1970

Modified venturimeter; a measuring device for solid-liquid mixtures, September 1970

M. Robinson

O. Yucel

W. H. Graf

Recommended Citation

Robinson, M.; Yucel, O.; and Graf, W. H., "Modified venturimeter; a measuring device for solid-liquid mixtures, September 1970" (1970). *Fritz Laboratory Reports.* Paper 1980.
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1980

Transport of Solid Suspensions in Conduits
Part II

MODIFIED VENTURIMETER; A MEASURING DEVICE FOR SOLID-LIQUID MIXTURES

M. Robinson, O. Yucel, and W. H. Graf
Fritz Engineering Laboratory
LEHIGH UNIVERSITY
Bethlehem, Penna. 18015

for the
Federal Water Quality Administration
Department of the Interior

WP-01478-02 (11020EKD)

September 1970

TABLE OF CONTENTS

ABSTRACT

The Venturimeter is shown to be a useful device in measuring the flow rate and the solids concentration of a sand-water mixture flow. Two different Venturimeters were tested at Lehigh University. The results are summarized, together with those from an earlier investigation at the University of California in Berkeley.

The pressure drop and the energy loss were observed. The former was correlated with the mixture discharge and the velocity at the throat of the Venturi. An average value for the flow coefficient was determined for each Venturi and compared with those of the standard clear-water Venturimeters. The relative energy loss due to the presence of the solids was correlated with the solids concentration. Convenient nomograms were presented for use in engineering applications.

1. INTRODUCTION

The Venturimeter, a reliable device for measuring the flow rate in clear-water systems, is investigated for its application in the determination of the mixture flow rate and the solids concentration in sand-water mixture flow.

Much of the theory for clear-water flow is applicable to the mixture flow as well. Only a slight modification is to be made for the relationship between the flow rate and the pressure drop. A second relation is derived from energy loss recorded across the Venturimeter to determine the solids concentration.

Two Venturimeters were tested at Lehigh University. The data from the 3 in. and 4 in.-Venturimeters are tabulated in Tables I and II, respectively. Two types of uniform sands were used, with sizes of d_{50} = 0.45 mm and 0.88 mm. Table III presents the data for a 3 in.-Venturi tested with two sizes of sand, d_{50} = 1.17 mm and 1.70 mm from an earlier investigation reported by Graf (1967) at the University of California in Berkeley.

Figures 1a, 1b, and 2 illustrate the geometrical characteristics of the Venturimeters tested both at Lehigh and at the University of California, Berkeley, respectively. The pressure drop, a_m, in ft, was correlated with the flow rate, Q, in gpm and the throat velocity, V, in fps. This is presented in Figs. 3 to 8. Figure 9 includes a diagram for the flow coefficient c_V of the standard clear-water Venturimeters. The average values of c_V obtained from the tests and sand-water mixture flow are also indicated within the limited range of Reynolds number covered for each Venturimeter.

Figures 10, 11, and 12 present a relationship between the energy loss for clear-water tests, b_o, in ft, and throat velocity, V, in fps. The relative energy loss, $(b-b_o)/b_o$, due to solids only, was plotted against the solids concentration, C, in percent, for each Venturimeter and for different sizes of sand as given by Figs. 13, 14, and 15.

A multi-variable regression analysis was made for the relationship between the total energy loss, b, and the solids concentration, C, and the velocity at the throat of the Venturimeter, V. These relationships are given in Figs. 16, 17, and 18 for each Venturimeter and for different sand sizes.

Figures 19, 20, and 21 illustrate the nomographic relationship obtained between the mixture pressure drop, a_m, the total energy loss, b, the solids concentration, C, and the velocity at the throat, V. These nomograms provide fast and sufficiently accurate solutions for the practical engineering purposes.

2. ANALYSIS

The familiar relationship between the flow rate and the pressure drop for a Venturimeter evolved from combining the equations of energy for steady clear-water flow and of continuity may be written as:

$$Q = c_V \frac{A_2}{\sqrt{1 - (A_2/A_1)^2}} \sqrt{2g} \sqrt{\frac{\Delta p}{\gamma}} \tag{1}$$

where Q is the volumetric flow rate; A_1 and A_2 are the cross sectional areas of the pipeline and the throat of the Venturimeter, respectively; Δp is the pressure difference between the entrance of the Venturimeter and its throat; γ is the unit weight of the liquid; and c_V is a flow coefficient to correct for the real fluid effects, and is a function of the meter shape, the throat-to-pipeline-diameter ratio, and the Reynolds number.

The laws that govern the liquid flow through a Venturimeter can also be applied to the solid-liquid mixture flows provided the proper assumptions and modifications are made. The only modification necessary to use Eq. (1) for mixture flow is that the pressure drop must be taken in terms of column of mixture. Thus, Eq. (1) can be rewritten as:

$$Q_m = \left[c_V \frac{A_2}{\sqrt{1 - (A_2/A_1)^2}} \sqrt{2g} \right] \sqrt{\frac{\Delta p}{\gamma_m}} \tag{2}$$

where subscript m refers to the mixture flow. The term in brackets in Eq. (2) is invariant for each Venturimeter. The pressure drop $\Delta p/\gamma_m$ is in terms of head of mixture, with $\gamma_m = \gamma\ (1-C) + \gamma_s C$, where γ_m, γ, and

γ_s are the specific weights of the mixture, water, and the sand, respectively; and C is the volumetric concentration. Designating this mixture pressure drop by a_m, it can be seen from Eq. (2) that the pressure drop due to mixture flow in column of mixture, a_m, is proportional to the square of the mixture flow rate, Q_m, or

$$a_m = C_m Q_m^2 \qquad (3)^*$$

The second relationship, required to determine the solids concentration in a two-phase flow, is found from the total energy loss, b, across the Venturimeter. It is dependent on both the flow rate and the solids concentration. The energy loss for clear-water flow through the Venturimeter, due to the friction, expansion, and contraction, designated by b_o, is solely dependent on the flow rate. Thus, the difference between the total energy loss and that for clear water, namely $(b - b_o)$, should be a function of the solids concentration and the geometry of the Venturimeter. This yields the relationship:

$$(b - b_o) = \text{fct } (C, \ell_V) \qquad (4)$$

where ℓ_V is the length of the Venturimeter over which the energy losses are recorded, and is invariant for each Venturimeter.

Equations (3) and (4) form the two relationships required for the determination of two unknowns, Q_m and C. Actual measurements of the pressure drop a_m, and the energy losses b and b_o will provide information on the value of the coefficient C_m, and on the form of the function fct.

---

[*] The coefficient, C_m, may be considered as being similar to the flow coefficient, c_V, for standard clear-water Venturimeters.

3. DESCRIPTION OF EXPERIMENTS

3.1 Lehigh Experiments

Two Venturimeters were tested for flow rates ranging from 160 to 600 gpm, and for solids concentrations up to 14 percent by volume. The geometrical characteristics of both the 3 in.- and the 4 in.-Venturimeters are given by Figs. 1a and 1b. The 3 in.-Venturimeter has a throat diameter of 2⅛ in. and the latter has a throat diameter of 2.0 in.

Two highly silica sands were used. The finer one had a mean size of d_{50} = 0.45 mm and a uniformity coefficient of d_{90}/d_{50} = 1.07. The coarser sand had a mean size of d_{50} = 0.88 mm and a uniformity coefficient of d_{90}/d_{50} = 1.21. Both sands had a specific gravity of 2.65. Both sands were observed to have virtually no sign of attrition; however, an abrasive effect was noted scouring away much of the nickel coating on the inside of the 3 in.-Venturimeter. No major attack was observed on the cast iron 4 in.-Venturimeter.

The Venturimeters were placed in a horizontal position along a 40 ft-test length along with two plexiglas observation sections to assure non-deposit flow. The deposit regime was not considered in this study.

The mixture flow rate, Q_m, and the solids concentration, C, were measured with the "Loop System", the use of which was given with detailed description by Einstein et al. (1966). These measurements were also checked with flow rate recordings on a Foxboro Magnetic

Flowmeter and with a sand-sampling device resembling the Pitot-tube. A discussion on the computational procedures is given in the Appendix.

The pressure drop and energy loss measurements were obtained by using mercury-water manometers. The manometer scales were graduated in tenths of an inch, readings to a hundredth of an inch were estimated, and each reading was converted to feet of water columns. Minor manometer fluctuations always existed, which was particularly the case for the more antiquated 4 in.-Venturimeter. This was attributed to be due partly to the uneven distribution of sediment concentration through the large system.

3.2 The University of California at Berkeley Experiments

A 3 in.-Venturimeter was tested by Graf (1967) with a system very similar to that at Lehigh University. The Venturimeter had a throat diameter of 2⅛ in.; its geometrical characteristics are illustrated in Fig. 2. The tests were carried out for flow rates ranging from 140 to 250 gpm, and for solids concentrations up to 17 percent by volume. The two types of sands used had mean sizes of $d_{50} = 1.17$ mm and $d_{50} = 1.70$ mm, respectively. The finer sand had a specific gravity of 2.61, and this was 2.73 for the latter. The testing system and procedures were reported to be similar to the ones employed at Lehigh University.

4. RESULTS

The data for the tests conducted at Lehigh University are summarized in Tables I and II. Table III is a summary of the data from the University of California at Berkeley tests. The data were evaluated to obtain relationships in conjunction with Eqs. (3) and (4) which were developed previously in Section 2.

4.1 Pressure Drop

The pressure drop was correlated with both the flow rate and the velocity at the throat of the Venturimeter. The relationships obtained by the method of least-squares are given by Figs. 3 through 8. Each set of data includes the clear water and the mixture data with two-sizes of sand for each Venturimeter tested. The effect of the solids has been taken care of by the fact that the pressure drop is expressed in terms of the mixture head.

4.1.1 Lehigh Experiments

Figures 3 and 4 show all the data for the 3 in.-Venturimeter tested. The data for the 4 in.-Venturimeter are plotted in Figs. 5 and 6. The scatter is little in all cases. Figures 3 and 5 give direct information on the flow rate in terms of the mixture pressure drop. Figures 4 and 6 provide information on the throat velocity; they are also used to determine the variation of the coefficient of flow for both Venturimeters tested.

4.1.2 The University of California at Berkeley Experiments

All the data for the 3 in.-Venturimeter tested have been shown in Figs. 7 and 8. The scatter is seen to be more than the case for the

Lehigh experiments. This is attributed to the following fact. In Lehigh experiments the non-deposit regime of flow was assured in all tests by use of the transparent observation sections; whereas such a control could not be done in the University of California at Berkeley experiments for low flow regimes particularly. Therefore, some of the data recorded were for the deposit-regime of flow. Naturally, significant changes in the cross sectional characteristics of the Venturimeter are expected under such conditions to result in considerable scatter.

4.1.3 Average Flow Coefficients

The flow rate through a Venturimeter is given by Eq. (2) which can also be written in terms of the throat velocity as:

$$V = c_V \sqrt{2g}\,\sqrt{a_m} \tag{5}$$

where V is the velocity at the throat of the Venturimeter; c_V is the flow coefficient and a_m is the mixture pressure drop in column of mixture. Thus, c_V can be obtained for each Venturimeter by making use of Figs. 4, 6, and 8, which give relationships in the form of:

$$a_m = C_m V^2 \tag{6}$$

The average values of the coefficient C_m obtained for each Venturimeter is given in the following:

		C_m
Lehigh Experiments,	3"-Venturi	0.0162
Lehigh Experiments,	4"-Venturi	0.0165
University of California at Berkeley Experiments,	3"-Venturi	0.0129

This coefficient, C_m, is to be determined experimentally for each Venturimeter. This does not represent any surprising disadvantage, since the coefficient, C_m, has to be determined, by tests, in any case for a Venturimeter, whether with or without the presence of solids in the liquid. The relationship between C_m and flow coefficient c_V may be obtained from Eqs. (5) and (6) which yield

$$c_V = \frac{1}{\sqrt{2g\ C_m}} \tag{7}$$

which gives an average value for the flow coefficient within the ranges of Reynolds number covered during the experiments. These ranges are: $2.63 \times 10^5 < Re < 9.91 \times 10^5$ and $2.75 \times 10^5 < Re < 1.0 \times 10^6$ for the 3 in.- and 4 in.-Venturimeters, respectively, tested at Lehigh University; and $2.30 \times 10^5 < Re < 4.18 \times 10^5$ for the 3 in.-Venturimeter tested at the University of California at Berkeley. The corresponding average coefficients of flow are plotted on Fig. 9 along with the ones for the standard clear-water Venturimeters. Obviously, the ranges of experiments for mixture flow are extremely limited. Therefore, no conclusive remarks can be made. Extensive experiments would have to be made for a wide range of Venturimeters, of solids size and concentrations, and of flow rates in order to obtain a chart for the coefficients of flow such as similar to the ones for the clear-water Venturimeters.

