THE ENTRAINMENT OF SOLIDS FROM FLUIDIZED BEDS

by

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Dear Sir:

I take pleasure in submitting this thesis entitled "The Entrainment of Solids from Fluidized Beds" in partial fulfillment of the requirements for the degree of Bachelor of Science in Chemical Engineering.

Respectfully submitted,

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I SUMMARY

With the increasing industrial usage of the fluidized technique for contacting fluids with solids, further knowledge of the design factors for fluidization processes are essential. Since the entrainment of the particles from a fluidized bed is one important design factor of which very little is known, an investigation was undertaken to study the effects of particle density on entrainment rates.

The materials used were polystyrene, glass, and iron spheres. The particle densities of these substances ranged from 65.9 lbs. per cu. ft. for the polystyrene to 470.5 lbs. per cu. ft. for the iron. The average particle diameters used were from 274 to 360 microns. The materials were fluidized by air in a system from which the entrained particles were continuously recycled. Air velocities were measured with a calibrated orifice; entrainment rates were found by diverting the material recycling into a weighing bottle for a length of time determined by a stop-watch.

It was found that:

1) The rate of entrainment for solids fluidized by air is dependent on the height of the dense bed if the bed is less than 9 in. in a 1¼ to 3 in. column and if the average particle size is greater than 306 microns.

2) Column diameter does not affect the rate of entrainment with 274 to 360 micron average diameter particles, a 4 in. bed depth, and a 44 in. outage in a $1\frac{1}{4}$ to 3 in. column. Column diameter does appear to affect entrainment rates at higher dense bed levels.

3) Ease of fluidization and steadiness of operation increases with 1) decreasing density, 2) increasing column diameter, and 3) decreasing particle size.

4) The data obtained may be tentatively correlated as

$$E = 6.3 \times 10^{-27} e^{69.1 \frac{V}{V_t}}$$

where E is the entrainment rate in lbs. per min. per sq. ft. of column cross sectional area, and $\frac{V}{V_t}$ is the ratio of superficial to free falling velocity.

It is recommended for future work on entrainment rates:

1) Study the effect of density variations with smaller diameter particles.

2) Investigate materials with average particle sizes between 274 and 360 microns in a column of larger diameter than 3 in.

3) Determine the effect of dense bed height on entrainment rates.

II INTRODUCTION

The already important technique of fluidization as a method of contacting solids with fluids shows ever expanding usage in new commercial processes. The first major industrial application of the fluidization technique was in the catalytic cracking of petroleum. Since then, solids fluidization methods have spread to a variety of uses. Among those industries currently employing fluidization processes are the dyestuff, paper and wood, non-ferrous metal, cement, and plastics industries.

The main reasons for this increasing popularity of fluidization are the superior heat and material transfer characteristics obtainable. With the violent agitation and consequent thorough mixing of the particles within the fluidized bed and the fluidizing medium, excellent heat transfer characteristics have been noted, both within the bed itself and from the bed to the surroundings. For this reason a fluidized bed offers a method of maintaining a constant temperature throughout a reactor even in the advent of a rapidly occurring, highly exothermic or endothermic reaction.

Furthermore, because of the rapid mixing within a fluidized bed, solids may be readily added or removed. As an additional advantage, the solids may be easily conveyed to or from the reactor by variations in the velocities of the fluidizing and transporting media.

In general entrainment of the solid particles from the fluidized bed is not a problem at low fluid velocities, but the obvious economic savings of lower size to capacity ratios require a high flow rate, where entrainment is a big consideration. For this reason entrainment of solids is a definite factor in design.

Most of the previous work done on fluidization is concerned with the general characteristics and conditions required for fluidization and do not mention the specific problem of entrainment.

Two general types of fluidization, called aggregate and particulate fluidization, are recognized. Particulate fluidization is characterized by gentle movement of evenly dispersed individual particles, the distance between particles increasing with increasing fluid velocity. Aggregative fluidization differs from particulate in that "bubbles," which cause considerable turbulance and mixing, are continually rising through the dense bed. It has been noted that there is an actual flow of gas from these pockets or "bubbles" to and from the surrounding area (3). If the size of these bubbles equalls the diameter of the column, the violent condition thus originated is called slugging.

As the velocity of the fluidizing medium is increased, particles are thrown into the space above the dense bed, forming a so called transition region. Some of these particles above the dense bed are then entrained from the system.

The causes for these types of fluidization are not certain but appear to be related to the fluid density and viscosity. Liquids in general produce particulate fluidization, while gases cause aggregative fluidization.

Bauer (1) was one of these earlier investigators who was interested mainly in the general characteristics of a fluidized bed. The problem of entrainment from a system consisting of a dense bed was not studied, but Bauer commented that investigation into this question "should prove to be of great interest."

Although references to work done on entrainment are sparse, some studies are available. Max Leva (3) observed entrainment from a binary system of coarse and fine sized irregularly shaped particles in a 1.32 inch inner diameter column. From his batch system he proposed that the data could be correlated by the equation

$$c = c_o e^{-2.303 K \theta}$$

where

c = concentration of fines, percent

c_o = initial concentration of fines, percent

K = a rate constant, reciprocal minutes

θ = time, minutes

The data were found to deviate from this relation at a low concentration of fines.

The rate constant K was found to vary with 1) the diameter and density of the fines, 2) the height of the bed, and 3) the velocity of the gas to the fourth power. K was found to be almost independent of the size of the larger component.

Using small spherical glass beads for his fluidized particles, Lyons (4) studied the effects of outage, or vertical height above the dense bed to the top of the tube, particle diameter, and air velocity on entrainment rate from a batch fluidized bed in a 3 inch inner diameter column. He presented a correlation for the rate of entrainment as a function of 1) outage, 2) column diameter, 3) the difference between the superficial air velocity and the terminal free falling velocity of the particles, 4) solid density, 5) fluid density,, and 6) fluid viscosity.

However, Garrett (1) found that Lyon's correlation was not correct in that it could not be applied to $1\frac{1}{4}$ and 2 inch inner diameter columns. Garrett went on to show that entrainment could be represented as a function of outage by

$$E = E_o e^{MO}$$

where E is the rate of entrainment, E_o and M are both functions of particle diameter and air velocity, while O is the outage.

By far the most inclusive single work available at the moment on the subject of entrainment is that by Hyman (3). Experimenting with a batch system, he determined entrainment rates using spherical glass beads of 29 to 75 micron diameters for a single component system. Column height was varied from 24 to 105 inches, inside column diameters were $1\frac{1}{4}$, 2, and 3 inches, while air velocity varied from 1.4 to 2.5 feet per second. The initial bed height was from 1 to 43 inches. For a double componet system he used 70 micron diameter glass beads for the fines and 152 or 452 micron diameter beads for the large sized particles.

For single component systems he found that the entrainment rate per unit cross section is dependent upon the interrelated effects of 1) outage, 2) column diameter, 3) gas velocity, 4) particle diameter, 5) some unknown properties of the solids other than size, and 6) dense bed height (only at very low values of bed height).

Hyman attempted to correlate his data but was unable to completely do so. For a single component system he gave the relation

$$E = K e^{-aH}$$

where E is the entrainment rate in pounds per second per square foot of column cross section; a is an inverse function of air velocity; K is a function of air velocity, the free falling velocity of the particles, and experimentally determined constants whose values depend upon the column diameter; H is outage in inches.

For a binary system of glass beads Hyman represented his data as

$$E_x = E_o\, x\, (1+\Delta)$$

where E_x is the rate of entrainment of the smaller component containing x weight fraction of the smaller component. E_o is the entrainment rate of the smaller component under the same conditions but in the absence of the large component. Δ is dependent upon x and an empirically determined constant, which is calculated for each particle size of the larger component.

A considerable amount of work has been done by a few investigators on the subject of entrainment rate from fluidized beds, but to date no satisfactory relationship has been proposed which will enable a rate prediction under all given operating conditions. What these investigators have shown about the rate of entrainment is that a complex relationship exists between this rate and a certain set of operating variables. These variables are summarized in the previous discussion of the work done by Hyman (3).

Although there has been no work done to directly determine the effect of particle density on entrainment rate, particle density is recognized by the majority of previous investigators as one of the essential factors in the evaluation of this rate.

Because of these facts and since entrainment is such an important problem in fluidization, a program of investigation on the effect of particle density in a continuous fluidized system was decided upon.

III PROCEDURE

The apparatus used was as shown in Figure 1. The column, disengaging section, and return tube are constructed of Lucite. Different column heights may be obtained by various combinations of the column sections and sealing the joints with tape. $1\frac{1}{4}$, 2, and 3 inch inner diameter columns were available. The column heights used were 48 in., 51 in., and 53 in. Outage was set at 44 in.

