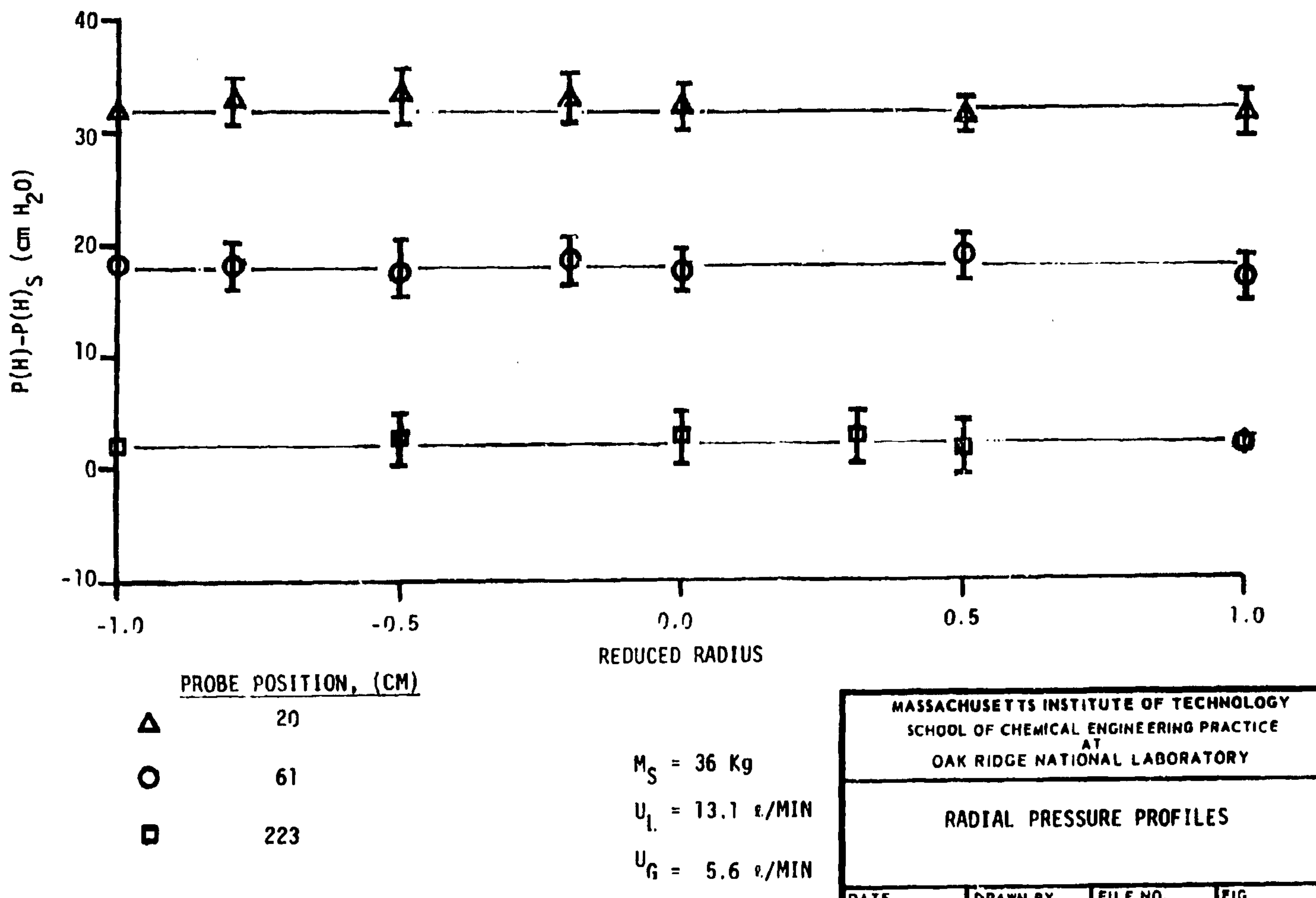

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RADIAL PRESSURE PROFILES

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5/17/77	JCE	CEPS-X-255	6

4.3 Volume Fraction Profiles

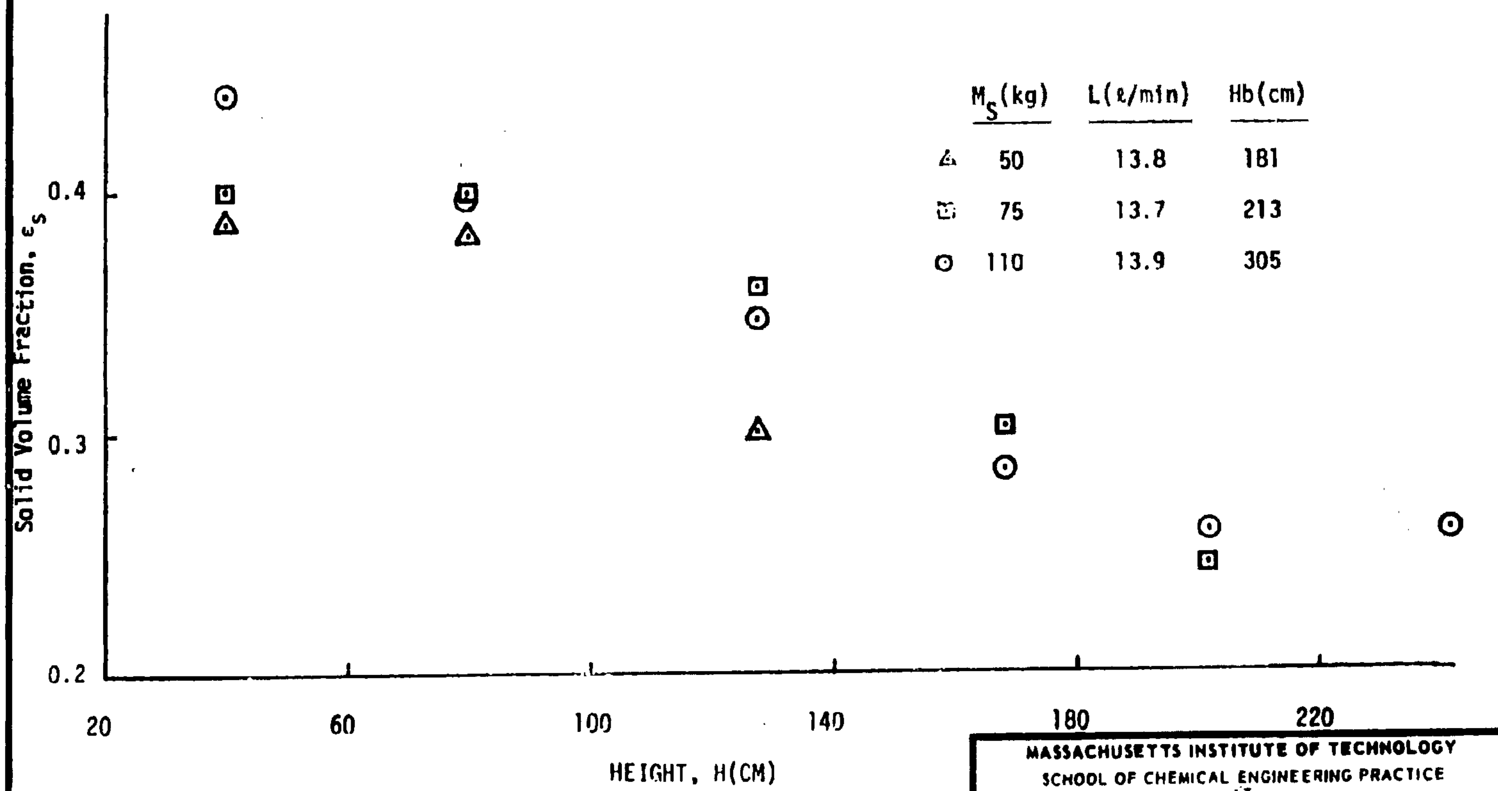
Volume fraction profiles were determined for 50, 75, and 110 kg loadings at each liquid and gas flow rate. Solid, liquid and gas volume fraction profile data are tabulated in Appendix 9.4. The variation of the solid volume fraction profile with loading and operating conditions is presented in Figs. 7 through 10. The solid fraction decreases with height at the minimum and maximum liquid operating velocities (no gas) as shown in Figs. 7 and 8, respectively. The volume fractions are, of course, smaller in Fig. 8 due to the larger bed volume. The introduction of gas into the bed made the distribution of solids more uniform at low gas flowrates (Fig. 9). At higher gas flowrates, the concentration of solids again decreased with height for 50 and 75 kg loadings but went through a maximum at approximately two-thirds the bed height for 110 kg (Fig. 10). The solids profile also went through a maximum at a lower liquid flowrate (10.0 ℓ/min) and the same gas flow rate for the 110 kg loading (Appendix 9.4). The uniformity of solids distribution in Fig. 9 can probably be attributed to solids being drawn along in bubble wakes. Greatly increasing the liquid flowrate (e.g. 75 kg case, Fig. 10) at low gas rates led to a decrease in the solids profile again which might be due to bubble break-up as suggested by Michelsen and Ostergaard (8). Inability to set the gas at a desired level made it difficult to isolate the effect of this flowrate on the holdups. Repetition of these experiments with a more systematic variation of flowrates should be performed to develop a correlation.