4.2 Energy Loss

The second relationship required, in addition to that of the pressure drop, is obtained from the energy loss data. The total energy loss, b, in ft of water column, in a mixture flow through a Venturimeter, consists of two components. The first component is the sum of the frictional loss and of the contraction-expansion losses. It is called "the clear-water energy loss", and designated by b_o in ft of water column. The second component is due to the presence of the solids in the mixture flow. It is given by $(b-b_o)$ in column of water.

Two somewhat similar relationships were obtained. (I) The energy loss due to solids, $(b-b_o)$, was correlated with the solids concentration, C. (II) The total energy loss, b, was correlated with the throat velocity, V, and the solids concentration, C. Either of the two relationships constitutes the second equation required. It should be emphasized that both energy loss equations cannot be used simultaneously since they are equivalent.

4.2.1 Relative Energy Loss due to the Solids

The relative value of the energy loss due to the presence of the solids, with respect to the clear-water energy loss, was expressed with a dimensionless quantity, or $(b-b_o)/b_o$. This quantity is expected to be a function of the solids concentration, only. By this consideration, a general relationship of the form of:

$$\frac{b-b_o}{b_o} = k\,C^n \qquad (8)$$

is suggested. The exponent n and the coefficient k might take different values under different conditions. For any Venturimeter and sand size, these coefficients have to be determined experimentally. The experiments reported herein were conducted to determine the coefficient k and the exponent n for the particular Venturimeters and the sand sizes used in the investigation.

The relative energy loss due to solids, $(b-b_o)/b_o$, was plotted as a function of the solids concentration, C, as illustrated in Figs. 13 through 15. Simple straight-line fits to the data, assuming that n = 1, yielded the following values for the coefficient k:

Experiment	Venturi	Sand Size d_{50}	k
Lehigh Univ.	3 in.	0.45 mm	0.076
Lehigh Univ.	3 in.	0.88 mm	0.109
Lehigh Univ.	4 in.	0.45 mm	0.067
Lehigh Univ.	4 in.	0.88 mm	0.100
Univ. of Calif., Berkeley	3 in.	1.17 mm	0.190
Univ. of Calif., Berkeley	3 in.	1.70 mm	0.120

It should be emphasized, again, that the values presented above reflect only a very limited number of data. If the assumption that n = 1 was not made, the coefficient k would have probably taken more consistent values for values of the exponent other than $n \approx 1$. However, this was not done in the present study, merely due to the fact that the limited data would not allow us to make strong conclusions.

4.2.2 Total Energy Loss

As a second approach, the total energy loss, b, in ft of water column, was correlated with the throat velocity, V, and the solids concentration, C. The relationships obtained with a multi-variable regression analysis represent the data very well, and are given in the following:

Experiment	Venturi	Sand Size d_{50}	Relationship
Lehigh Univ.	3 in.	0.45 mm	$b = 0.37 \frac{V^2}{2g} + 7.06C$
Lehigh Univ.	3 in.	0.88 mm	$b = 0.31 \frac{V^2}{2g} + 20.90C$
Lehigh Univ.	4 in.	0.45 mm	$b = 0.44 \frac{V^2}{2g} + 51.12C$
Lehigh Univ.	4 in.	0.88 mm	$b = 0.50 \frac{V^2}{2g} + 61.32C$
Univ. of Calif., Berkeley	3 in.	1.17 mm	$b = 0.38 \frac{V^2}{2g} + 4.57C$
Univ. of Calif., Berkeley	3 in.	1.70 mm	$b = 0.32 \frac{V^2}{2g} + 4.85C$

where:

b = total energy loss, in ft of water column

V = mixture velocity at Venturi throat, in fps

C = solids concentration, in fraction by volume

Figures 16 through 18 illustrate the above relationships in graphical form.

4.3 Engineering Applications

The mixture velocity, V, and the solids concentration, C, through a pipe can be determined if the pressure drop, a, in water column and the energy loss, b (or$(b-b_o)/b_o$), across the Venturimeter are known. For each Venturimeter and sand size tested, two equations are available, namely the pressure drop, a, and the total energy loss, b, both measured in ft of water column as functions of the throat velocity, V, and the solids concentration, C. For each such case, these two unknowns, i.e., V and C, are determined by a trial and error procedure.

For a faster calculation, a nomogram is more convenient to use for this purpose provided the desired accuracy is met. Figures 19 through 21 present such nomograms for each series of tests. It should again be remarked with emphasis that these nomograms are valid only for the very conditions under which the experiments were carried out, such as, the geometry of the Venturimeter and the size of the sand.

5. CONCLUSIONS

Experiments were conducted to explore the applicability of the Venturimeter as a measuring device in solid-liquid mixture flow. The data for three different Venturimeters and for four different sand sizes revealed the following conclusions:

1. The mixture flow rate, Q_m, is related to the pressure drop, a_m, measured in column of mixture, in a similar manner as is the clear-water flow rate, Q, to the pressure drop, a, measured in column of water. The general equation is of the form:

$$a_m = C_m Q_m^2 \tag{A}$$

The coefficient, C_m, must be determined experimentally in either case.

2. The solid concentration, C, is related to the relative energy loss due to the solids, $(b-b_o)/b_o$, as given by the general relationship in the form of:

$$\frac{b-b_o}{b_o} = k\, C^n \tag{B}$$

The coefficient k and the exponent n must be determined experimentally for any particular Venturimeter and sand size.

3. The two equations (A) and (B) obtained in each case have to be solved simultaneously (by a trial-and-error procedure) to determine the unknowns, namely the mixture flow rate, Q_m, and the solids concentration, C.

4. For the particular Venturimeters and sand sizes tested at Lehigh University and at the University of California at Berkeley, convenient nomograms are presented for the purposes of faster computation in engineering applications.