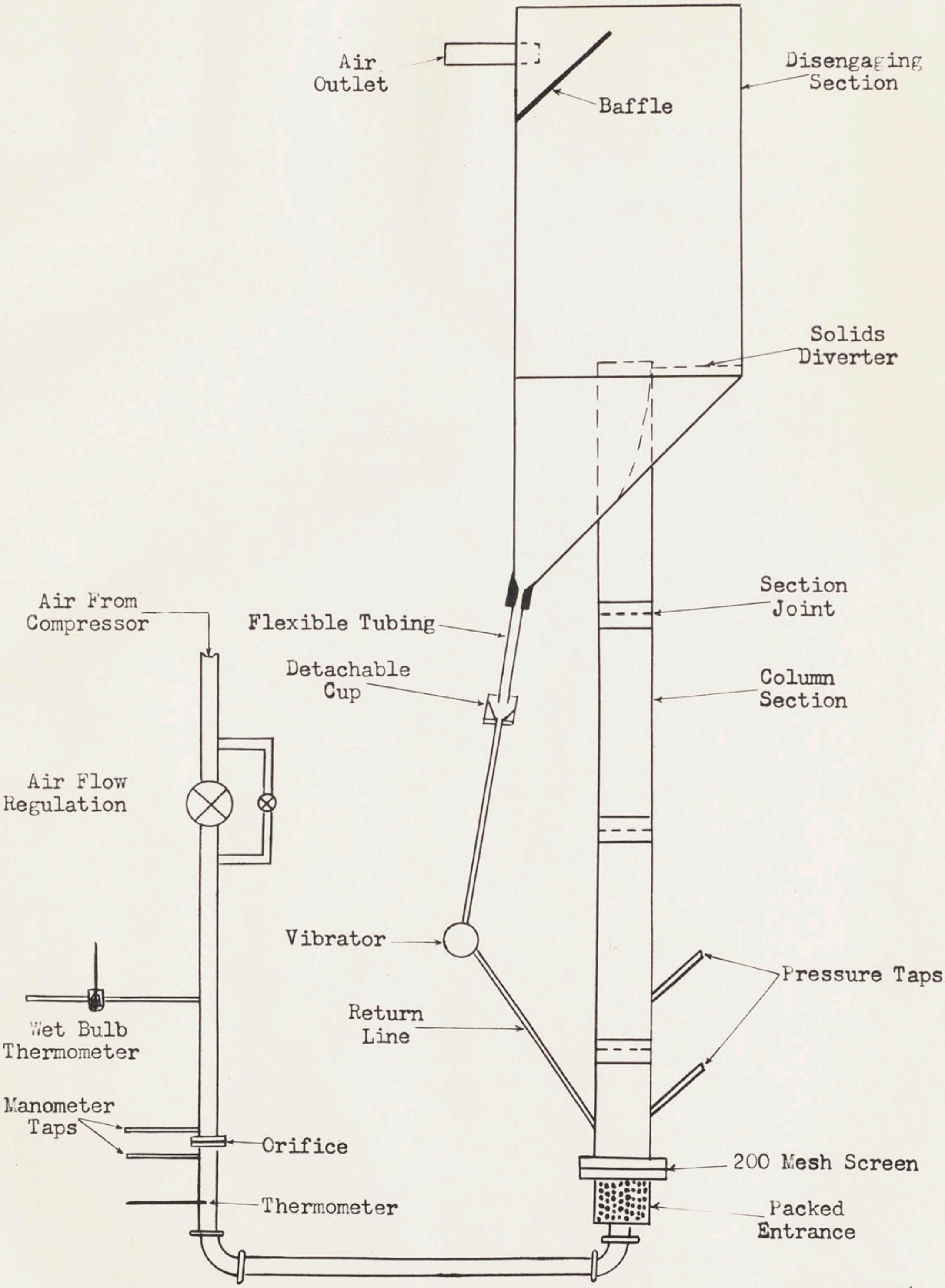
The disengaging section reduced the velocity of the air and allowed the solids to be collected at the bottom of the column, where they were continuously recycled. The height of the solids in the small diameter return line were maintained at a high enough level to prevent air from flowing up the return line. A vibrator in the return line was necessary to assure adequate flow of the return solids.

At the base of the column was a section packed with 1/16 inch glass beads under a 200 mesh screen. These were used to support the charge that is introduced to the column and to flatten out any irregularities in the air flow.

The air flow was measured by the use of four calibrated orifices connected to liquid filled U-tubes. These orifices were used both singly and in parallel. The relative humidity of the air was held for the most part between 45% and 60% to minimize electrostatic effects, which were noted by Hyman (3).

Figure 1

SKETCH OF APPARATUS



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The particles used were polystyrene, particle density 65.9 lbs. per cu. ft., glass, particle density 154.5 lbs. per cu. ft., and iron, particle density 470.5 lbs. per cu. ft. The average particle diameter of the glass was 306 microns; the iron was 306 and 274 microns; and the polystyrene was 361 microns. Particle diameters were determined from microphotographs such as Figures 2, 3, and 4. Solid densities were found by water displacement in a pyknometer.

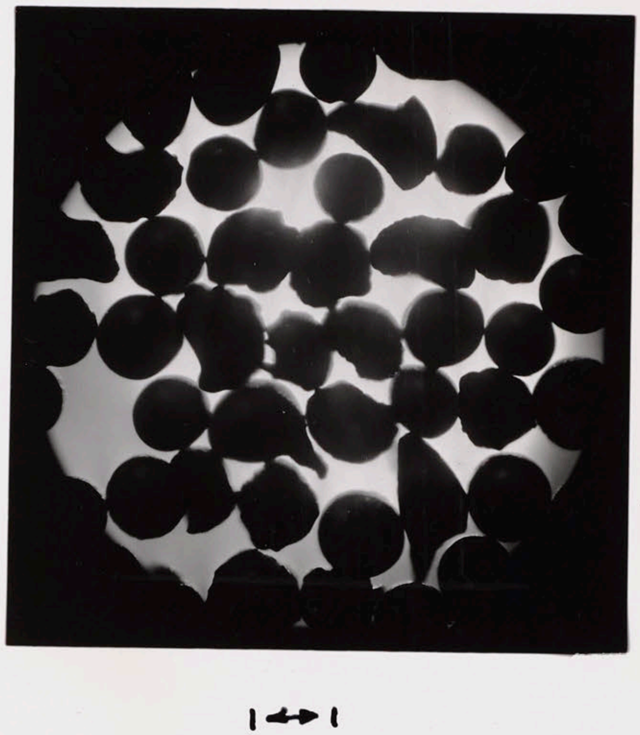
For an experimental run particles of the same size and uniform density were charged into the column. Enough material was added so that the height of the dense bed was at the desired bed depth at the chosen air velocity. The entrainment rates were measured by diverting the recycling solids in the return line into a weighing bottle for a length of time measured with a stopwatch.

The dense bed height was measured by observation of the pressures in the bed at various levels. Pressure taps were located at 1, 4, 7, 9, and 11 in. from the bottom of the bed in the 3 in. column and at 2, 4, 6, 8, and 10 in. in the $1\frac{1}{4}$ and 2 in. columns. Since the pressure within the dense bed is much higher than the pressure in the disperse phase above the bed, bed height could be determined.

This procedure was repeated for the three materials in each of the three columns. Since the required velocity for entrainment varied considerably with the different density

Figure 2

Photomicrograph of Iron



500 microns

Figure 3

Photomicrograph of Glass

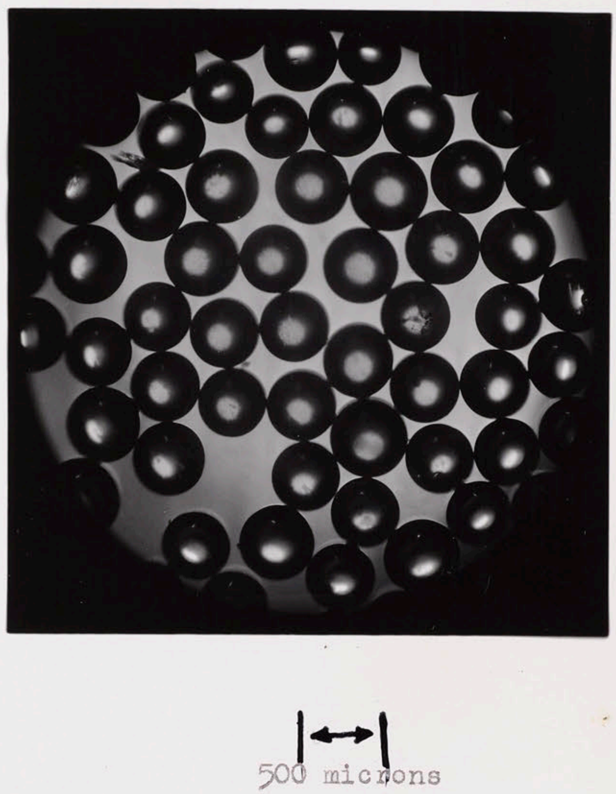
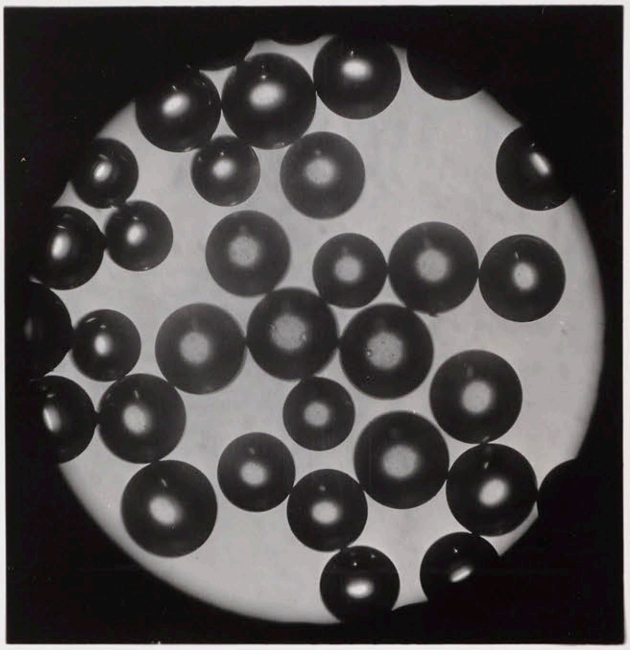


Figure 4

Photomicrograph of Polystyrene



500 microns

materials, runs at more than one velocity were made in each column with each material.