4.4 Oxygen Concentration Profiles

Oxygen concentration profiles were only determined for the 36-kg loading. The axial concentration variation as a function of liquid and gas flowrate is presented in Fig. 11. The greatest transfer between the liquid and gas occurs at the lowest flowrates. The oxygen concentration in the exit gas at these flowrates is approximately three percent of the equilibrium value (Appendix 9.2). Thus, the transfer between phases could be further improved by decreasing the liquid flowrate, installing a sparger on the gas inlet line, and redistributors within the column.

Unfortunately, holdup data were only taken at one liquid and gas flowrate for this loading (48.3 and 5.6 ℓ/min). If the data in Fig. 9 are also representative of the 36 kg loading, the volume fraction profile should be more uniform at the lowest liquid and gas flowrates. This might also account for the greater mass transfer at these conditions.

As shown in Fig. 12, there was no significant radial concentration variation. Although it seems unlikely that such a variation would exist, the present method of drawing a sample from within the column through the detector cell might be too insensitive to detect it. Insertion of a probe into the column would provide a more accurate determination.



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SOLID VOLUME FRACTION PROFILE FOR TWO-PHASE SYSTEM AT MINIMUM FLUIDIZATION

DATE	DRAWN BY	FILE NO.	FIG.
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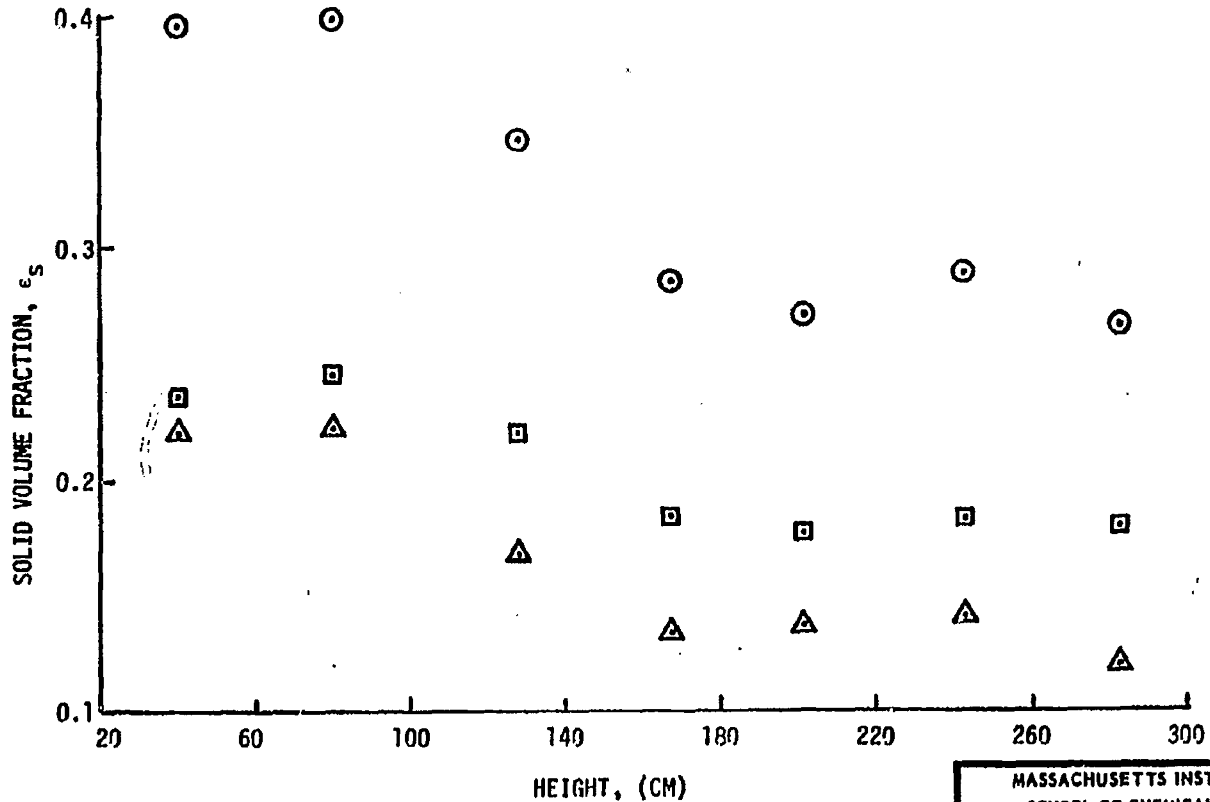