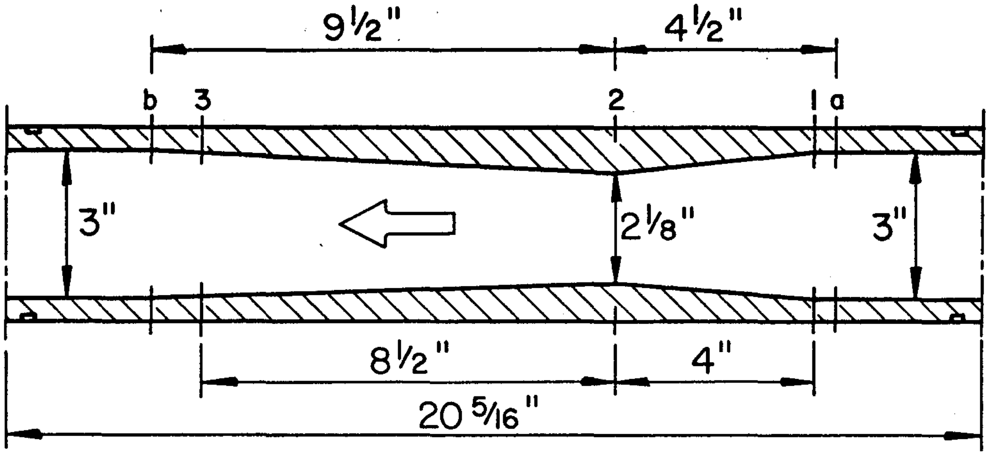


Fig. 1a 3 in.-Venturi Tested in Lehigh Experiments

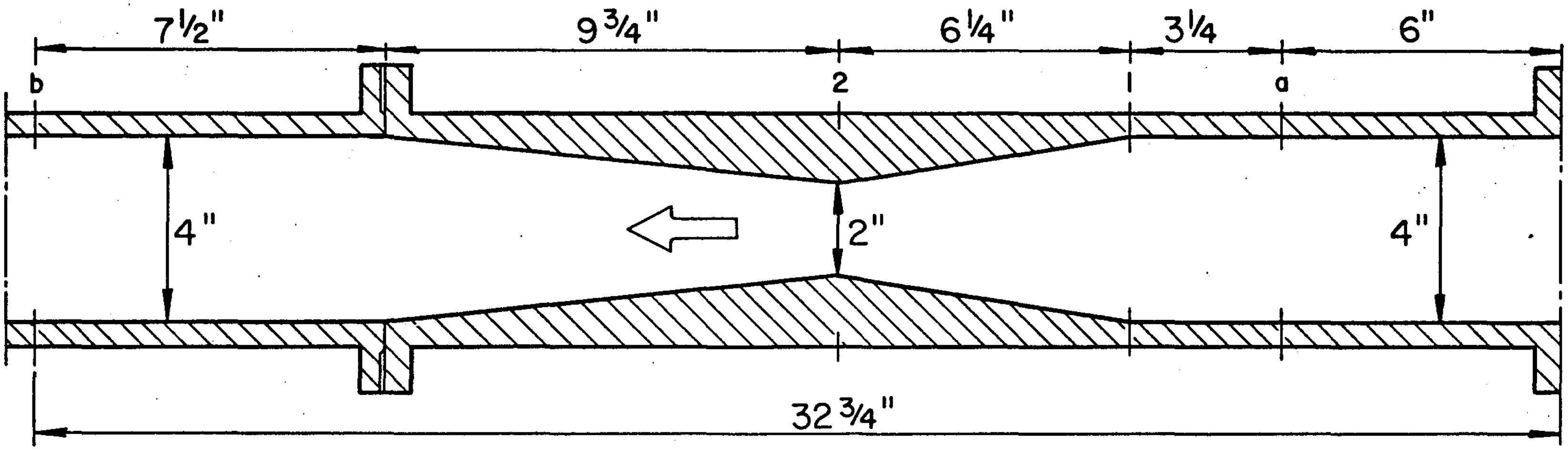


Fig. 1b 4 in.-Venturi Tested in Lehigh Experiments

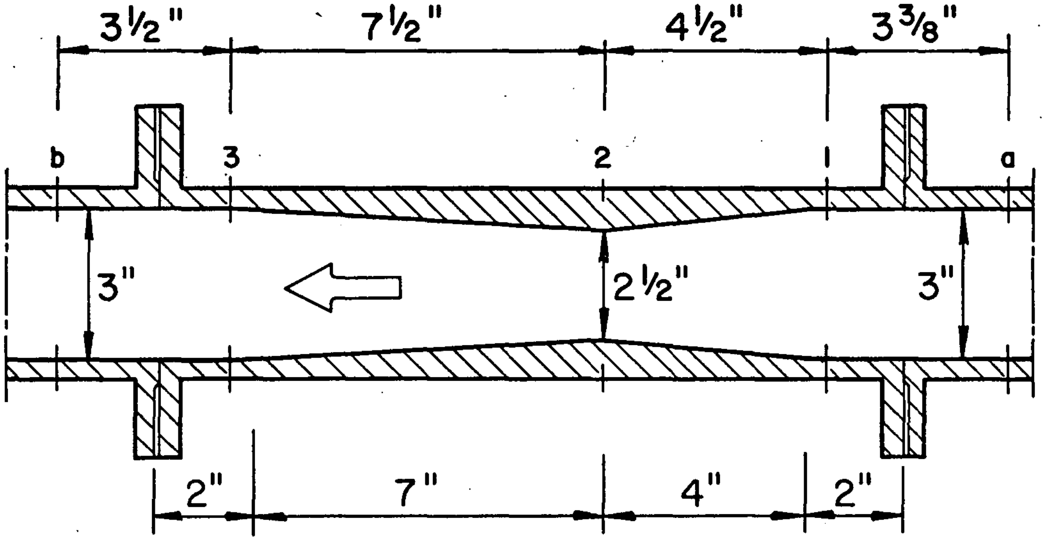


Fig. 2 3 in.-Venturi Tested in University of California at Berkeley Experiments

Lehigh Experiments
3 in.-Venturi

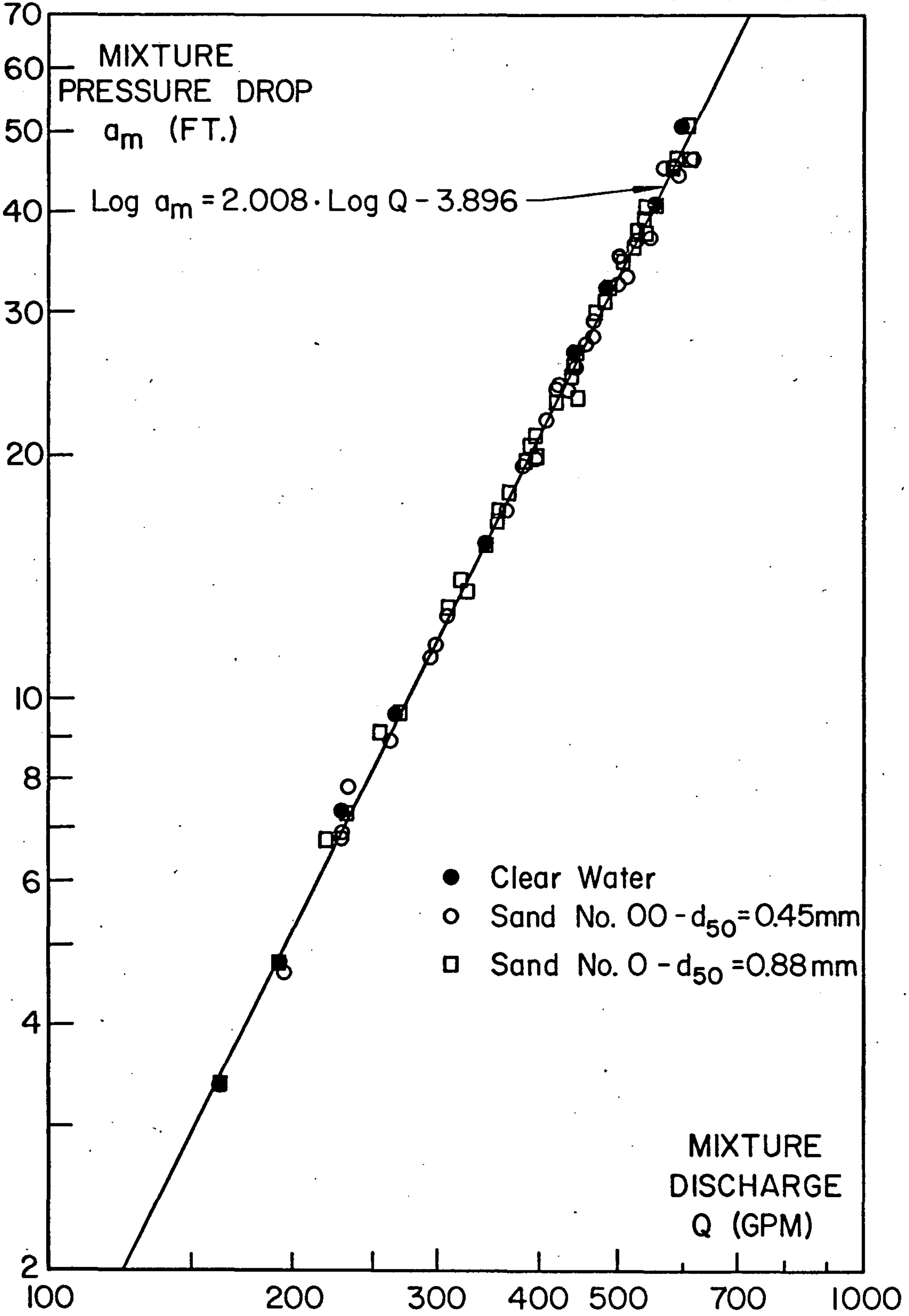


Fig. 3 Mixture Pressure Drop-Discharge Relationship (Lehigh Experiments, 3 in.-Venturi)

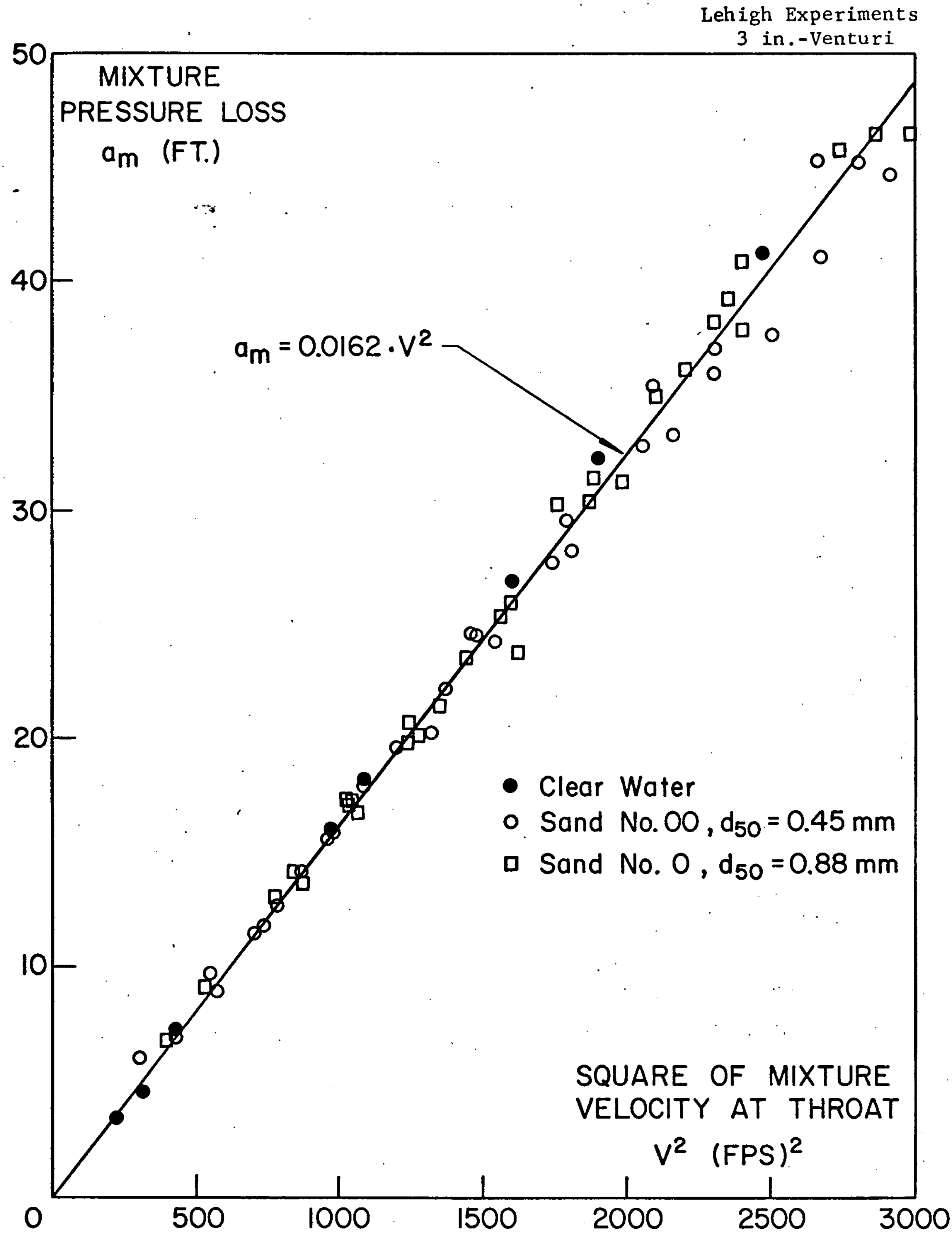


Fig. 4 Mixture Pressure Drop-Throat Velocity Relationship
(Lehigh Experiments, 3 in.-Venturi)

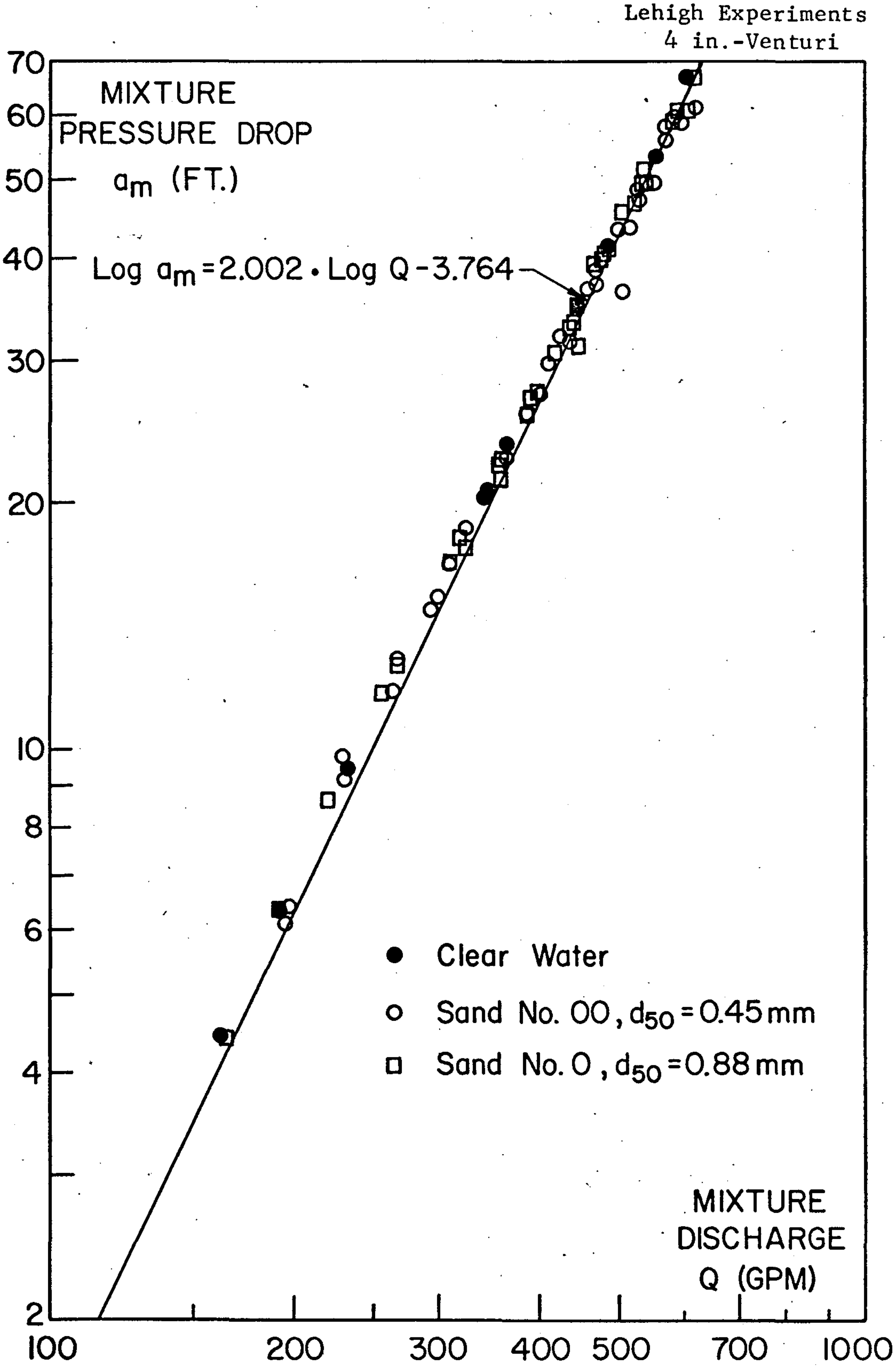


Fig. 5 Mixture Pressure Drop-Discharge Relationship
(Lehigh Experiments, 4 in.-Venturi)