Further details of the procedure used and a summary of the data taken are included in the Appendix.

IV RESULTS

The fluidization of the particles used was moderately steady. The iron showed a tendency to slug when the height of the dense bed was greater than 4 in.; the glass particles slugged when the dense bed height was greater than 7 in. For each material slugging was exhibited with approximately the same dense bed height in each of the $1\frac{1}{4}$, 2, and 3 in. columns. The smoothness of the fluidization increased with 1) increasing column diameter, 2) decreasing particle density, and 3) decreasing particle size.

The results of the experimental runs are plotted on Figures 5, 6, 7, and 8. Figures 5, 6, and 7 show the logarithm of the entrainment rate, E, lbs. per min. sq. ft., as a function of the superficial air velocity V, ft. per sec. Figure 5 is for iron shot, 306 and 274 microns in diameter, density 470.5 lbs per cu. ft. A constant outage of 44 in. was obtained using a column height of 48 in. and a dense bed height of 4 in. It was found that if the dense bed height were raised above the 4 in. level, serious slugging resulted. This slugging was more pronounced in the $1\frac{1}{4}$ in. column and decreased as column diameter increased. Entrainment rate is seen to be independent of column diameter, but dependent upon particle size.

Figure 6 shows ln E vs. V for the glass beads, particle diameter 306 microns, particle density 154.5 lbs. per cu. ft.

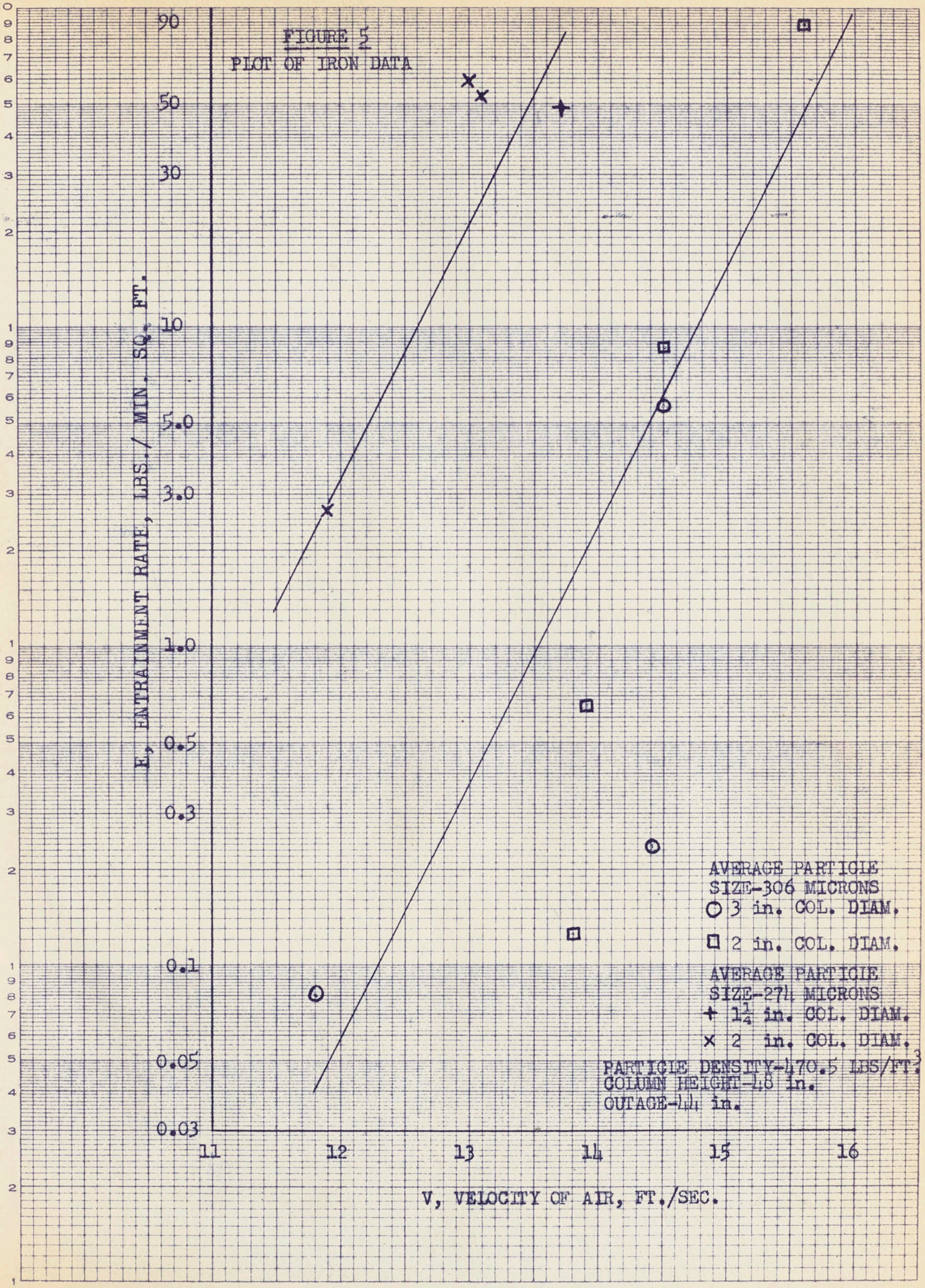


FIGURE 5
PLOT OF IRON DATA
E, ENTRAINMENT RATE, LBS./ MIN. SQ. FT.
90
50
30
10
5.0
3.0
1.0
0.5
0.3
0.1
0.05
0.03
11
12
13
14
15
16
V, VELOCITY OF AIR, FT./SEC.
AVERAGE PARTICLE
SIZE-306 MICRONS
3 in. COL. DIAM.
2 in. COL. DIAM.
AVERAGE PARTICLE
SIZE-274 MICRONS
1 1/4 in. COL. DIAM.
2 in. COL. DIAM.
PARTICLE DENSITY-470.5 LBS/FT.3
COLUMN HEIGHT-48 in.
OUTAGE-44 in.