	M_S(kg)	L(ℓ/min)	Hb(cm)
△	50	60.5	339
□	75	42.2	335
○	110	18.1	321

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SOLID VOLUME FRACTION
TWO PHASE AT MAXIMUM
OPERATING FLOWRATE

DATE	DRAWN BY	FILE NO.	FIG.
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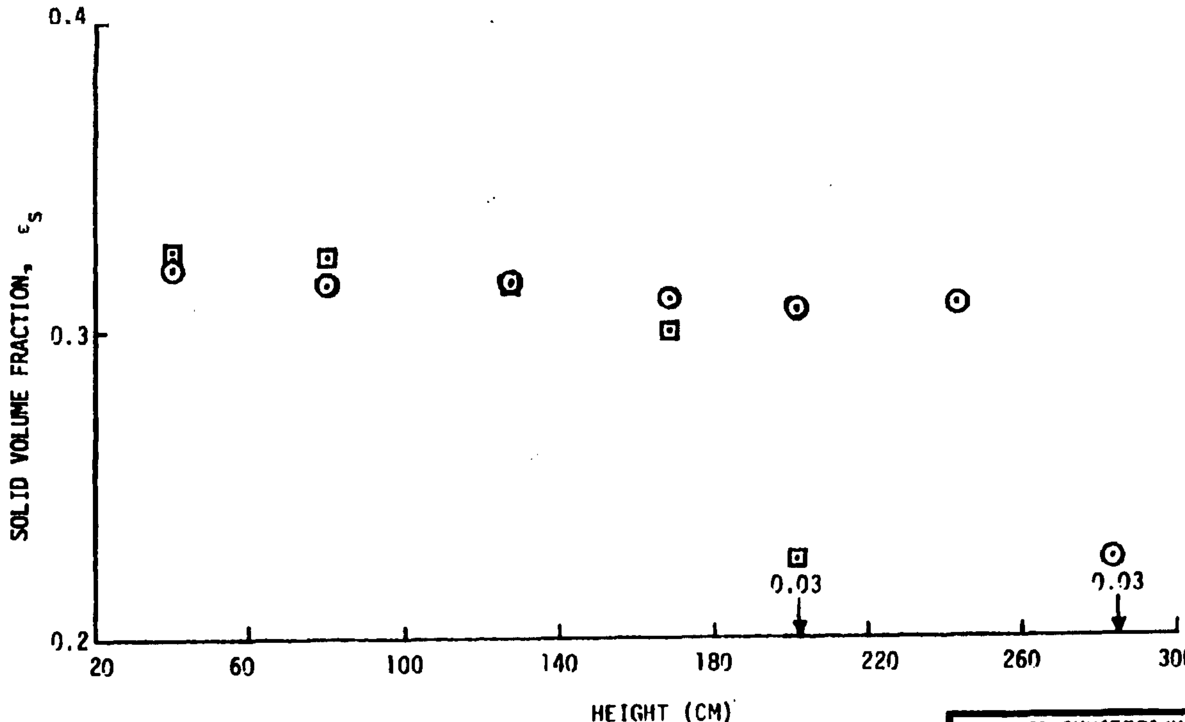

	M_S(kg)	L(ℓ/min)	G	Hb(cm)
□	75	13.4	1.4	230
○	110	13.8	6.7	292

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SOLID VOLUME FRACTIONS, THREE PHASE, NEAR MINIMUM FLUIDIZATION

DATE	DRAWN BY	FILE NO.	FIG.
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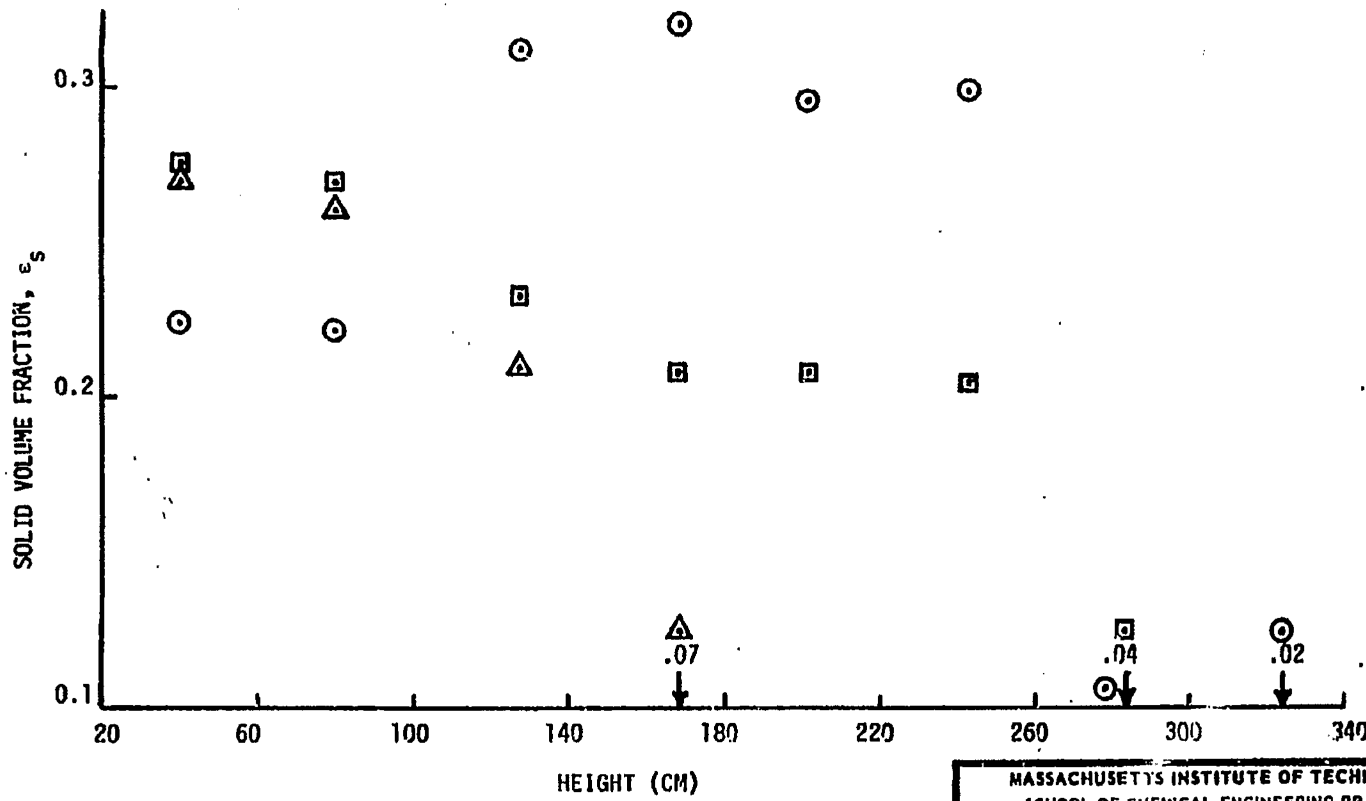