Lehigh Experiments
4 in.-Venturi

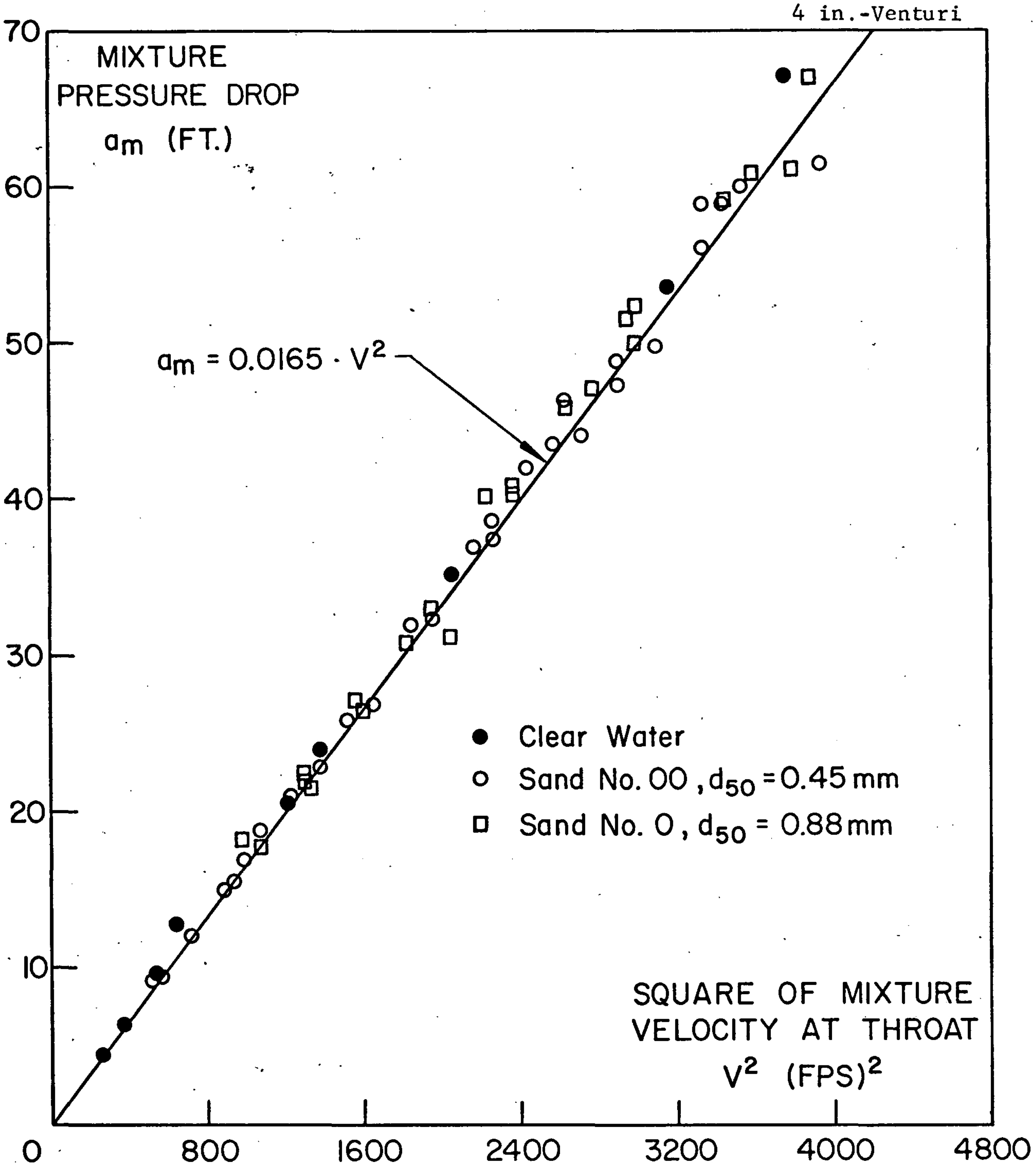
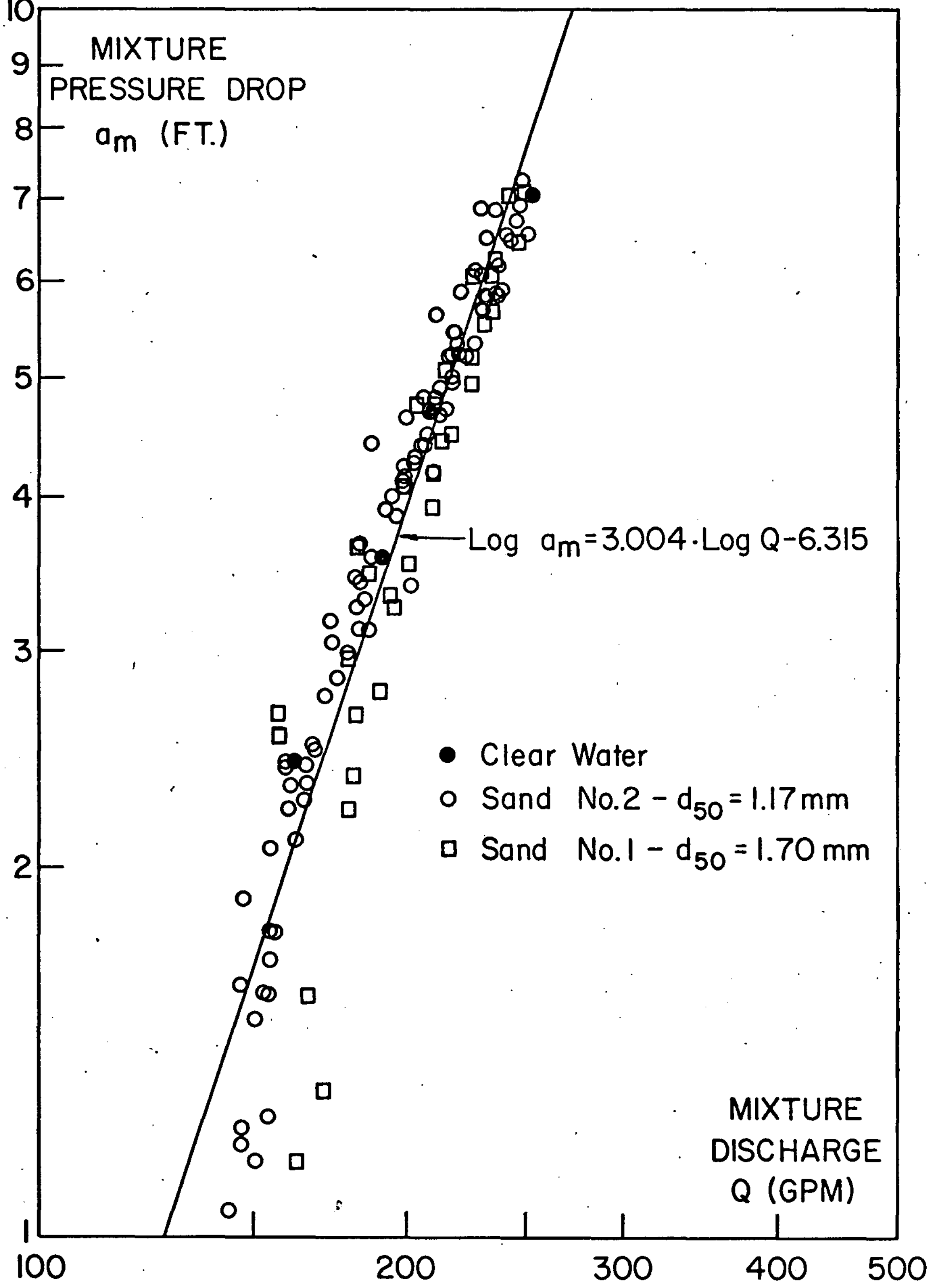


Fig. 6 Mixture Pressure Drop-Throat Velocity Relationship
(Lehigh Experiments, 4 in.-Venturi)



University of California at Berkeley
Experiments, 3 in.-Venturi

Fig. 7 Mixture Pressure Drop-Discharge Relationship (University of California at Berkeley Experiments, 3 in.-Venturi)

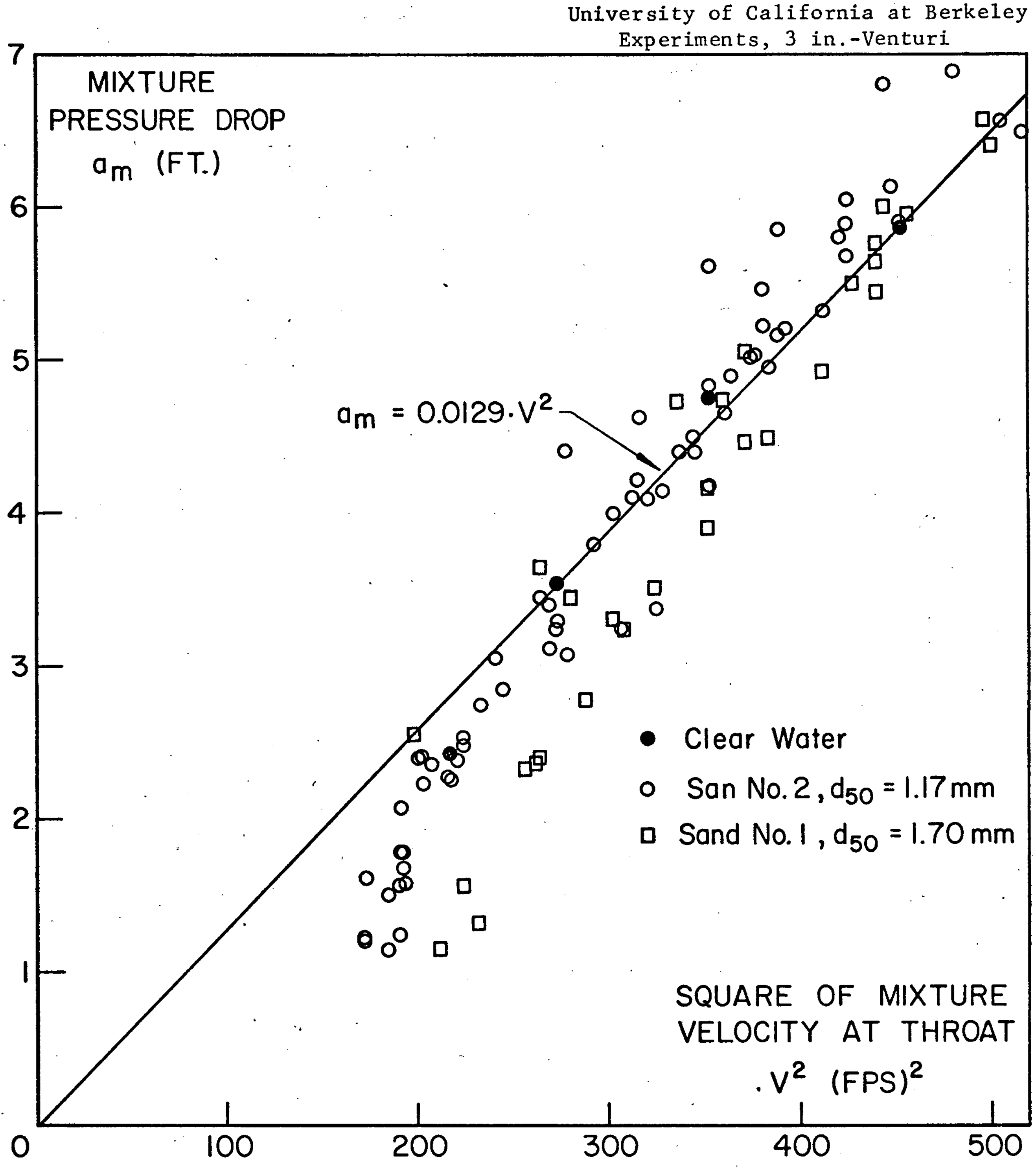


Fig. 8 Mixture Pressure Drop-Throat Velocity Relationship (University of California at Berkeley Experiments, 3 in.-Venturi)