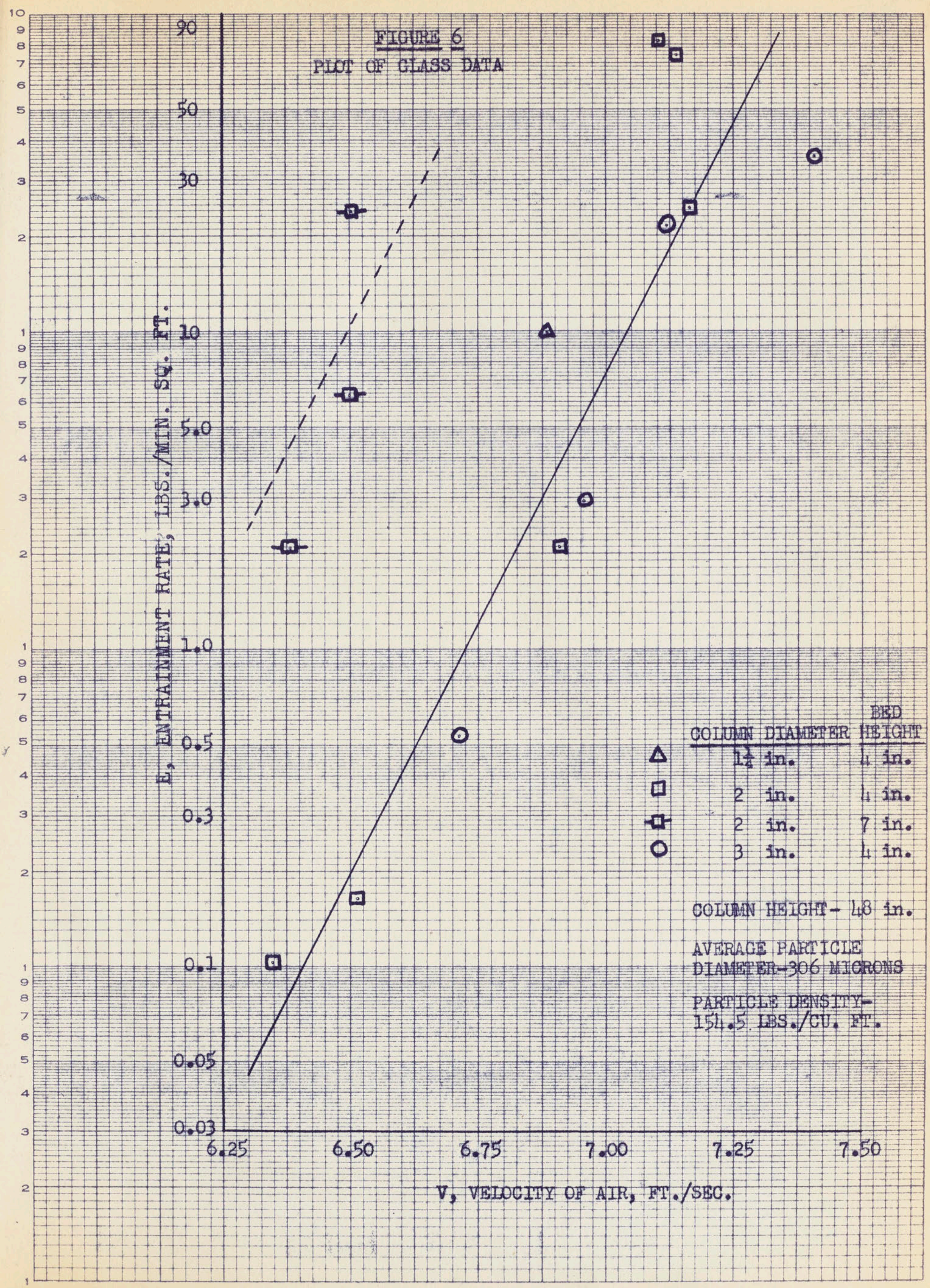


FIGURE 6
PLOT OF GLASS DATA
E, ENTRAINMENT RATE, LBS./MIN. SQ. FT.
V, VELOCITY OF AIR, FT./SEC.
90
50
30
10
5.0
3.0
1.0
0.5
0.3
0.1
0.05
0.03
6.25
6.50
6.75
7.00
7.25
7.50
COLUMN DIAMETER
BED HEIGHT
1½ in. 4 in.
2 in. 4 in.
2 in. 7 in.
3 in. 4 in.
COLUMN HEIGHT- 48 in.
AVERAGE PARTICLE DIAMETER-306 MICRONS
PARTICLE DENSITY- 154.5 LBS./CU. FT.

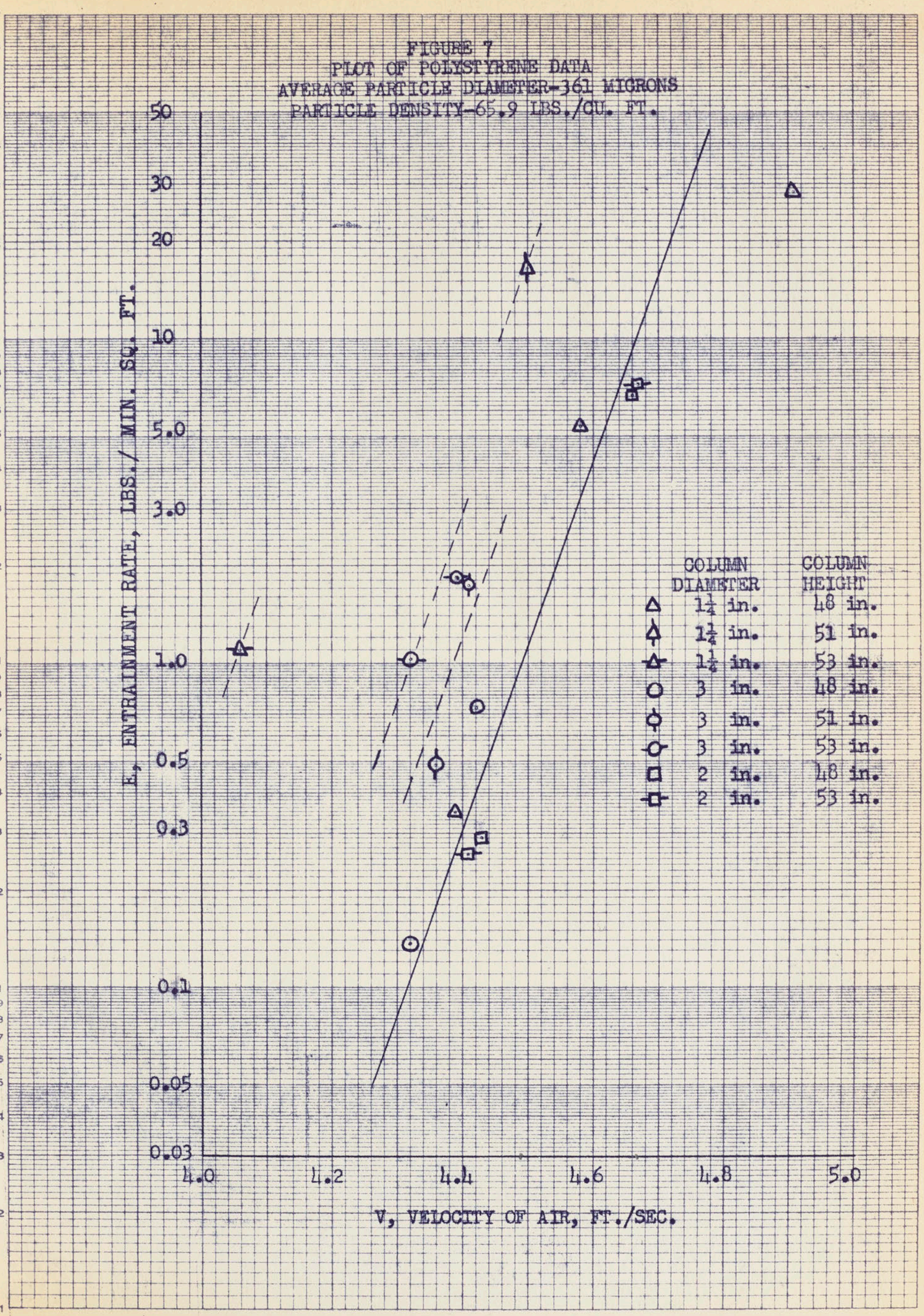


FIGURE 7
PLOT OF POLYSTYRENE DATA
AVERAGE PARTICLE DIAMETER-361 MICRONS
PARTICLE DENSITY-65.9 LBS./CU. FT.
E, ENTRAINMENT RATE, LBS./ MIN. SQ. FT.
V, VELOCITY OF AIR, FT./SEC.
50
30
20
10
5.0
3.0
1.0
0.5
0.3
0.1
0.05
0.03
4.0
4.2
4.4
4.6
4.8
5.0
COLUMN DIAMETER
COLUMN HEIGHT
1¼ in. 48 in.
1¼ in. 51 in.
1¼ in. 53 in.
3 in. 48 in.
3 in. 51 in.
3 in. 53 in.
2 in. 48 in.
2 in. 53 in.