	M_S(kg)	L(ℓ/min)	G	Hb(cm)
△	50	20.6	20.2	[illegible]
□	75	31.9	3.2	319
○	110	14.6	11.0	289

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SOLID VOLUME FRACTION, THREE PHASE AT INTERMEDIATE FLUIDIZATION

DATE	DRAWN BY	FILE NO.	FIG.
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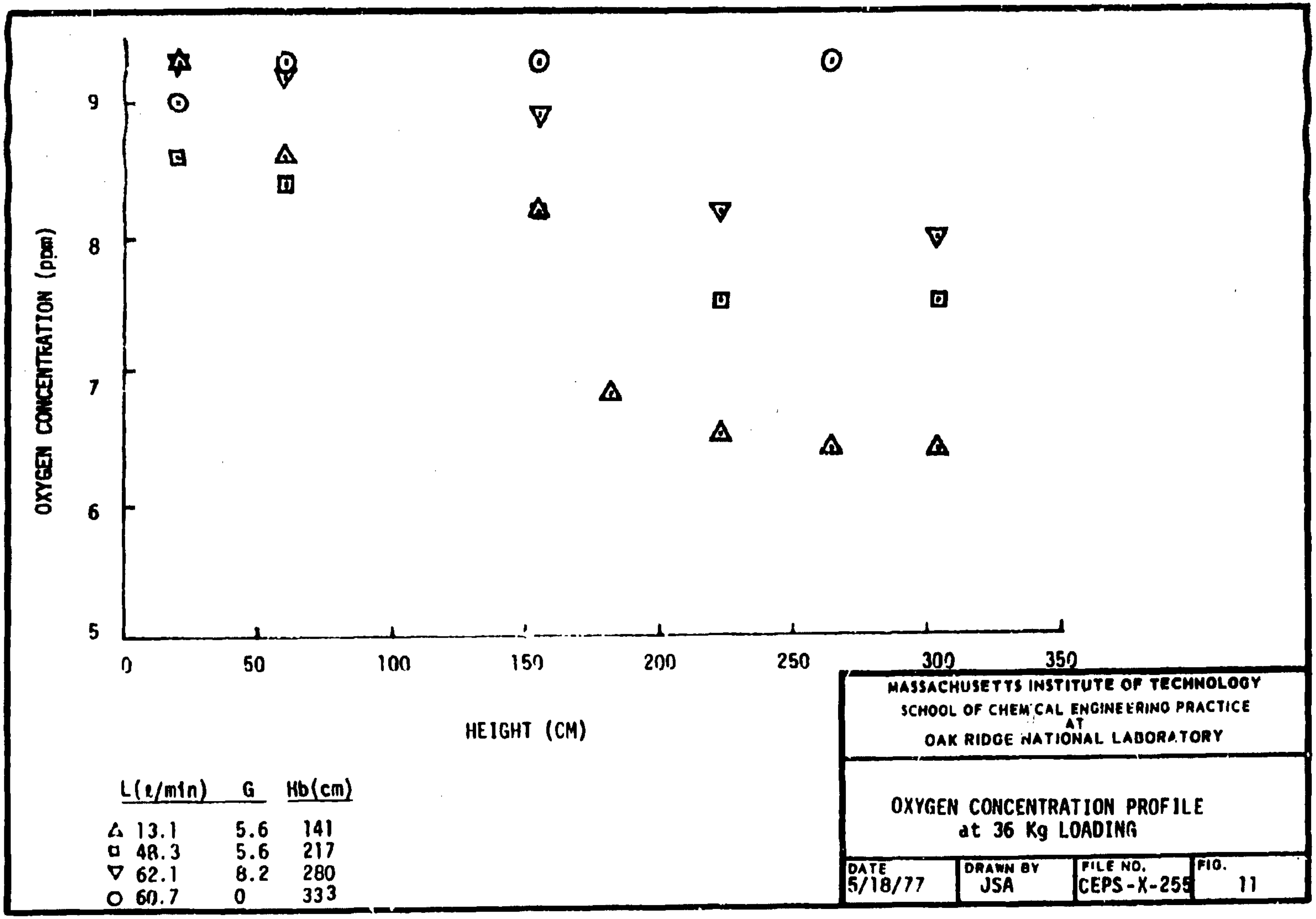
OXYGEN CONCENTRATION (ppm)
9
8
7
6
5
0
50
100
150
200
250
300
350
HEIGHT (CM)
L(ℓ/min) G Hb(cm)
△ 13.1 5.6 141
□ 48.3 5.6 217
▽ 62.1 8.2 280
○ 60.7 0 333
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OXYGEN CONCENTRATION PROFILE
at 36 Kg LOADING
DATE
5/18/77
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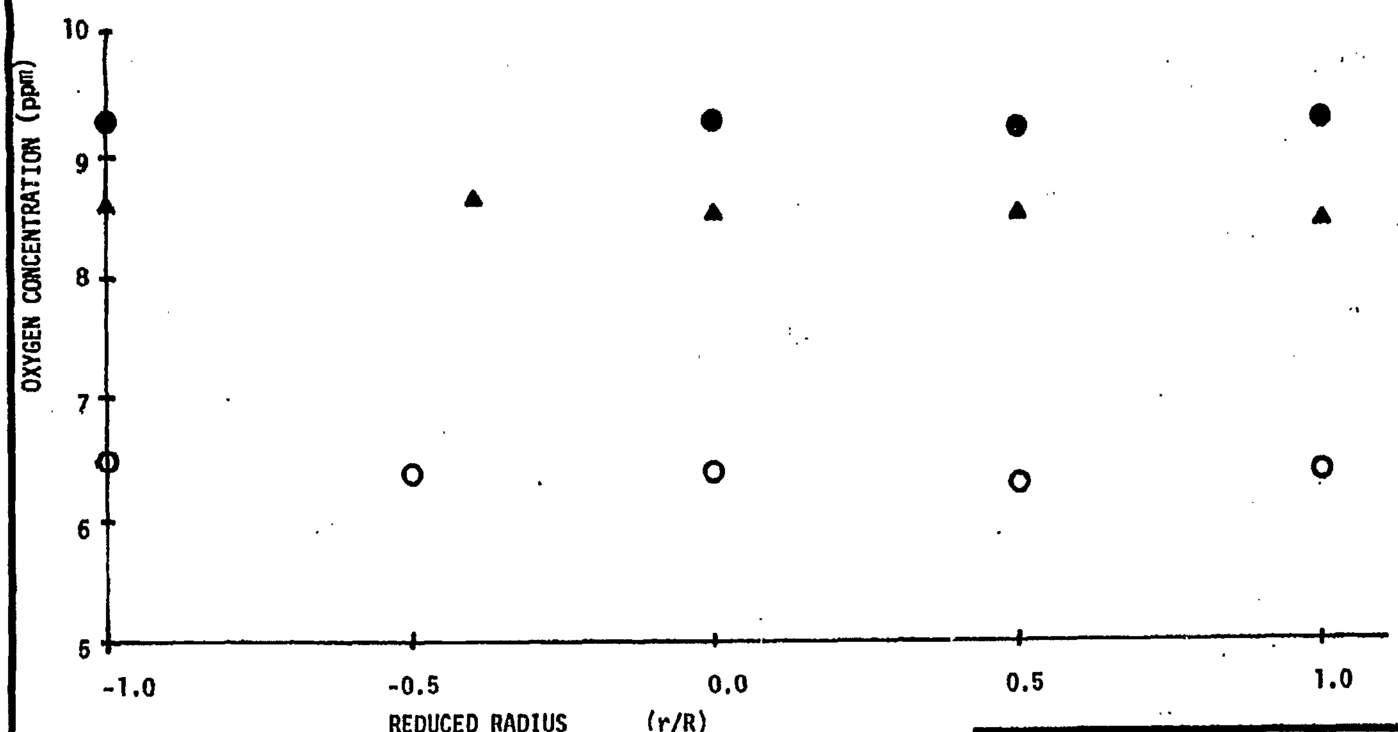
FILE NO.
CEPS-X-255
FIG.
11