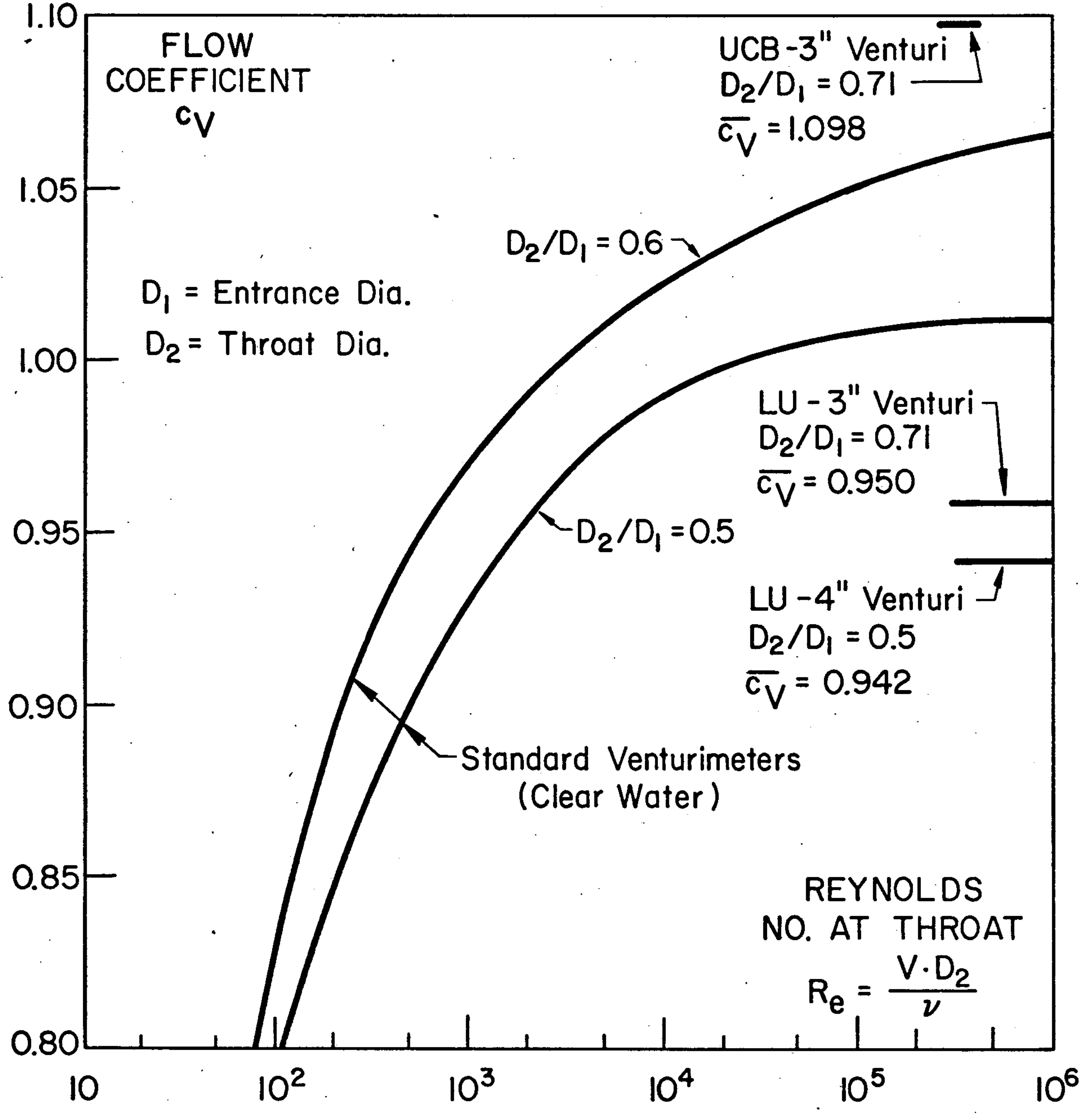


Fig. 9 Average Flow Coefficient of the Mixture Flow for the Venturimeters Tested at the University of California at Berkeley and at Lehigh University as Compared to the Flow Coefficients for Standard Venturimeters with Clear-Water Flow

Lehigh Experiments
3 in.-Venturi

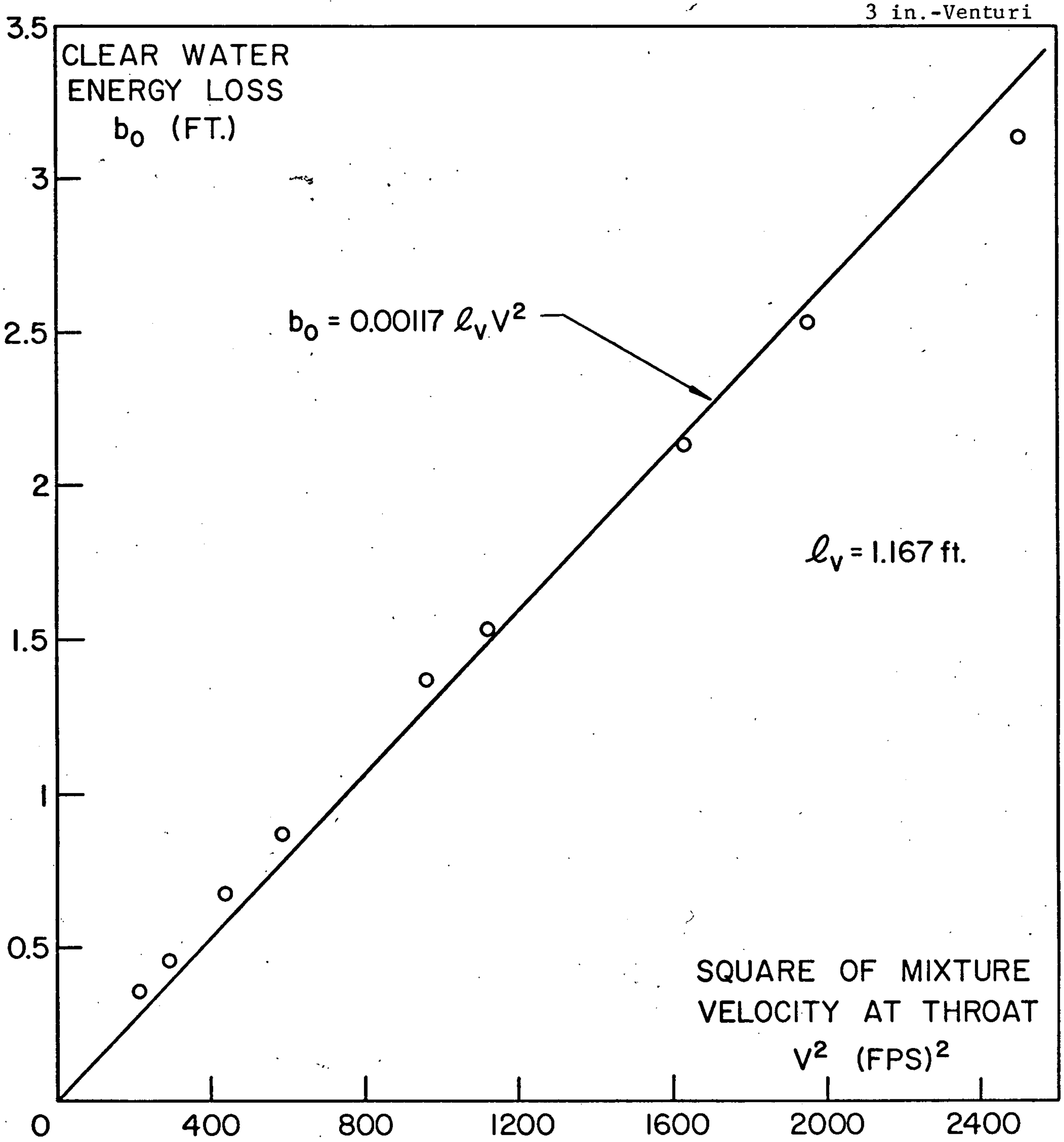


Fig. 10 Clear-Water Energy Loss-Throat Velocity Relationship
(Lehigh Experiments, 3 in.-Venturi)

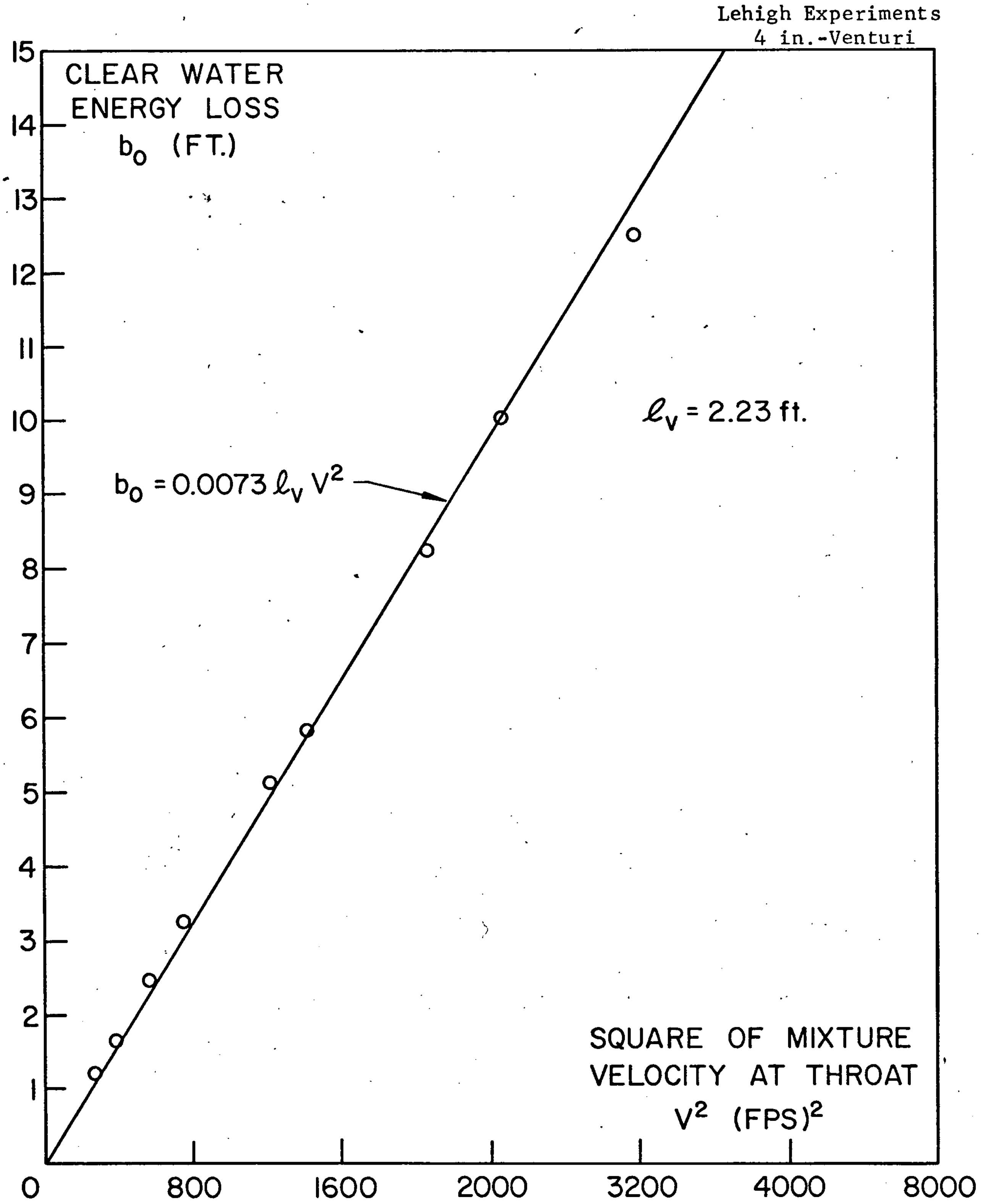


Fig. 11 Clear-Water Energy Loss-Throat Velocity Relationship
(Lehigh Experiments, 4 in.-Venturi)