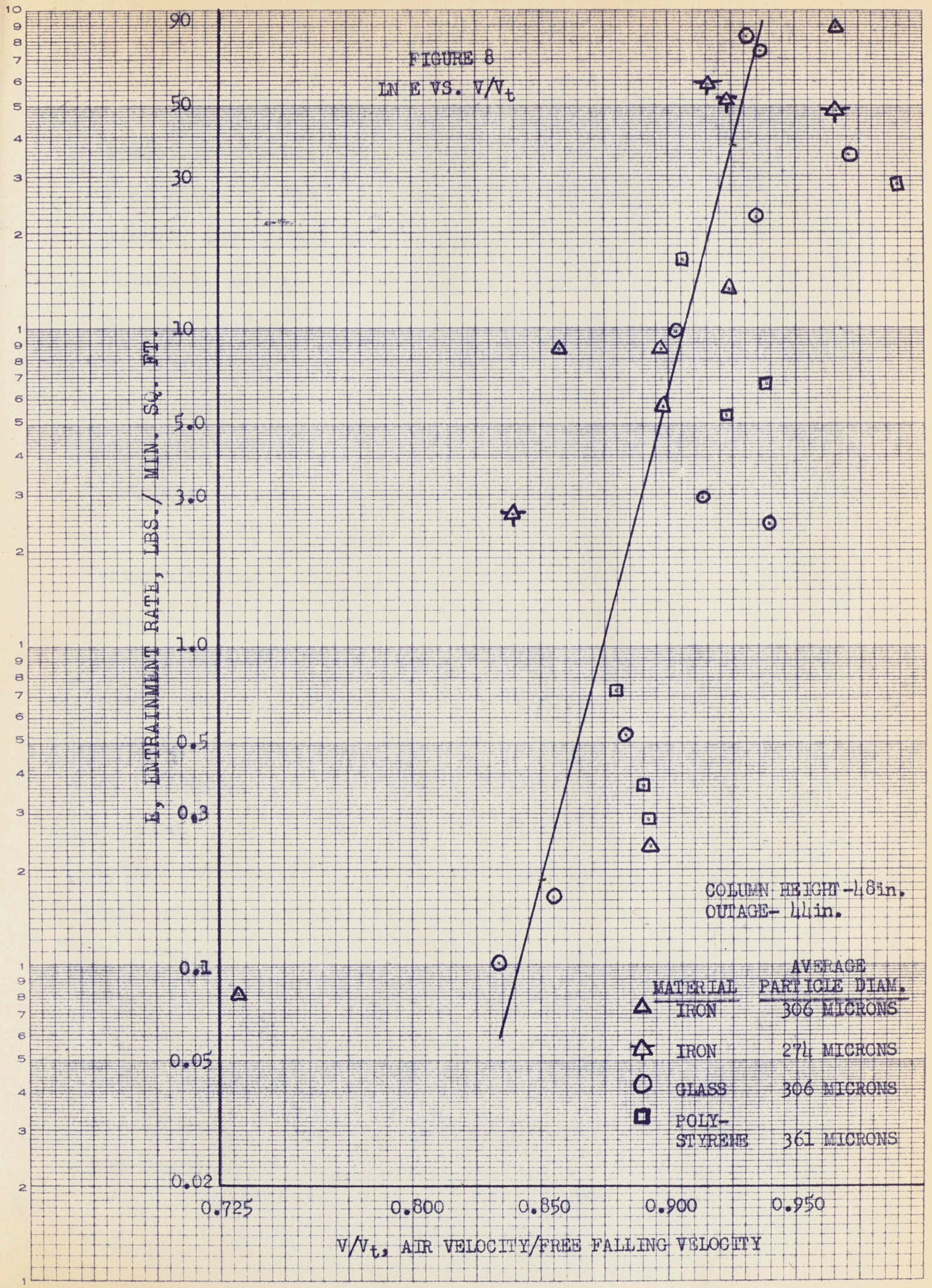


FIGURE 8
LN E VS. V/V_t
E, ENTRAINMENT RATE, LBS. / MIN. SQ. FT.
V/V_t, AIR VELOCITY/FREE FALLING VELOCITY
90
50
30
10
5.0
3.0
1.0
0.5
0.3
0.1
0.05
0.02
0.725
0.800
0.850
0.900
0.950
COLUMN HEIGHT-48in.
OUTAGE- 44in.
MATERIAL
AVERAGE PARTICLE DIAM.
IRON 306 MICRONS
IRON 274 MICRONS
GLASS 306 MICRONS
POLY-STYRENE 361 MICRONS

Again, no clear-cut difference is discernible in the entrainment rate, E, for the three different diameter columns. Outage, for comparative purposes with the data on iron, Figure 5, was 44 in. in a 48 in. column. For the three points determining the dashed line, which shows a greater entrainment rate at a given air velocity, the bed depth was increased to 7 in. in the 48 in. column. These three points were the only exception to the use of a 44 in. outage. Any increase in bed depth over 7 in. caused slugging.

Figure 7 is a plot of ln E vs. V for the polystyrene, particle size 361 microns, particle density 65.9 lbs. per cu. ft. Operation with a 4 in. bed with a 48 in. column showed that E was independent of the diameter of column used. When the bed depth was increased from 4 in. to 7 in. to 9 in. in the $1\frac{1}{4}$ in. and 3 in. columns with a constant 44 in outage, the entrainment rates for these columns increased. Increasing the bed depth to 9 in. with 44 in. outage for the 2 in. column did not appear to increase the rate of entrainment at constant V.

Figure 8 is an attempt at correlating the data for the iron, glass, and polystyrene. The plot in Figure 8 of ln E vs. $\frac{V}{V_t}$, where $\frac{V}{V_t}$ is the superficial to free-falling velocity ratio, contains all the data taken with a 4 in. dense bed and an outage of 44 in. The equation of the line in Figure 8 was found to be

$$E = 6.3 \times 10^{-27} e^{69.1\frac{V}{V_t}}$$

V DISCUSSION OF RESULTS

The original purpose of this study was to investigate the effects of particle density on entrainment rates. This involves much more than merely holding all other variables constant while varying only particle density. To begin with, the extreme sensitivity of entrainment rates to slight changes in velocity (See Figures 5-8) coupled with the fact that materials of different densities will entrain at far different velocities necessitated a series of velocity readings in order to obtain a basis for comparison of the entrainment rates with the variation in particle density. Similarly, variations between the entrainment rates (lbs. per min. sq. ft.) with column diameter had been noted (1, 2, 3, 4). Consequently, entrainment rates were studied in each of the $1\frac{1}{4}$, 2, and 3 in. columns.

Hyman (2) found that with a dense bed deeper than 3 in. entrainment rate was independent of bed depth for glass beads of 29 to 75 micron particle diameter. At first, it was assumed in this study, using much larger sized particles, that entrainment rates would be independent of bed depth. With iron there was no choice; a higher bed than 4 in. could not be attained without slugging. With the 306 micron glass beads, however, entrainment rate was found to increase if bed depth were increased (Figure 6). The outage for these three runs at increased bed depth was decreased, but previous work (2, 3, 4, 6) shows that this small percentage change in outage could not account for more than a 5 fold change in entrainment rate, as compared with the 50 fold change in rate shown in Figure 6. This shows, then, that the entrainment rate for the 306 micron glass beads is not independent of bed depth until at least a 7 in. bed depth in a 2 in. column. Further increases in bed depth were not possible, since above a 7 in. bed slugging was exhibited.

With the polystyrene beads, (Figure 7) increasing the dense bed height from 4 in. to 9 in. while keeping the same outage shows a 50 fold increase in entrainment rate in the $1\frac{1}{4}$ and a 12 fold increase in rate in the 3 in. columns. For some reason, an increase in bed depth did not increase the entrainment rate in the 2 in. column. Again, entrainment rates do not appear to be independent of bed depth for a bed depth less than 9 in., with the possible exception of the 2 in. column. Higher dense beds were not obtainable since at higher bed levels the solids recycling to the base of the column via the return line would not enter the column without plugging the line.

It could be argued that the increase in entrainment rate caused by increasing the height of the dense bed was due to unsteadiness or slugging. This is possible with the glass particles, for slugging was evident if the dense bed height exceeded 7 in. The polystyrene particles, however, did not show signs of unsteady fluidization or slugging at any of the dense bed heights used.

From the above discussion it appears that entrainment rates may be a function of dense bed height up to a dense bed of at least 7 to 9 in. in a $1\frac{1}{4}$ to 3 in. column for all particles in the 274 to 360 micron diameter range. With the exception of the constancy of entrainment rate with a variation in bed depth shown by polystyrene in the 2 in. column, there is no real indication that entrainment rate for the 274 to 360 micron particles can be considered independent of bed depth. Because of operational difficulties, however, no truly quantitative data were obtained concerning the direct effect of dense bed depth variations on entrainment rates.

Reference to Figures 5, 6, and 7 shows that at a 4 in. dense bed depth and a 44 in. outage, no difference in entrainment rates due to column diameter is visible. It should be noted that this lack of determinable column diameter effect is particularly apparent when it is realized that entrainment rates were such a strong function of velocity that a 1% variation in velocity could produce a two fold change in entrainment rate. Precision in determining velocities was about 1%, but the accuracy, or true value, was not as good

(See Appendix for details). Since the main object of this study is to determine the general nature of entrainment, the lower accuracy is not as serious as it might sound. As long as the data are internally consistent (precise), a basis for comparison is available. The precision in the determination and adjustment of all variables is judged sufficient to limit the error in entrainment rate to a three fold change (see Appendix). For this reason, a 6 fold column diameter effect could be concealed by inaccuracies in data.

Some semblance of a column diameter effect was noted with the polystyrene (Figure 7) at a 9 in. bed depth with a 44 in. outage. If the points representing the entrainment rates at a 9 in. bed depth are compared, a definite difference in entrainment rate (per cross sectional area) appears to exist, at a given air velocity. The entrainment rate for the 1¼ in. column is 50 times that of the 2 in. column, while the entrainment rate of the 3 in. column is 12 times that of the 2 in. column. Because of the operational difficulties involved at these higher dense bed depths, these relationships are subject to some doubt. For this reason no correlation was attempted concerning the apparent column diameter effect at the 9 in. bed depth.

Two operational problems, static electricity and particle sizing, are discussed in the Appendix, but should be mentioned here. As shown by Hyman (3) and others (1, 2, 4), serious electrostatic effects occur if the humidity of the air is too low. If the humidity is too high, the particles become damp and begin to cling together. This effect is illustrated in table A4 of the Appendix, which shows a run in which high relative humidity (70%) cut the entrainment rate by a factor of 8.

Particle sizing refers to the effect, again as noted by previous workers (1, 2, 3, 4, 5, 6) of the more rapid entrainment of smaller particles. Figure 5 shows a comparison of the different entrainment rates obtained at the same velocity with iron of 274 micron diameter and 306 micron diameter. The entrainment rate of the 274 micron particles is roughly 40 times that of the 306 micron particles at the same air velocity. At a fairly high rate of recycle, the effect of particle sizing is substantially reduced (see Appendix).

One of the major differences between this project and the work of the previous investigators (2, 3, 6) referred to is that in this study the solids entrained from the top of the column are continuously recycled to the base of the column. The previous investigators used a batch system where the amount of material in the bed was continually varying. This would mean that the entrainment rate would be continually varying and that each entrainment rate was the result of only one reading. With the continuous system used in this project each entrainment rate is an average of a series of readings. Each series comprises a run. For this reason the continuous system, as opposed to a batch system, would tend to offer much better control of the operating variables and a consequent greater reliability of results, particularly if particle sizing is a problem.