M_S = 36 KG

H_B = 140 CM

L = 13.1 ℓ/MIN

G = 5.6 ℓ/MIN

PROBE HEIGHT (CM)

○ 20

▲ 61

● 264

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RADIAL OXYGEN PROFILE NEAR MINIMUM FLUIDIZATION

DATE	DRAWN BY	FILE NO.	FIG.
5-18-77	BWB	CEPS-X-255	12

There were significant problems in obtaining reproducible data with the oxygen concentration probe. The original Y.S.I. probe had an unsupported membrane that oscillated with the column pressure. This was replaced with an Instrumentation Laboratory probe that was accurate to approximately 0.5 ppm.

Although the oxygen concentration data are sparce, an estimate of an overall mass transfer coefficient was made assuming that each column section between sampling ports could be treated as a well mixed reactor. The values of K_La ranged from 0.02 to 0.14 min^{-1} (Appendix 9.3). However, an order of magnitude estimate of 0.1 min^{-1} is a more realistic volume when the uncertainty in the oxygen concentration measurements and assumption of the calculation are considered.

5. CONCLUSIONS

1. The minimum operating flowrate is independent of loading and for this coal is approximately 14 ℓ/min.

2. The maximum liquid flow rates are approximately 88, 60, 42, and 18 ℓ/min at 36, 50, 75, and 110 kg coal, respectively.

3. With no gas flow, the solids holdup decreases with height at both the minimum and maximum liquid flowrates.

4. The least variation of solid and gas holdup with height occurs at the minimum gas and liquid flowrate.

5. The maximum oxygen mass transfer occurred at the lowest liquid and gas flowrate.

6. No radial variations in either pressure or oxygen concentration were detected.

6. RECOMMENDATIONS

1. Attempt to fluidize the bed at liquid-to-gas flowrate ratios (L/G) less than one.

2. Determine the oxygen concentration profile and mass transfer at low liquid and gas flowrates ($L/G \leq 1$) for several coal loadings.

3. Decrease the bubble size by installing redistributors and a sparger at the gas inlet.

4. Install a flowmeter on the gas inlet line to facilitate operating the column.

5. Install a cyclone separator to contain the solids if the column is to be operated at large flowrates.

7. ACKNOWLEDGMENTS

We wish to thank J. M. Begovich for his ideas, C. W. Hancher for his direction and laboratory expertise, and G. B. Dinsmore for his assistance in procurement of laboratory equipment.

8. LOCATION OF DATA

Original data are tabulated in notebook A-7555-G, p. 70-99, on file at the M.I.T. Practice School Office, Bldg. 3001, Oak Ridge National Laboratory.

Therefore,

$$K = \frac{\varepsilon_L'}{\varepsilon_S'} = \frac{(\rho_S - \rho_T)(\rho_S - \rho_L)}{(\rho_S - \rho_L)(\rho_T - \rho_L)} = \frac{\rho_S - \rho_T}{\rho_T - \rho_L} \quad (6)$$

Since ρ_L and ρ_T were known and since ρ_S was determined from the dried coal, K could be calculated. With K the volume fractions within the bed section can now be determined:

$$\varepsilon_G + \varepsilon_L + \varepsilon_S = 1 \quad (7)$$

$$K = \frac{\varepsilon_L}{\varepsilon_S} \quad (8)$$

$$\Delta\rho = [\rho_S \varepsilon_S + \rho_G \varepsilon_G + \rho_L \varepsilon_L] g\Delta h \quad (9)$$

Therefore,

$$\varepsilon_S = \frac{\Delta\rho/g\Delta h - \rho_G}{K(\rho_L - \rho_G) + (\rho_S - \rho_G)} \quad (10)$$

If $\rho_G << \rho_S$ or ρ_L, Eq. (10) can be approximated with:

$$\varepsilon_S = \frac{\Delta\rho}{(K\rho_L + \rho_S) g\Delta h} \quad (11)$$

9.2 Approach of Gas and Liquid Oxygen Concentration to Equilibrium

The oxygen mass transfer was greatest at 13.1 ℓ/min liquid and 5.6 ℓ/min nitrogen flowrate. The ratio of outlet liquid and gas concentration can be compared to the equilibrium value to determine if transfer between the phases was complete. From the data in Fig. 11, the liquid oxygen concentration varied from 9.3 to 6.4 ppm. At 20 °C the solubility ratio is:

$$H = 4.0 \times 10^4 = \frac{Po_2}{Xo_2} \qquad (12)$$

The outlet water concentration was 6.4 ppm or 2×10^{-4} mole/ℓ. Thus Xo_2 was:

$$Xo_2 = \frac{2 \times 10^{-4}}{2 \times 10^{-4} + 55.5} = 3.6 \times 10^{-6} \qquad (13)$$

and

$$Po_2 = (4.0 \times 10^4)(3.6 \times 10^{-6}) = 1.4 \times 10^{-1} \text{ atm.} \qquad (14)$$

Now if the loss of oxygen from the water is assumed to be in the gas,

$$9.3 - 6.4 = 2.9 \text{ ppm } O_2 \text{ transferred}$$

or

$$\frac{(2.9 \times 10^{-3} \text{gm } O_2)}{\ell}\frac{(13.1\ \ell\ H_2O)}{\text{min}} = 3.8 \times 10^{-2}\ \frac{\text{gm } O_2}{\text{min}} \qquad (15)$$

Assuming an ideal gas and 1 atmosphere total pressure,

$$3.8\times10^{-2}\ \frac{\text{gm } O_2}{\text{min}}\left(\frac{1\text{ mole}}{32\text{ gm}}\right)\left(\frac{22.4\ \ell}{\text{mole}}\right) = 0.026\ \ell/\text{min} \tag{16}$$

Since the nitrogen flow rate was 5.6 ℓ/min, the outlet oxygen mole fraction was,

$$Yo_2 = \frac{0.026}{0.026 + 5.6} = 4.62 \times 10^{-3} \tag{17}$$

and

$$Po_2 = (4.62 \times 10^{-3})(1\text{ atm}) = 4.62 \times 10^{-3}\text{ atm} \tag{18}$$

Thus,

$$\frac{4.62 \times 10^{-3}}{1.44 \times 10^{-1}} = 3.2\%\text{ of the equilibrium value} \tag{19}$$

9.3 Estimate of K_La

Application of mass transfer theory to the 15-ft tapered column must be prefaced with a consideration of which parameters vary through the column and how they vary. The tapering causes an increase in cross-sectional area with height and a resulting decrease in superficial velocity. There is a significant pressure change with height and this pressure change affects the interfacial area per unit volume as well as the equilibrium oxygen concentrations in the liquid and gas.