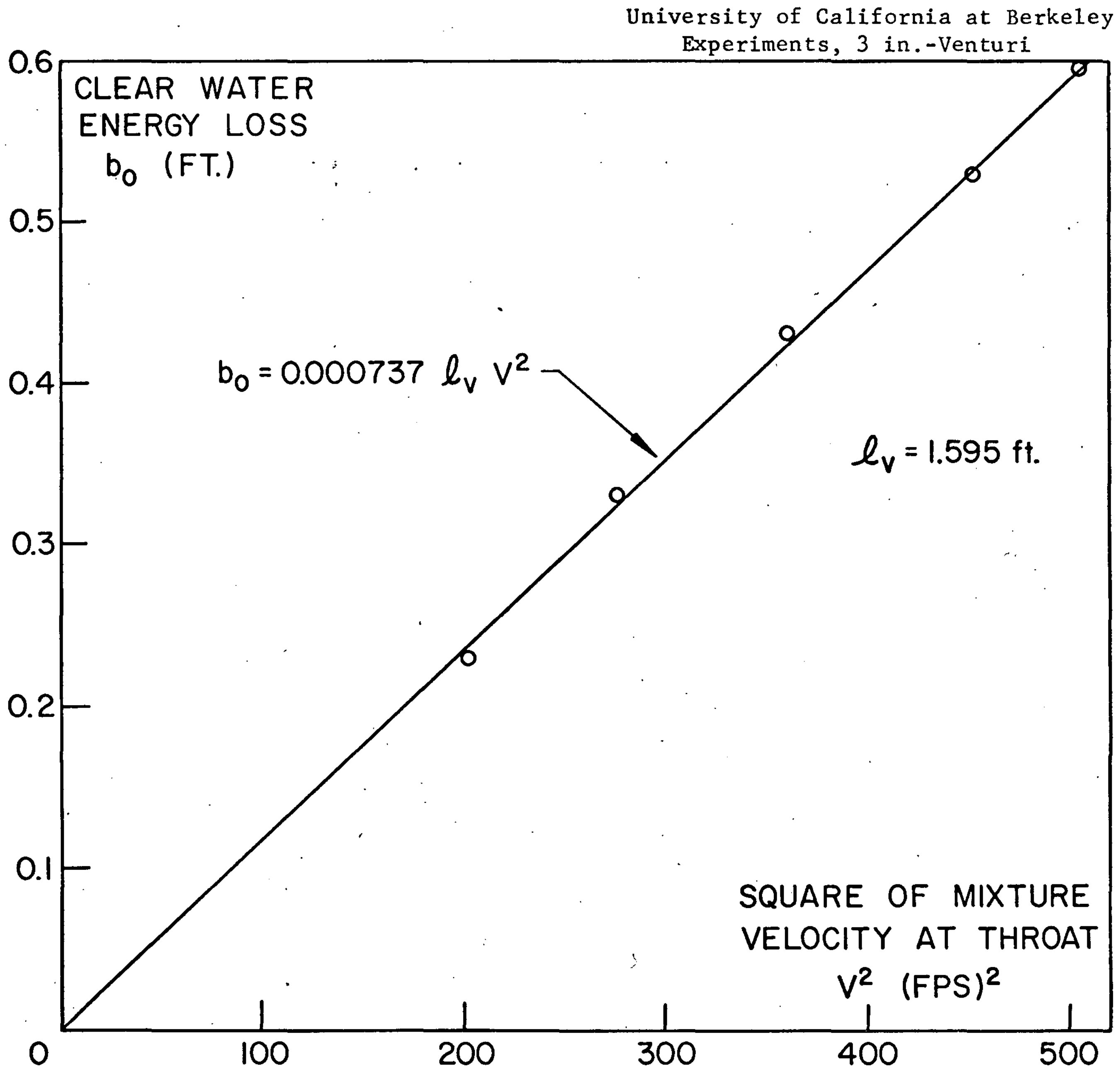
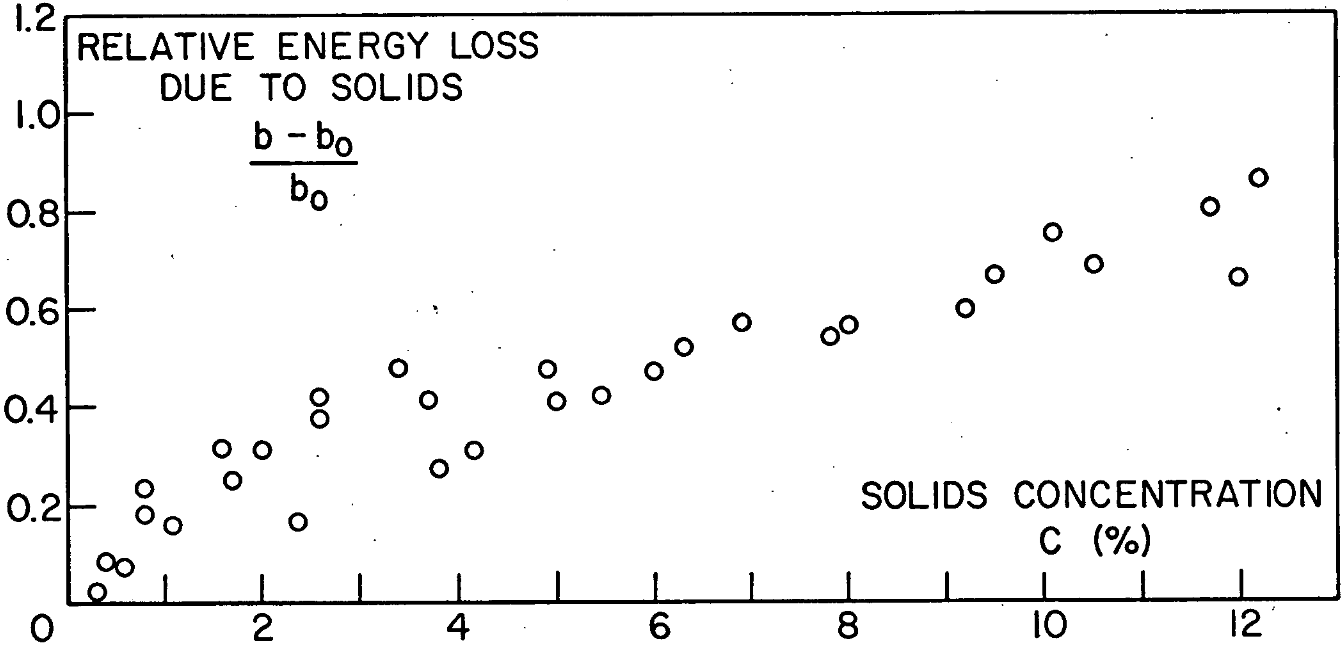
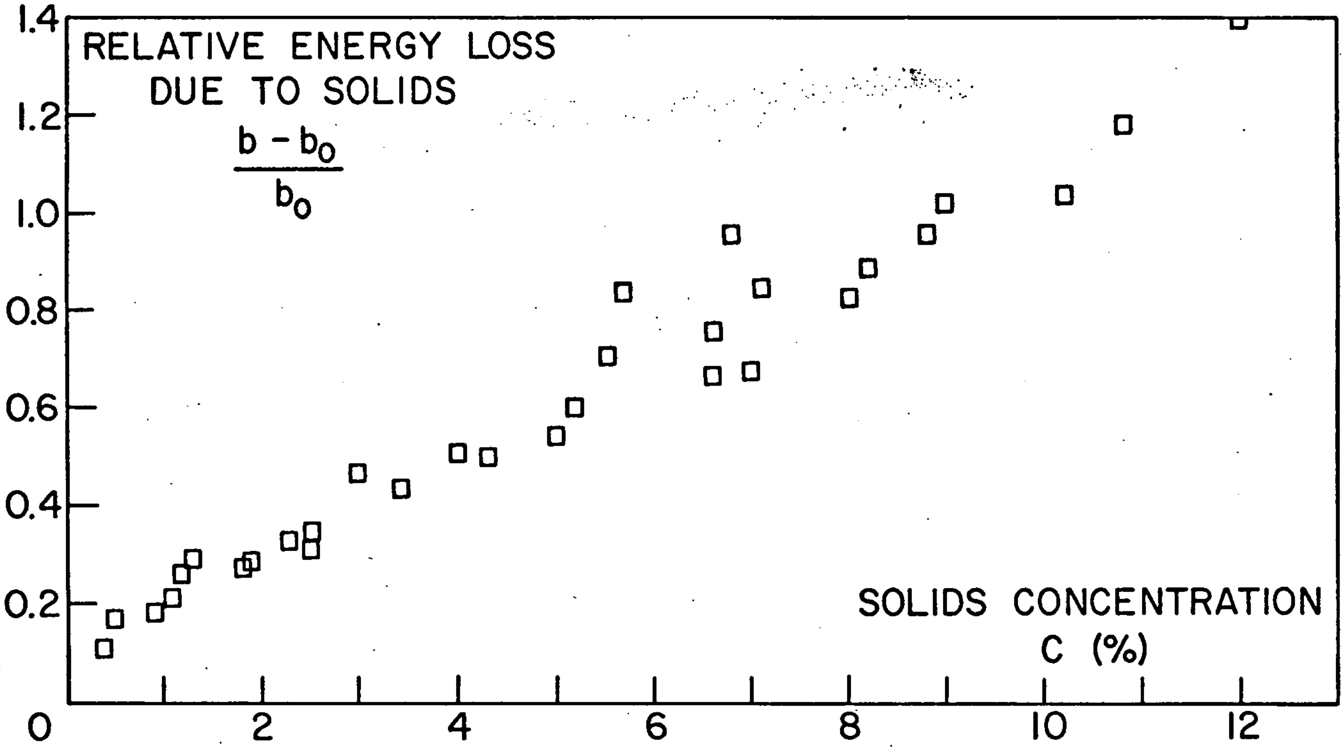


Fig. 12 Clear-Water Energy Loss-Throat Velocity Relationship (University of California at Berkeley Experiments, 3 in.-Venturi)



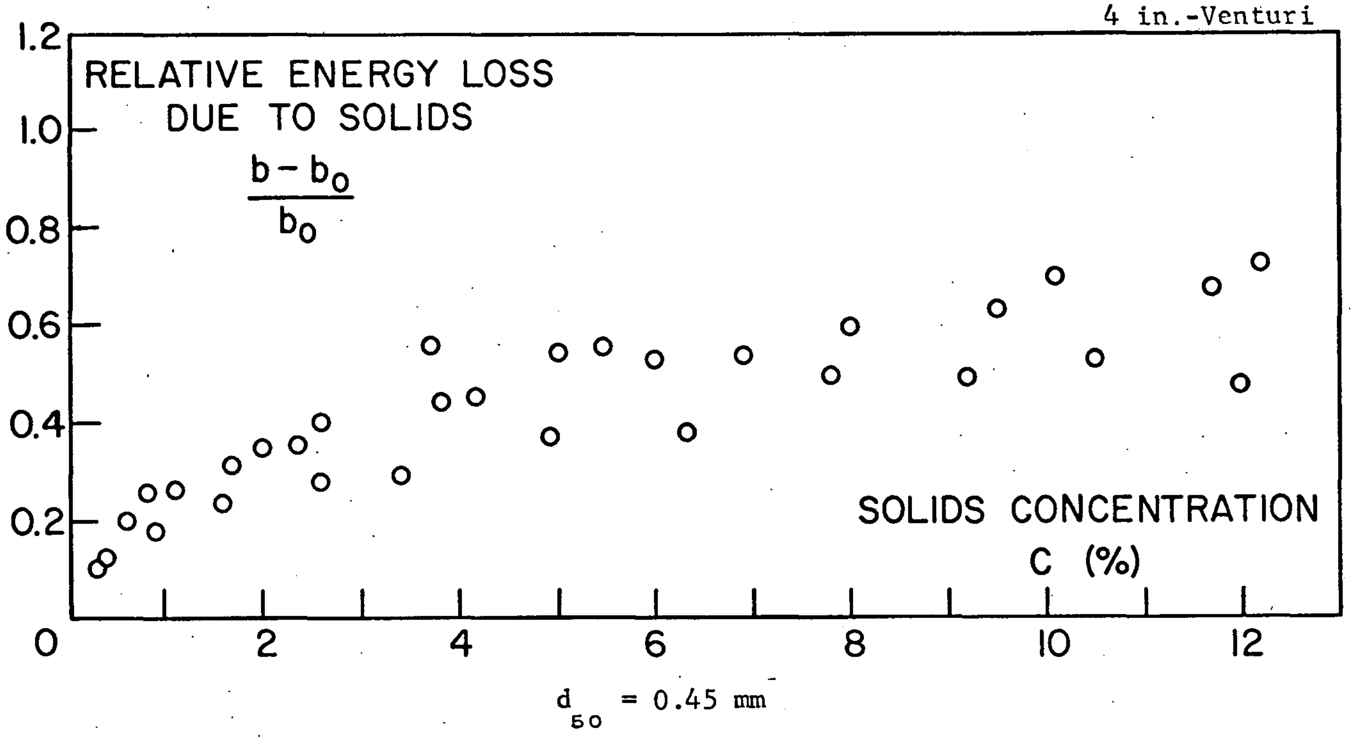
d_{50} = 0.45 mm



d_{50} = 0.88 mm

Fig. 13 Relative Energy Loss due to Solids -
Solids Concentration Relationship
(Lehigh Experiments, 3 in.-Venturi)