Comparison with the data of Hyman (2) reveals that the ratio of superficial air velocity to free falling terminal velocity $\frac{V}{V_t}$ for the 29 to 75 micron diameter glass spheres always exceeded unity. The present study shows a $\frac{V}{V_t}$ ratio of between 0.732 and 0.99. Hyman correlates the entrainment rate as a function of $\left(\frac{V-V_t}{V_t}\right)^{\frac{3.7}{2.7V}}$. Since in this study $\frac{V-V_t}{V_t}$ would always be a negative number and V was never less than 4 ft. per sec., entrainment rates using Hyman's correlation would be complex numbers! For this reason, comparison of the correlation of Hyman with the data of this study would give quite impossible results.

Experimentation revealed that the data obtained could be tentatively correlated by a plot of ln E vs. $\frac{V}{V_t}$, where E is the entrainment rate in lbs. per min. sq. ft. of cross sectional area and $\frac{V}{V_t}$ is the ratio of superficial to free falling terminal velocity. The slope and intercept of the plot (Figure 8) give the following relation:

$$E = 6.3 \times 10^{-27} e^{69.1\frac{V}{V_t}}$$

This correlation attempts to show not only the relation between different particle densities, but also the particle size variation that did exist between the materials used. The relationship holds only for a 4 in. dense bed depth with an outage of 44 in. in a $1\frac{1}{4}$ to 3 in. column. Average particle sizes ranged from 274 to 361 microns.

The main significance of this correlation is that the variation in entrainment rates for particles of different densities may be accounted for as a function of the ratio of superficial velocity to terminal free falling velocity in the range of variables studied. This correlation does not attempt to do more than indicate a general trend.

VI CONCLUSIONS AND RECOMMENDATIONS

From the results of the investigation it may be concluded that:

1. The rate of entrainment for solids fluidized by air is dependent of the height of the dense bed if the bed is less than 9 in. in a $1\frac{1}{4}$ to 3 in. column with an average particle size greater than 306 microns.

2. Within the realm of experimental error column diameter does not affect the rate of entrainment with 274 to 361 micron average diameter particles, a 4 in. bed depth, and a 44 in. outage in a $1\frac{1}{4}$ to 3 in. column. Column diameter does appear to affect entrainment rates at higher dense bed levels.

3. Ease of fluidization and steadiness of operation increases with 1) decreasing density, 2) increasing column diameter, and 3) decreasing particle size.

4. Slugging will exist at a bed depth above 4 in. for iron shot (306 micron average particle diameter) in a $1\frac{1}{4}$ in. to 3 in. column. Similarly, slugging will exist at a bed depth of 7 in. for glass (306 micron average particle diameter) in a $1\frac{1}{4}$ in. to 3 in. column.

5. The correlation of Hyman (<u>3</u>) of E as a function of $\left(\frac{V-V_t}{V_t}\right)^{\frac{3.7}{2.7V}}$ is no good for use with the data of this study.

6. The data may be tentatively correlated as

$$E = 6.3 \times 10^{-27} e^{69.1 \frac{V}{V_t}}$$

where E is the entrainment rate in lbs. per min. sq. ft. of cross section and $\frac{V}{V_t}$ is the ratio of superficial to free falling terminal velocity.

Recommendations for further study:

1) Investigate the effect of variations in density with smaller diameter particles.

2) Investigate the effect of materials with particle sizes between 274 and 361 microns in a column of diameter greater than 3 in.

3) Determine the effect on entrainment rates of dense bed height.

VII APPENDIX

A. SAMPLE CALCULATIONS AND ERROR ANALYSIS

1. Entrainment Rate

The entrainment rate, E, lbs. per min. per sq. ft. of column cross sectional area, was obtained by diverting the solids flowing through the return line into a weighed bottle for a given length of time. The average weight of material collected was determined to 0.2 grams by direct weighing on an analytical balance. The average time during which the sample was collected was measured with a stopwatch to the nearest half second. A number of such entrainment readings were taken for each run. During each run all variables were held constant; consequently, the average of the entrainment readings taken during the run determine the entrainment rate. The number of readings taken and the length of the run depended upon the constancy of the entrainment readings. The minimum standard for accepting a run was set at 3 readings taken over a 20 minute period. For this reason runs H2 (2 readings) and H11b (2 readings) were thrown out. The entrainment rate thus obtained is divided by the column cross sectional area to obtain the entrainment rate per unit cross sectional area. The error measurement of the column diameter was negligible according to Hyman (3), who used the same columns as were used in this study. Shown below is a sample calculation for the first run taken, number H1.

For the first reading taken in Run H1:

Time of Day - 2:50 p.m.

Interval-60±0.5 sec. or 0.8%

Weight Collected - 175.5 ± 0.2 or 0.1%

$$\text{Entrainment reading} = \frac{175.5 \pm 0.1\%}{60 \pm 0.5\%} = 175.5 \pm 0.6\% \text{ gm./min.}$$

Determination of the Entrainment Rate for Run H1:

Time of Day (p.m.)	Entrainment Reading (gm./min.)	Deviation
2:50	175.5	16.0
3:05	212.2	20.7
3:20	202.1	10.6
3:35	193.0	1.5
3:50	182.2	9.3
4:00	191.0	0.5
4:20	190.2	1.3
4:35	191.6	0.1
4:55	185.6	5.9
	9 ⌊1723.4	$\sqrt{9(9-1)}$ ⌊65.9
Average reading	191.5	7.8

Entrainment Rate = 191.5 ± 7.8 gm./min. or 4%

$$\text{Entrainment rate} = \frac{191.5 \pm 4\%}{3.14.6\,\frac{(1.25)^2}{144(4)}} = 49.6 \pm 4\% \text{ lbs./min. sq. ft.}$$

2. Calibration of Orifices

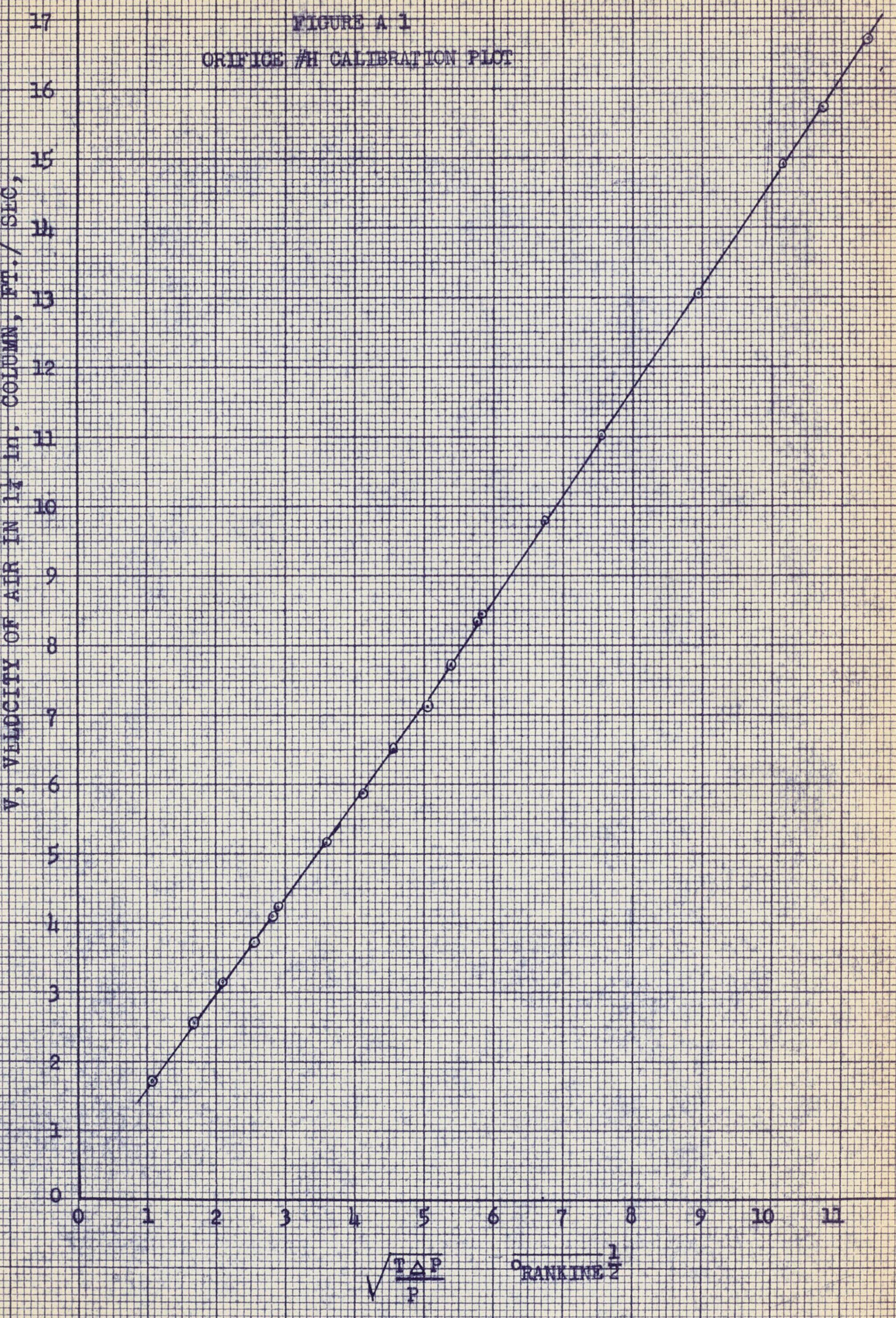
Air flow through orifice #H was determined by the use of a dry test meter to within 0.05 cu. ft./min. It should be noted, however, that the 0.05 cu. ft./min. refers to the precision in reading the meter. The accuracy or true reading of the meter could not be readily determined at the high flow rates used. In this study precision is much more important than accuracy, for the main problem here is to determine the general effects on entrainment rates of a change in velocity.