In the absence of holdup data or tracer tests to estimate dispersion within the column, an order of magnitude calculation for K_La, the overall mass transfer coefficient, can be estimated by equating the dissolved oxygen concentration change between two column positions to the rate of transfer to the gas phase. That is,

$$U_L A[C_{L_1} - C_{L_2}] = K_La\ V_S[C_{L_2} - C_L^*] \tag{20}$$

where C_L^* would be the liquid oxygen concentration in equilibrium with the gas phase concentration and V_S is assumed equal to the reactor volume between the two measuring points. The assumption has also been made that the average liquid concentration is equal to the outlet concentration, i.e., a CSTR. The section inlet and outlet concentrations (C_{L_1} and C_{L_2}) are known but the section volume and C_L^* must be calculated. For a tapered section of column,

$$V_S = \frac{\pi h}{3}(r_1^2 + r_1 r_2 + r_2^2) \quad (21)$$

The equilibrium concentration, C_L^*, can be estimated with Henry's Law.

$$X_{O_2}^* = \frac{C_L^*}{C_L + C_{H_2O}} = \frac{P_{O_2}}{H} = \frac{Y_{O_2} P_T}{H} \quad (22)$$

$$C_L^* = \frac{C_{H_2O}}{\left(\frac{H}{Y_{O_2} P_T} - 1\right)} \quad (23)$$

Now, both Y_{O_2} and P_T vary with column position,

$$P_T = P_A + P_S + P_H \quad (24)$$

assuming the water level was at 400 cm,

$$P_T = P_A + \rho g[400 - H + \Delta H] \quad (25)$$

where ΔH is the manometer reading and H is the height from the bottom of the column. The mole fraction in the gas, Y_{O_2}, is calculated from the decrease in the liquid oxygen concentration and the nitrogen flow rate as shown in Appendix 9.2 with the exception that the gas molar volume is corrected for the pressure variation. Once the variables are determined as at each column position, $K_L a$ can be calculated from

$$K_L a = \frac{U_L A(C_{L_1} - C_{L_2})}{V_S(C_{L_2} - C_L^*)}$$

Data for one experiment and the calculated values of $K_L a$ are listed in Table 2.

TABLE 2: DATA FOR CALCULATING $K_L a$

H(cm)	P_T(atm)	V_G(ℓ/mole)	C_L(ppm)	ΔC_L(ppm)	C_L^*(ppm)	$(C_{L_1} - C_{L_2})/(C_{L_2} - C_L^*)$	V_S(ℓ)	$K_L a$(min^{-1})
20	1.42	17.2	9.3	0.7	0.05	8.15×10^{-2}	15.6	6.84×10^{-2}
61	1.37	17.8	8.6					
101	1.32	18.4	-					
155	1.26	19.3	8.2	1.4	0.11	2.08×10^{-1}	19.7	1.38×10^{-1}
182	1.23	19.8	6.8	0.3	0.02	4.63×10^{-2}	29.9	2.03×10^{-2}
223	1.19	20.5	6.5					