Lehigh Experiments
4 in.-Venturi



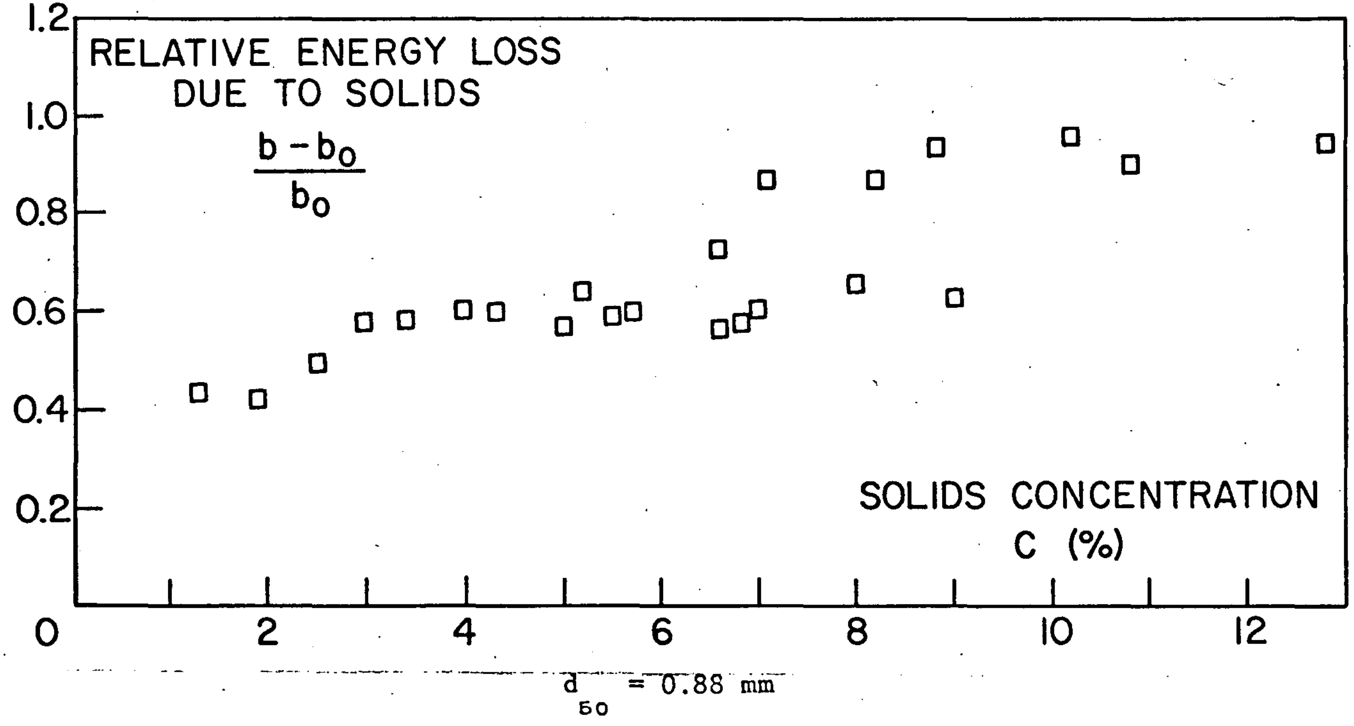
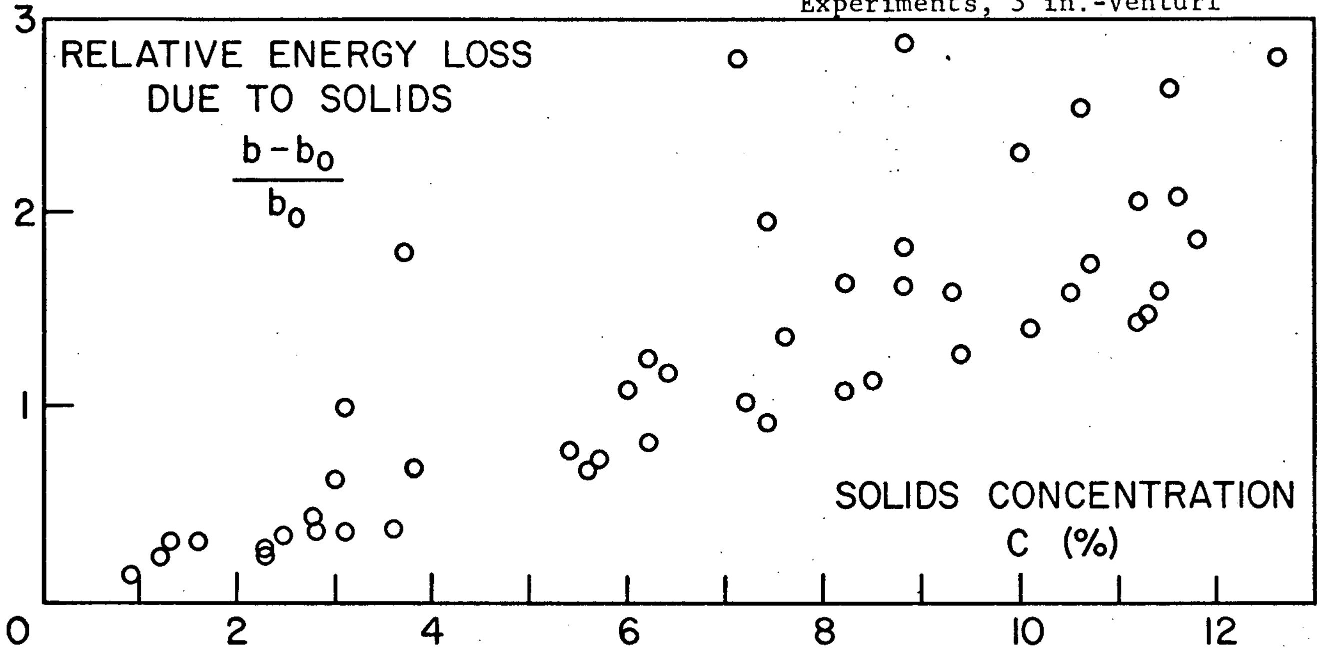
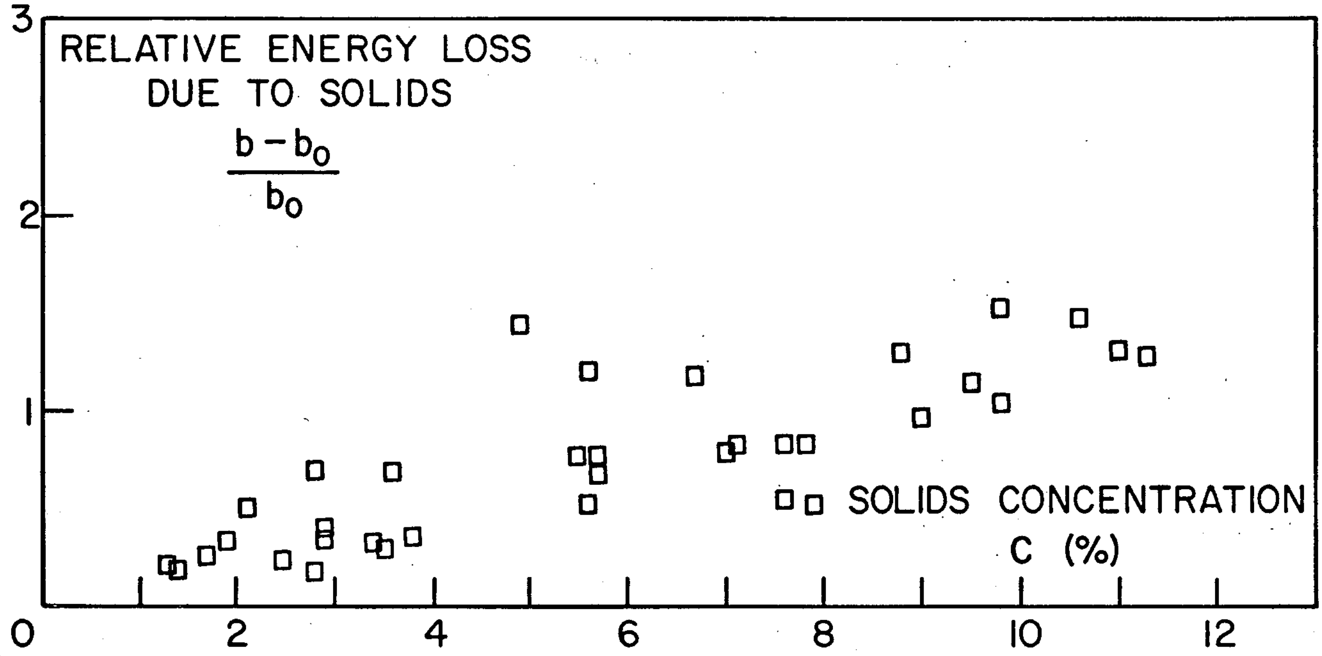


Fig. 14 Relative Energy Loss due to Solids - Solids Concentration Relationship (Lehigh Experiments, 4 in.-Venturi)

University of California at Berkeley
Experiments, 3 in.-Venturi



d_{50} = 1.17 mm



d_{50} = 1.70 mm

Fig. 15 Relative Energy Loss due to Solids - Solids Concentration Relationship (University of California at Berkeley Experiments, 3 in.-Venturi)