The pressure drop across the orifice and the static pressure at the orifice were measured to the nearest 0.1 inch of water. The temperature of the air was measured to 0.5 $^{\circ}F$ with a thermometer. Barometeric pressure was read to the nearest half inch of water. Time was measured with a stopwatch to the nearest second. The data on the orifice was plotted as $\sqrt{\frac{T\Delta P}{P}}$ versus V_o, where T is the temperature of the air at the orifice, P is the pressure drop across the orifice, and P is the air pressure at the orifice, V_o is the velocity of the air in ft./sec. at the $1\frac{1}{4}$ in. column (V_o is at orifice conditions). The deviation from actual diameter of the $1\frac{1}{4}$ inch column was found by Hyman (3) to be negligible. Table A1 shows the data for the calibration plot (Figure A1). Below is a sample calculation for the orifice calibration plot.

ΔP	Pressure drop	25.03 ± 0.1	inches water or 0.4%
T	Air Temperature	78 $^{\circ}F$ or 538 $^{\circ}$Rankine	$\pm 0.5^{\circ}$ or 0.1%
	Static Pressure Reading	1.10 ± 0.1	inches water
	Barometric Pressure	404.5 ± 0.5	inches water
P	Absolute Static Pressure	406.6 ± 0.6	inches water or 0.15%

FIGURE A 1

ORIFICE #H CALIBRATION PLOT



$$\sqrt{\frac{T\Delta P}{P}} = \sqrt{\frac{(538\pm0.1\%)(25.03\pm0.4\%}{(406.6\pm0.6\%)}} = 5.76\pm0.5\%$$

Air flow rate 8.38±0.05 cu. ft./min. or 0.6%

Time 120±1 sec. or 0.4%

$$V_o = \frac{(8.38\pm0.6\%)}{(120\pm0.4\%)(3.1416)\frac{(1.25)^2}{144}} = 8.31\pm1.0\%$$

Table A1
Orifice H Calibration Data

$\sqrt{\frac{T\Delta P}{P}}$ °Rankine$^{\frac{1}{2}}$	V_o Ft./Sec.
1.10	1.70
1.70	2.51
2.10	3.12
2.55	3.70
2.85	4.09
2.95	4.21
3.59	5.13
4.12	5.87
4.57	6.50
5.05	7.11
5.44	7.71
5.76	8.31
5.82	8.42
6.74	9.78
7.56	11.01
8.29	12.09
8.95	13.05
9.60	14.00
10.17	14.90
10.74	15.72
11.39	16.70

The calibration curves for orifices #1, 2, 3 as determined by Lang (4) are shown in Figure A2. Lang plotted $\frac{T\Delta P}{P}$ versus the air flow rate, cu. ft. per minute. Precision, as estimated by Lang is 1%; accuracy is about 7%. All four

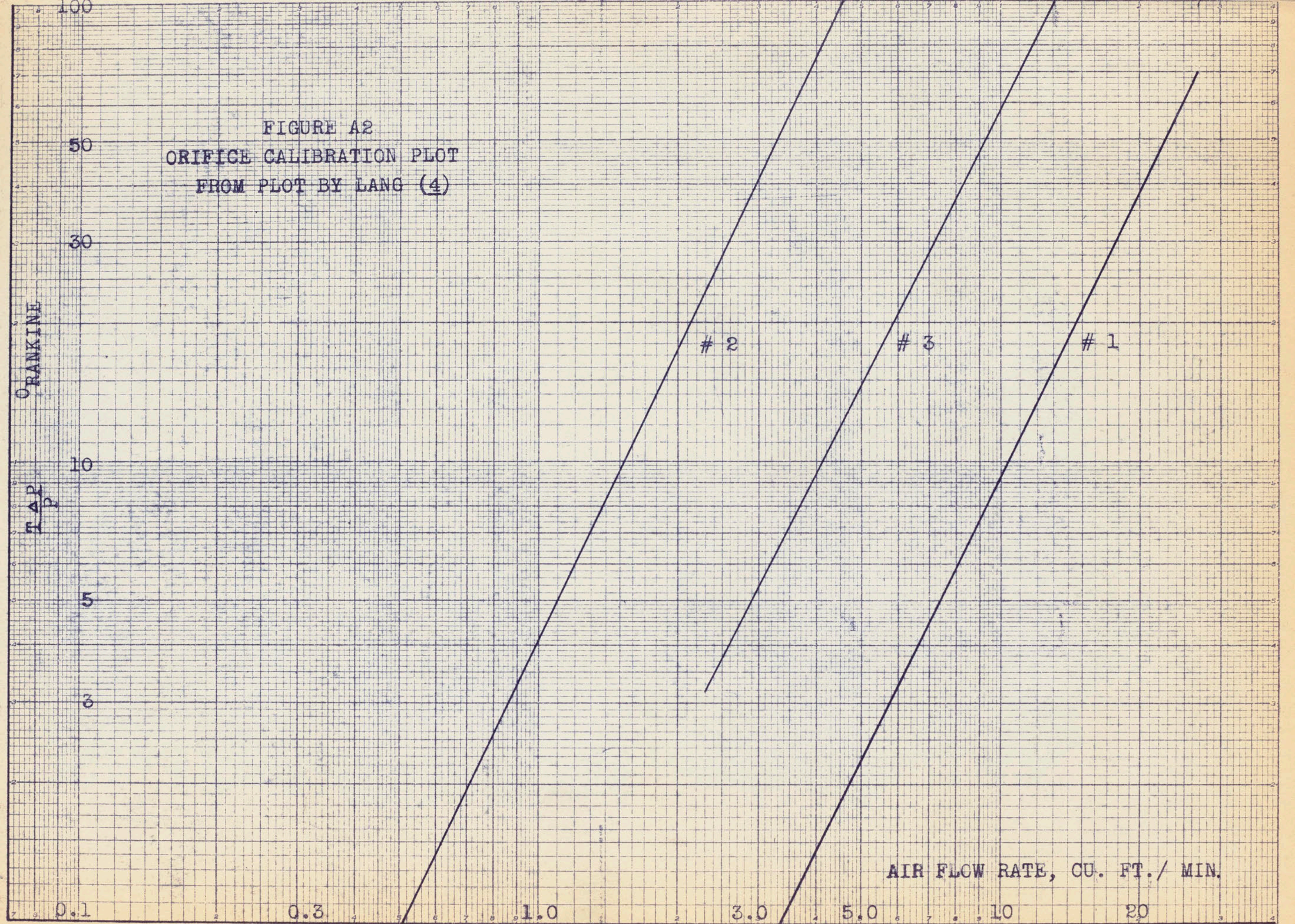


FIGURE A2
ORIFICE CALIBRATION PLOT
FROM PLOT BY LANG (4)
2
3
1
$\frac{T \Delta P}{P}$ °RANKINE
AIR FLOW RATE, CU. FT./ MIN.
100
50
30
10
5
3
0.1
0.3
1.0
3.0
5.0
10
20

orifices, 1, 2, 3, H, were checked by Lang and found to be consistent to 1%.

3. Velocity of Air

Using the orifice calibrations shown above, the following is a sample calculation of the superficial air, velocity, V, for run number H1. Errors are the same as described in the calibration of the orifice.

ΔP = 58.5±0.1 in H_2O or 0.17%

T = 531±0.5 ^oR. or 0.7%

Barometric Pressure	416. ± 0.5 in H_2O
Static Pressure	72.1 ± 0.1 in H_2O
P Absolute Static Pressure	488.1 ± 0.6 in H_2O or 0.12%

$$\sqrt{\frac{T\Delta P}{P}} = \sqrt{\frac{(531\pm0.5\%)(58.5\pm0.17\%)}{(488.1\pm0.12\%)}} = 8.05\pm0.9\%$$

V_o from plot then = 11.7 ft./sec.±1%

$$V = V_o \frac{(P)}{\text{Barometric Pressure}}$$

$$V = \frac{(11.72\pm1\%)(488.1\pm0.12\%)}{(416\pm0.12\%)} = 13.71\pm1.4\% \text{ ft./sec.}$$

4. Free Falling Velocity

A complete explanation of terminal velocity calculations may be found in Perry's Handbook (7).

5. Dense Bed Height

Dense bed height was determined by observation of the pressure readings at various heights in the column. Previous investigators (2, 3, 6) reported much higher pressures in the dense bed than in the transition region above the dense bed. For this reason the sudden drop in the pressure readings taken at 2, 4, 6, 8, and 10 inches from the bottom of the $1\frac{1}{4}$ in. column, as illustrated for Run #H1 in Table A2 below, indicated the level of the bed. At the same time, the dense bed depth was visually determined by shining the beam of a flashlight through the column. Visual observations and pressure tap observations were in general agreement.