M_S = 36 Kg
L = 13.1 ℓ/min
G = 5.6 ℓ/min

9.4 Tabulation of Data and Operating Conditions

```
COAL LOADING =  36.0 KG
STATIC HEIGHT = 104.0 CM
VALUE OF ZERO MEANS NO MEASUREMENT .
L = 13.6 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 140.7 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H20
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          46.6 21.8  28.6  21.8  21.8  22.1  22.0  21.5   0.0
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          .220  .002  .000  .000  .000  .000  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
  0.0 AND   0.0 CM .002 .998 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           2.7  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 52.3 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 270.3 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H20
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          49.2 44.0  38.8  33.3  31.2  28.9  26.7  26.7   0.0
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          .002  .000  .002  .000  .000  .000  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
  0.0 AND   0.0 CM .002 .998 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 58.4 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 360.0 CM
CONDITION = MAXIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H20
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          54.2 51.4  48.6  45.3  43.7  41.6  39.8  37.4  35.2
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          .002  .000  .002  .002  .000  .000  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
  0.0 AND   0.0 CM .002 .998 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 62.1 L/MIN
G =  8.2 L/MIN
BED HEIGHT = 280.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H20
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          52.3 48.6  44.7  39.7  37.7  36.1  35.5  35.4  35.3
DENSITY, G/CM3
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HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          .000  .000  .000  .000  .000  .000  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
  0.0 AND   0.0 CM **** **** ****
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           9.3  9.2   0.0   8.9   0.0   0.2   0.0   0.0   0.0
L = 13.1 L/MIN
G =  5.6 L/MIN
BED HEIGHT = 101.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          51.3 42.5  33.6  22.3  21.4  21.5  21.7  21.7  21.3
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          .000  .000  .000  .000  .000  .000  .000  .000  .002
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
  0.0 AND   0.0 CM **** **** ****
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           9.3  8.6   0.0   8.2   6.8   6.5   6.4   6.4   0.0
L = 48.3 L/MIN
G =  5.6 L/MIN
BED HEIGHT = 217.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          48.2 43.2  38.0  31.6  28.9  26.1  26.1  26.1  25.5
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.116 1.119  .000 1.097  .000 1.279  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
 20.0 AND  61.0 CM .189 .717 .094
 61.0 AND 155.0 CM .174 .741 .085
155.0 AND 223.0 CM .144 .783 .073
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           8.6  8.4   0.0   8.2   0.0   7.5   0.0   7.5   0.0
L = 60.7 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 330.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          53.5 49.2  45.0  40.0  37.0  34.8  32.0  29.7  29.0
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.097 1.110  .000 1.071 1.083 1.078 1.069  .000  .000
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
 20.0 AND  61.0 CM .184 .816 .000
 61.0 AND 155.0 CM .154 .846 .000
155.0 AND 182.0 CM .137 .863 .000
182.0 AND 223.0 CM .144 .856 .000
223.0 AND 263.5 CM .131 .869 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           9.0  9.3   0.0   9.3   0.0   0.0   0.0   9.3   0.0
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COAL LOADING =  50.0 KG
STATIC HEIGHT = 132.0 CM
VALUE OF ZERO MEANS NO MEASUREMENT
L = 13.8 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 101.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          53.2 44.3  35.4  25.0  21.9  22.1  22.3  21.8  21.8
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.222 1.212 1.216 1.138 1.000  .000  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
 20.0 AND  61.0 CM .387 .613 .000
 61.0 AND 101.0 CM .382 .618 .000
101.0 AND 155.0 CM .301 .699 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.2  0.0   0.0   0.3   0.0   0.0   0.0   0.0   0.0
L = 60.5 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 339.0 CM
CONDITION = MAXIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          56.1 52.4  46.5  41.2  39.1  35.8  32.9  29.6  27.3
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.116 1.120 1.130 1.074 1.075 1.078 1.079 1.058  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
 20.0 AND  61.0 CM .211 .789 .000
 61.0 AND 101.0 CM .223 .777 .000
101.0 AND 155.0 CM .168 .832 .000
155.0 AND 182.0 CM .133 .867 .000
182.0 AND 223.0 CM .137 .863 .000
223.0 AND 263.5 CM .140 .860 .000
263.5 AND 304.0 CM .119 .881 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  2.0   1.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 54.5 L/MIN
G =  5.4 L/MIN
BED HEIGHT = 289.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          52.3 49.2  43.6  38.3  35.7  32.2  29.2  27.4  26.7
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.114 1.123 1.123 1.083 1.080 1.077 1.066 1.005  .000
VOLUME FRACTIONS
     BETWEEN          ES   EL   EG
 20.0 AND  61.0 CM .190 .711 .099
 61.0 AND 101.0 CM .198 .704 .097
101.0 AND 155.0 CM .163 .756 .081
155.0 AND 182.0 CM .136 .798 .066
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182.0 AND 223.0 CM .131 .804 .065
223.0 AND 263.5 CM .119 .821 .059
PPM OXYGEN
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          0.0  0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 20.6 L/MIN
G = 20.2 L/MIN
BED HEIGHT = 231.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
         45.8 39.6 33.0  25.0  23.6  23.2  23.2  22.9  22.3
DENSITY, G/CM3
HEIGHT   20CM  61CM  101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.176 1.172 1.162 1.112 1.024  .300  .000  .000  .002
VOLUME FRACTIONS
     BETWEEN          ES    EL    EG
 20.0 AND  61.0 CM .269  .596  .135
 61.0 AND 101.0 CM .260  .612  .129
101.0 AND 155.0 CM .210  .687  .103
155.0 AND 182.0 CM .068  .899  .033
PPM OXYGEN
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          0.0  0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0


COAL LOADING =  75.0 KG
STATIC HEIGHT = 182.0 CM
VALUE OF ZERO MEANS NO MEASUREMENT
L = 42.2 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 335.0 CM
CONDITION = MAXIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
         65.2 58.5 51.0  41.2  34.3  30.7  32.2  27.6  24.6
DENSITY, G/CM3
HEIGHT   20CM  61CM  101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.135 1.131 1.145 1.108 1.099 1.100 1.105 1.097  .000
VOLUME FRACTIONS
     BETWEEN          ES    EL    EG
 20.0 AND  61.0 CM .237  .763  .000
 61.0 AND 101.0 CM .246  .754  .000
101.0 AND 155.0 CM .221  .779  .000
155.0 AND 182.0 CM .184  .816  .000
182.0 AND 223.0 CM .178  .822  .000
223.0 AND 263.5 CM .183  .817  .000
263.5 AND 304.0 CM .180  .820  .000
PPM OXYGEN
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          0.0  0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 20.7 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 291.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT   20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
         65.8 62.6 59.5  48.5  36.9  31.6  26.7  23.5  23.4
DENSITY, G/CM3
HEIGHT   20CM  61CM  101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.159 1.165 1.166 1.137 1.132 1.134 1.125  .000  .000
VOLUME FRACTIONS
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     BETWEEN            ES    EL    EG
 20.0 AND  61.0 CM .289 .711 .000
 61.0 AND 101.0 CM .296 .704 .000
101.0 AND 155.0 CM .268 .732 .000
155.0 AND 182.0 CM .240 .760 .000
182.0 AND 223.0 CM .239 .761 .000
223.0 AND 263.5 CM .233 .767 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          2.0  4.0   1.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 13.7 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 213.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          64.4 55.2  46.1  34.6  30.1  23.7  22.5  22.3  21.8
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.222 1.227 1.222 1.185 1.156 1.122  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN            ES    EL    EG
 20.0 AND  61.0 CM .401 .599 .000
 61.0 AND 101.0 CM .401 .599 .000
101.0 AND 155.0 CM .360 .640 .000
155.0 AND 182.0 CM .302 .698 .000
182.0 AND 223.0 CM .245 .755 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 12.3 L/MIN
G =  3.2 L/MIN
BED HEIGHT = 234.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          66.4 57.2  46.0  37.2  31.8  23.7  22.4  22.2  21.7
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.223 1.226 1.214 1.204 1.200 1.182  .000  .000  .000
VOLUME FRACTIONS
     BETWEEN            ES    EL    EG
 20.0 AND  61.0 CM .322 .520 .158
 61.0 AND 101.0 CM .317 .529 .154
101.0 AND 155.0 CM .315 .529 .156
155.0 AND 182.0 CM .306 .543 .151
182.0 AND 223.0 CM .292 .565 .143
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 31.9 L/MIN
G =  3.2 L/MIN
BED HEIGHT = 319.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          65.4 58.1  50.8  42.9  39.4  34.1  29.3  24.2  23.8
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.180 1.176 1.171 1.130 1.130 1.130 1.126 1.012  .000
VOLUME FRACTIONS
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    BETWEEN           ES    EL    EG
 20.0 AND  61.0 CM .275  .589  .136
 61.0 AND 101.0 CM .269  .599  .132
101.0 AND 155.0 CM .233  .651  .116
155.0 AND 182.0 CM .208  .688  .104
182.0 AND 223.0 CM .208  .688  .104
223.0 AND 263.5 CM .215  .692  .103
263.5 AND 304.0 CM .039  .952  .009
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 13.4 L/MIN
G =  1.4 L/MIN
BED HEIGHT = 230.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          65.1 56.0  46.8  35.9  30.4  22.6  22.3  21.7  21.5
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.222 1.213 1.218 1.203 1.192 1.010  .000  .000  .000
VOLUME FRACTIONS
    BETWEEN           ES    EL    EG
 20.0 AND  61.0 CM .326  .514  .160
 61.0 AND 101.0 CM .324  .518  .158
101.0 AND 155.0 CM .316  .527  .157
155.0 AND 182.0 CM .300  .552  .148
182.0 AND 223.0 CM .034  .966  ****
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0


COAL LOADING = 110.0 KG
STATIC HEIGHT = 242.0 CM
VALUE OF ZERO MEANS NO MEASUREMENT
L = 18.1 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 321.0 CM
CONDITION = MAXIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          82.1 71.3  61.1  49.4  44.1  37.8  31.0  24.3  22.3
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.226 1.219 1.220 1.170 1.151 1.152 1.173 1.132  .000
VOLUME FRACTIONS
    BETWEEN           ES    EL    EG
 20.0 AND  61.0 CM .397  .603  .000
 61.0 AND 101.0 CM .399  .601  .000
101.0 AND 155.0 CM .348  .652  .000
155.0 AND 182.0 CM .286  .714  .000
182.0 AND 223.0 CM .271  .729  .000
223.0 AND 263.5 CM .289  .711  .000
263.5 AND 304.0 CM .267  .733  .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
```

```
L = 13.9 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 305.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          82.1 71.1  60.7  48.3  42.6  35.1  28.1  22.2  21.7
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.264 1.232 1.213 1.179 1.144 1.146 1.145  .000  .000
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
 20.0 AND  61.0 CM .441 .559 .000
 61.0 AND 101.0 CM .397 .603 .000
101.0 AND 155.0 CM .347 .653 .000
155.0 AND 182.0 CM .285 .715 .000
182.0 AND 223.0 CM .259 .741 .000
223.0 AND 263.5 CM .260 .740 .000
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 13.8 L/MIN
G =  6.7 L/MIN
BED HEIGHT = 292.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          78.5 69.4  61.9  48.4  43.2  35.2  27.4  22.4  22.0
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.213 1.230 1.210 1.210 1.201 1.205 1.203 1.008  .000
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
 20.0 AND  61.0 CM .321 .521 .158
 61.0 AND 101.0 CM .316 .529 .156
101.0 AND 155.0 CM .317 .529 .154
155.0 AND 182.0 CM .310 .535 .154
182.0 AND 223.0 CM .307 .540 .152
223.0 AND 263.5 CM .308 .538 .153
263.5 AND 304.0 CM .027 .970 .003
PPM OXYGEN
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 14.6 L/MIN
G = 11.0 L/MIN
BED HEIGHT = 289.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT    20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          75.0 67.6  60.6  49.4  33.9  35.7  28.2  22.7  21.9
DENSITY, G/CM3
HEIGHT    20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
        1.214 1.135 1.206 1.208 1.202 1.197 1.196 1.037 1.006
VOLUME FRACTIONS
     BETWEEN           ES   EL   EG
 20.0 AND  61.0 CM .224 .668 .108
 61.0 AND 101.0 CM .222 .671 .107
101.0 AND 155.0 CM .313 .533 .154
155.0 AND 182.0 CM .321 .556 .122
182.0 AND 223.0 CM .296 .534 .170
223.0 AND 263.5 CM .299 .553 .149
263.5 AND 304.0 CM .106 .848 .046
304.0 AND 344.5 CM .018 .973 .008
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PPM OXYGEN
HEIGHT     20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
            0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 10.0 L/MIN
G = 11.1 L/MIN
BED HEIGHT = 279.0 CM
CONDITION = MINIMUM FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT     20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
           78.2 68.3  59.8  47.6  41.8  32.9  24.8  22.2  21.5
DENSITY, G/CM3
HEIGHT     20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          1.219 1.217 1.226 1.222 1.218 1.216 1.185 1.011  .000
VOLUME FRACTIONS
      BETWEEN            ES   EL   EG
 20.0 AND  61.0 CM .327 .514 .159
 61.0 AND 101.0 CM .331 .506 .164
101.0 AND 155.0 CM .334 .501 .164
155.0 AND 182.0 CM .329 .508 .163
182.0 AND 223.0 CM .325 .514 .160
223.0 AND 263.5 CM .303 .548 .149
263.5 AND 304.0 CM .037 .949 .014
PPM OXYGEN
HEIGHT     20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
            0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
L = 14.7 L/MIN
G =  0.0 L/MIN
BED HEIGHT = 309.0 CM
CONDITION = INTERMEDIATE FLUIDIZATION
PRESSURE ABOVE STATIC HEAD, CM H2O
HEIGHT     20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM

           81.5 70.2  59.3  46.8  41.9  34.8  28.2  22.1  21.8
DENSITY, G/CM3
HEIGHT     20CM  61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
          1.243 1.222 1.175 1.148 1.149 1.150 1.162  .000  .000
VOLUME FRACTIONS
      BETWEEN            ES   EL   EG
 20.0 AND  61.0 CM .414 .586 .000
 61.0 AND 101.0 CM .349 .651 .000
101.0 AND 155.0 CM .286 .714 .000
155.0 AND 182.0 CM .265 .735 .000
182.0 AND 223.0 CM .267 .733 .000
223.0 AND 263.5 CM .278 .722 .000
PPM OXYGEN
HEIGHT     20CM 61CM 101CM 155CM 182CM 223CM 264CM 304CM 345CM
            0.0  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
```