Table A2
Dense Bed Depth

Run H1

Pressure tap distance from bottom of column	Pressure Reading
2 in.	7.0 in. water
4 in.	4.5 in. water
6 in.	3.5 in. water
8 in.	3.2 in. water
10 in.	3.0 in. water

Observed bed depth = 4 inches
Estimated error = ±0.5 inches

6. Outage

Outage is simply the difference between the column height and the height of the dense bed. For Run H1 the height of the dense bed was 4±0.5 inches, column height was 48±0.1 inches; therefore the outage was 44±0.6 inches or 1.5%.

7. Particle Size

Particle size was determined from microphotographs taken of the different particle samples. With the glass particles 87 particles were measured in this manner to give an average particle size of 306 microns with an average deviation of 15 microns or 5%. The polystyrene average particle diameter was found to be 361 microns with an average deviation of 5%. All particles observed were within the stated screen size. That is, all the glass particles were between 295 and 351 microns (corresponding to U. S. Standard screen sizes of 50 and 45 mesh). Because the screening methods were the same for the 45 to 50 mesh iron, the average particle diameter was taken as being the same as that of the glass, or 306 microns. The average particle size of the 50 to 60 mesh screen iron was, on the basis of the above discussion, taken as the geometric mean of these two mesh sizes, or 274 microns.

8. Particle Density

Density measurements were made with a pyknometer. The particles were weighed to 0.001 gram on analytical balance. Temperature was measured to 0.1 ^{o}C. The following is a sample calculation for the glass particles used.

Density of water at 26.2±0.1 ^{o}C (Perry (7))=0.99675 gm./ml. ±0.003%

Wt. water = 26.0124±0.001 gm. or 0.004%

$$\text{Vol. pyknometer} = \frac{26.0124 \pm 0.004\%}{0.99675 \pm 0.003\%} = 26.0972 \text{ ml.} \pm 0.007\%$$

Wt. glass = 15.3956±0.001 gm. or 0.007%

Wt. of water required to fill pyknometer when glass is present = 19.8063±0.001 or 0.005%

Density of water at 28.4±0.1% °C (Perry (7)) = 0.99614 gm./ml.±0.003%

$$\text{Volume of water} = \frac{19.8063 \pm 0.005\%}{0.99614 \pm 0.003\%} = 19.8832 \pm 0.008\% \text{ ml.}$$

$$\text{Density of glass} = \frac{15.3956 \pm 0.007\%}{(26.0972 \pm 0.007\%) - (19.8832 \pm 0.008\%)}$$

Density = 2.477±0.022% gm./ml. or 154.5±0.02% lb./cu. ft.

B. OPERATIONAL PROBLEMS

1. Particle Sizing

When particles of unequal size, but similar shape and density, are fluidized, the smaller diameter particles have been shown to entrain at a much higher rate (2, 3, 4, 5, 6). This means that at a given velocity the entrainment readings for a mixture of slightly different sized particles would gradually decrease, as the more rapidly entrained, smaller particles are removed. If the entrained particles were returned immediately to the base of the column, no difference in entrainment rate would be noted, but if, as in this study, some material is allowed to accumulate in the return line, definite changes in entrainment rate over time are found. At higher entrainment rates the rate of recycle will reduce these variations in entrainment readings due to this particle sizing on entrainment readings for runs H20 and H22. Notice that at the higher entrainment rate in H22 the entrainment readings are almost constant.

Table A3

Run H20

Material---glass spheres, average particle size 306 microns.
3 in. diameter column. Air velocity 6.78 ft./sec.

Time of Day (p.m.)	Entrainment Reading (gm./min.)
2:35	13.8
2:45	8.5
3:05	6.1
3:20	3.7
The materials were thoroughly remixed at this point.	
3:30	32.4
3:45	11.7
3:55	14.5
4:05	4.2

Run H22

Material---glass spheres, average particle size 306 microns.
3 in. diameter column. Air velocity 7.41 ft./sec.

Time of Day (p.m.)	Entrainment Reading (gm./min.)
4:10	737
4:20	714
4:50	871
5:00	828

2. Humidity

Previous workers (1, 2, 3, 6) have shown that strong electrostatic effects were created in their air fluidized beds if the humidity of the air were too low. The effects were such that a definite spark could be drawn from the apparatus. The static electricity caused the particles to cling to gether and to the wall of the apparatus, thus affecting the entrainment rate. If the relative humidity of the air were held between 45 and 60%, these electrostatic effects were reported to be substantially eliminated.

In the present investigation, some electrostatic effects were noted, especially with the glass any polystyrene beads even when the relative humidity, as determined by wet and dry bulb thermometer readings, were held between 45 and 60%. At the higher relative humidity used in Run H15 (70%) the beads became damp and started to cling together, thus lowering the entrainment rate substantially. This observation shows that the 45 to 60% relative humidity range for the air does appear to be the best humidity operating range in order to minimize both electrostatic and particle wetting effects. The results of Run H15 are shown in Table A4 below.

Table A4

Run H15

Material---glass spheres
Column---2 inch Lucite column.

Relative Humidity	Time of Day (p.m.)	Entrainment Reading (gm./min.)
48%	4:30	705
48%	4:40	760
48%	4:50	770
70%	5:00	164
70%	5:10	232
48%	5:15	460 (beads still wet)

Table A5

Summary of Data

Run #	Material	Col. Hgt. (in.)	Col. Diam. (in.)	Observed Bed (in.)	No. of Readings	Length of run (min.)	$\bar{E}$ lbs./ min. ft.^{2}	V ft./sec.	% Rel. Humidity	V/V_t
H1	Iron	48	$1\frac{1}{4}$	4	9	125	49.6	13.71	50	0.967
H2	"	48	2	4	2	(run thrown out- too few readings)				
H3a	"	48	2	4	3	40	53.5	13.1	40	0.924
H3b	"	48	2	4	4	90	59.6	13.0	50	0.916
H4	"	48	2	4	5	50	2.64	11.9	60	0.839
H5	"	48	3	4	6	60	0.082	11.8	35	0.732
H6a	"	48	2	4	3	35	0.657	13.9	50	0.861
H6b	"	48	2	4	3	25	0.129	13.8	50	0.855
H7	"	48	2	4	9	70	89.0	15.6	48	0.966
H8	"	48	3	4	3	40	5.7	14.5	50	0.898
H9	"	48	2	4	3	45	8.64	14.5	58	0.898
H10	"	48	3	4	3	65	0.237	14.4	32	0.893
H11a	Glass	48	2	4	3	60	24.7	7.16	60	0.940
H11b	"	48	2	8	2	(run thrown out-too few readings)				
H12	"	48	2	7	4	20	24.0	6.50	50	0.854
H13	"	48	2	4	6	75	0.101	6.35	47	0.834
H14	"	48	2	4	4	30	0.162	6.52	70	0.835
H15	"	48	2	4	3	20	75.2	7.13	48	0.936
H16	"	48	2	4	5	80	82.6	7.10	45	0.932
H17	"	48	2	7	6	70	6.28	6.50	40	0.854
H18	"	48	2	7	3	20	2.1	6.41	56	0.842
H19	"	48	3	4	5	60	22.0	7.12	45	0.935
H20	"	48	3	4	8	90	0.534	6.72	50	0.884

Table A5 (Continued)

Run #	Material	Col. Hgt. (in.)	Col. Diam. (in.)	Observed Bed (in.)	No. of Rdgs.	Length of run (min.)	E lbs./min. ft.^{2}	V ft./sec.	% Rel. Humid.	V/V_t
H21	Glass	48	3	4	5	45	2.93	6.96	48	0.914
H22	"	48	3	4	4	50	35.4	7.41	52	0.973
H23	"	48	$1\frac{1}{4}$	7	3	40	9.97	6.88	48	0.903
H24	Polystyrene	48	$1\frac{1}{4}$	4	4	45	0.35	4.39	47	0.885
H25	"	48	$1\frac{1}{4}$	4	3	50	28.3	4.91	46	0.990
H26	"	48	$1\frac{1}{4}$	4	5	45	5.28	4.58	62	0.924
H27	"	48	$1\frac{1}{4}$	5	4	45	16.2	4.50	50	0.906
H28	"	48	2	4	3	45	0.289	4.43	50	0.893
H29	"	48	2	5	4	45	6.67	4.66	52	0.939
H30	"	53	2	9	4	30	0.257	4.41	61	0.829
H31	"	53	2	9	5	50	7.16	4.67	61	0.941
H32	"	53	$1\frac{1}{4}$	9	4	55	1.11	4.06	53	0.817
H33	"	48	3	4	6	75	0.138	4.32	51	0.870
H34	"	48	3	7	4	40	1.75	4.41	50	0.879
H35	"	51	3	7	5	45	0.49	4.26	50	0.858
H36	"	51	3	9	4	40	1.81	4.39	53	0.885
H37	"	53	3	9	5	50	1.02	4.32	49	0.870
H38	"	53	3							

C. NOMENCLATURE

E	Entrainment rate, pounds per minute per square foot of column cross sectional area
ΔP	Pressure drop across the orifice used to measure the air flow, inches of water
P	Absolute static pressure of the air at the orifice, inches of water
V	Superficial air velocity in the columns used, feet per second at the column conditions
V_o	Superficial air velocity in the columns used, feet per second, at the orifice conditions
V_t	Terminal free falling particle velocity, feet per second
T	Air temperature, degrees Rankine

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