9.5 Nomenclature

A	column cross sectional area, cm^2
C_{H_2O}	liquid phase water concentration, ppm
C_L	liquid phase oxygen concentration, ppm
C_{L_1}	C_L entering column section, ppm
C_{L_2}	C_L exiting column section, ppm
C_L^*	C_L in equilibrium with gas phase oxygen concentration, ppm
g	gravitational acceleration, 980 cm/sec^2
Δh	length between two column ports, cm
H	distance from bottom of column, cm
ΔH	manometer reading, cm H_2O
Hb	height of fluidized bed, cm
Hbs	height of static coal bed, cm
K	liquid to solid holdup ratio
$K_L a$	overall mass transfer coefficient, min^{-1}
M_S	mass of coal in bed, kg
M_T	total mass in sample, gm
P_A	atmospheric pressure, atm
P_H	pressure during operation at height H up column, cm H_2O, atm
P_S	pressure of static bed/water at height H, cm H_2O, atm
P_T	total pressure, atm
$\overline{P}_T$	average column section pressure, atm
ΔP	pressure difference, cm H_2O
p_{O_2}	partial pressure oxygen in gas, atm
r_1, r_2	column radius at inlet and outlet to section, cm
U_L	liquid superficial velocity, cm/sec

$\underline{V}_G$	gas molar volume, ℓ/mole
$\overline{V}_G$	average molar volume for column section, ℓ/mole
x_{O_2}	mole fraction in liquid
y_{O_2}	mole fraction in gas
V_S	volume of column section, cm^3
ε_L, $\varepsilon_{L'}$	liquid volume fractions in column and port sample
ε_S, $\varepsilon_{S'}$	same for solid volume fraction
ρ_G	gas density, gm/cm^3
ρ_L	liquid density, gm/cm^3
ρ_S	solids density, gm/cm^3
ρ_T	total density of port sample, gm/cm^3
θ	column angle from vertical, degree

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