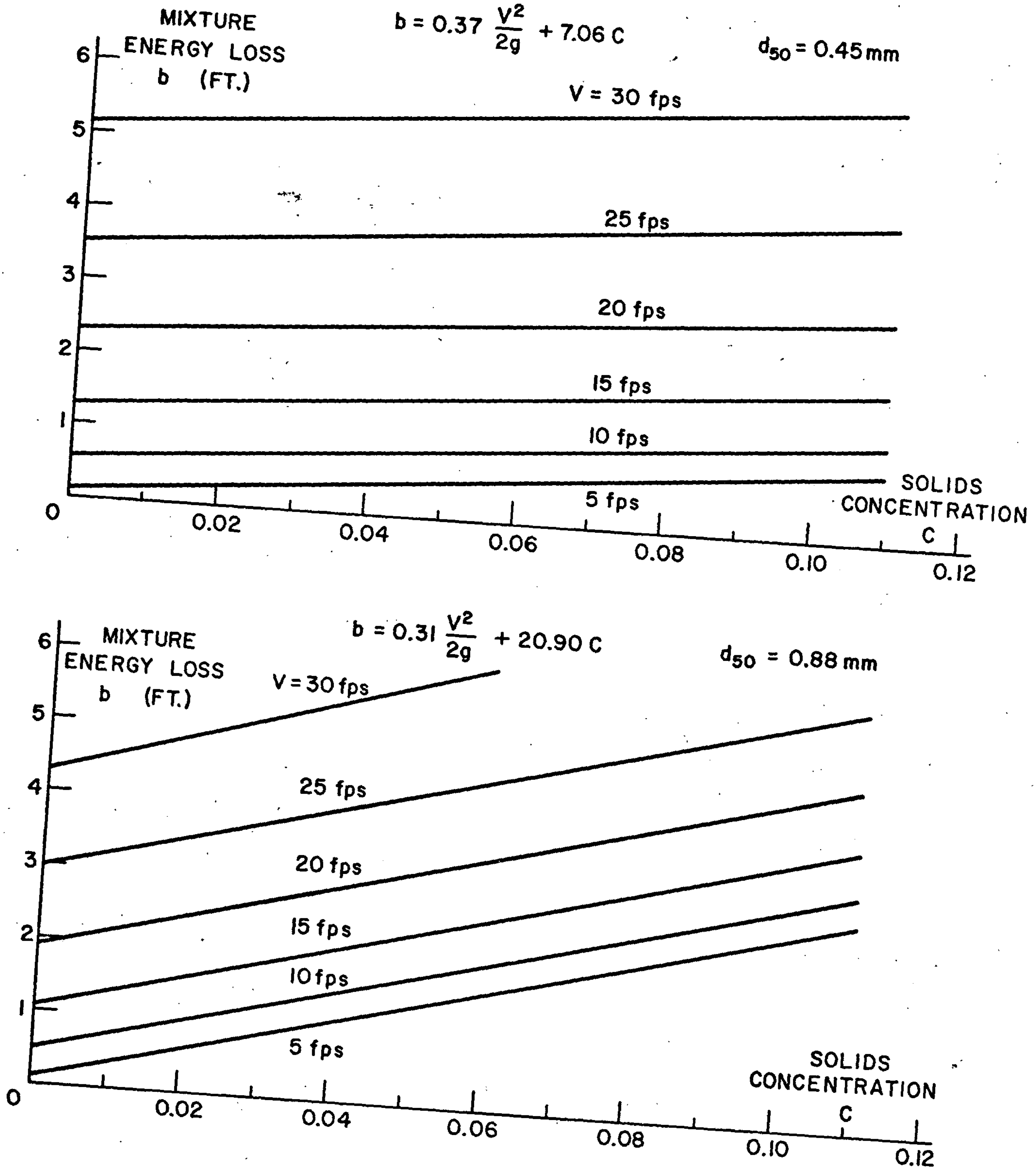
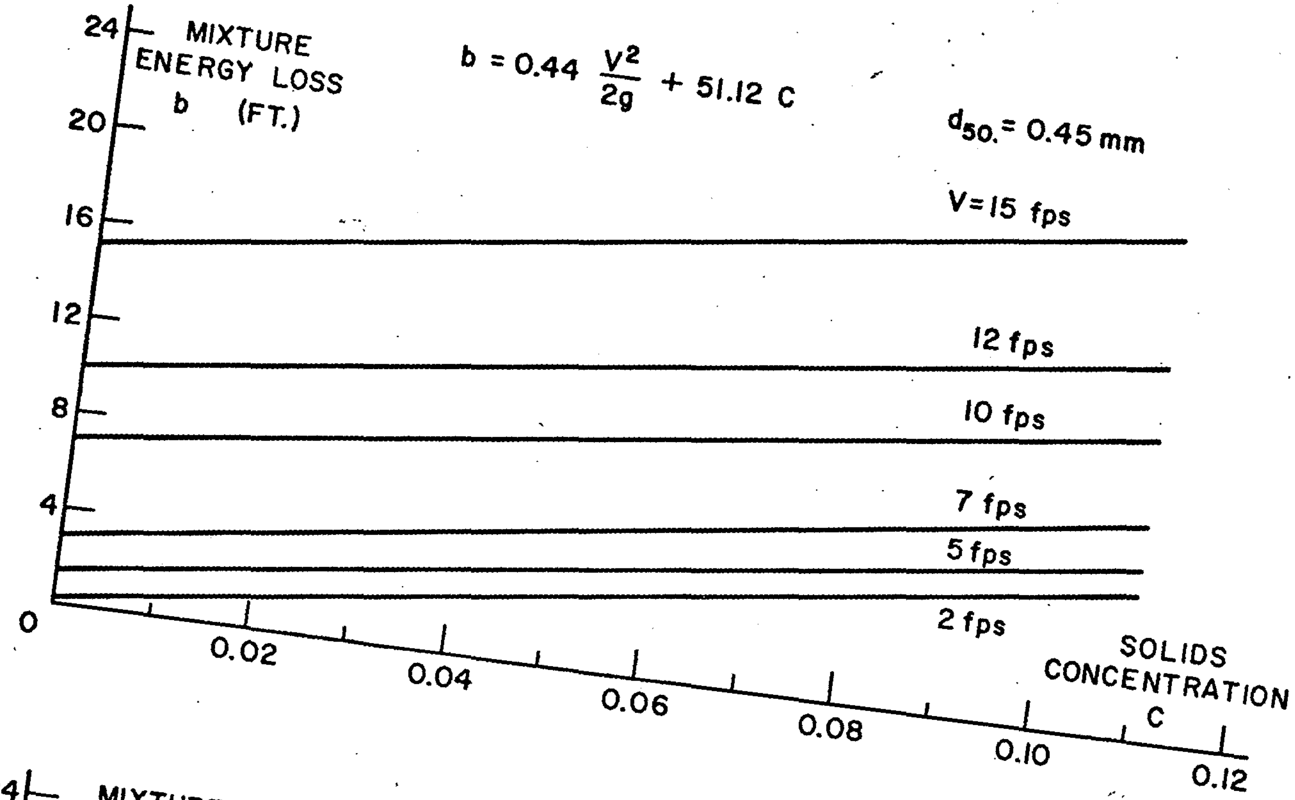


Fig. 16 Relationship between the Energy Loss and Solids Concentration, Velocity as a Parameter (Lehigh Experiments, 3 in.-Venturimeter)



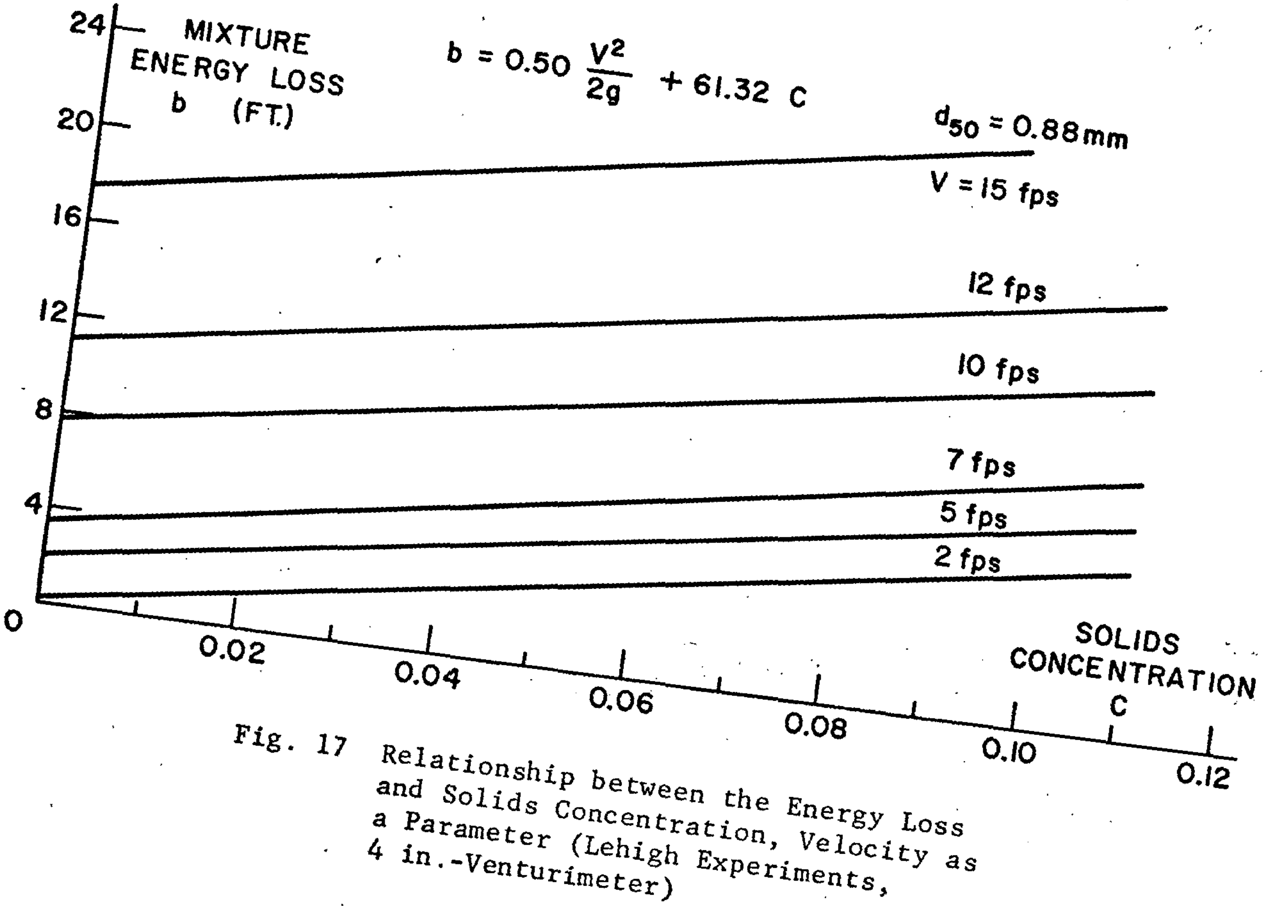


Fig. 17 Relationship between the Energy Loss and Solids Concentration, Velocity as a Parameter (Lehigh Experiments, 4 in.-Venturimeter)

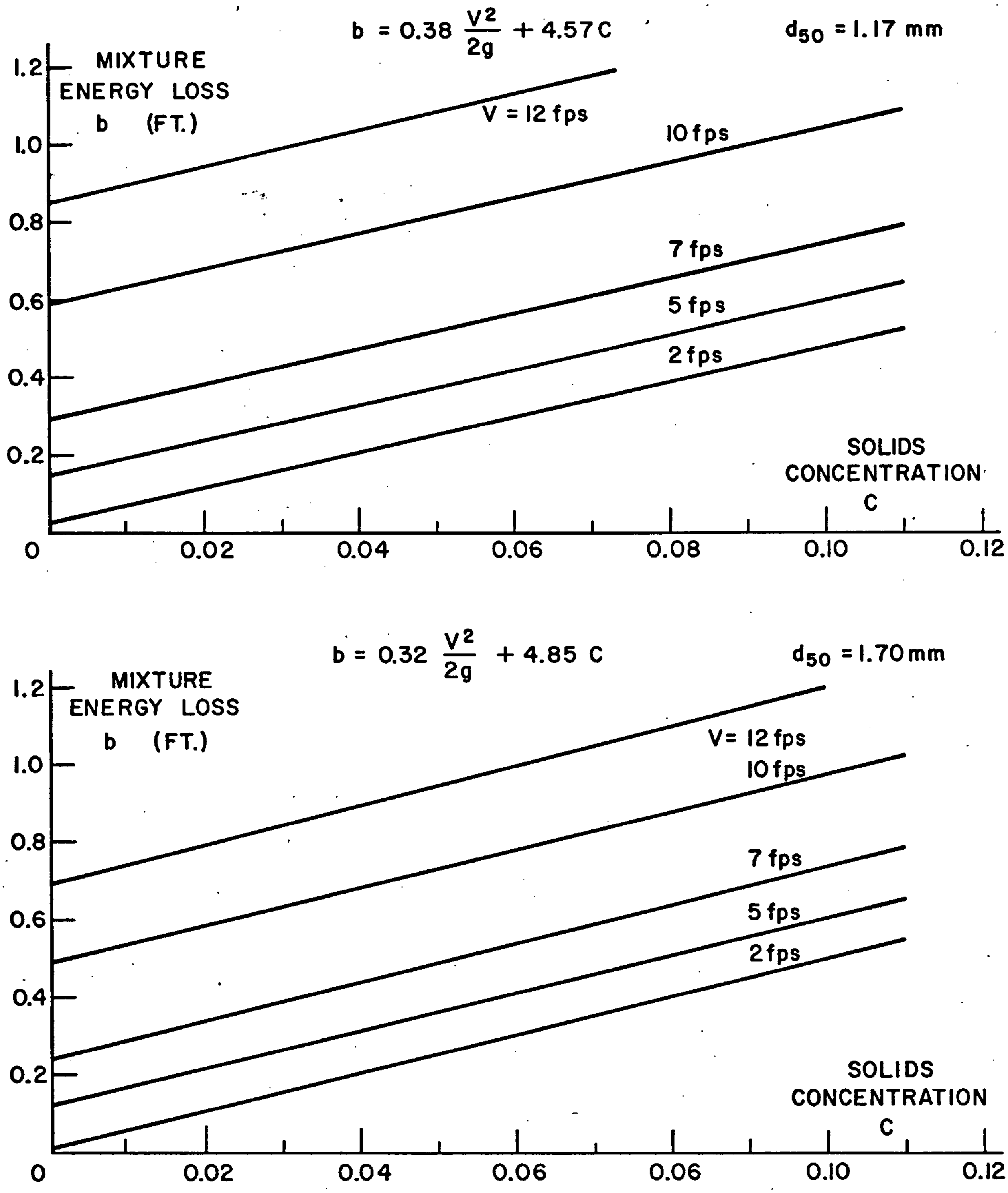


Fig. 18 Relationship between the Energy Loss and Solids Concentration, Velocity as a Parameter (University of California at Berkeley Experiments, 3 in.-Venturi)

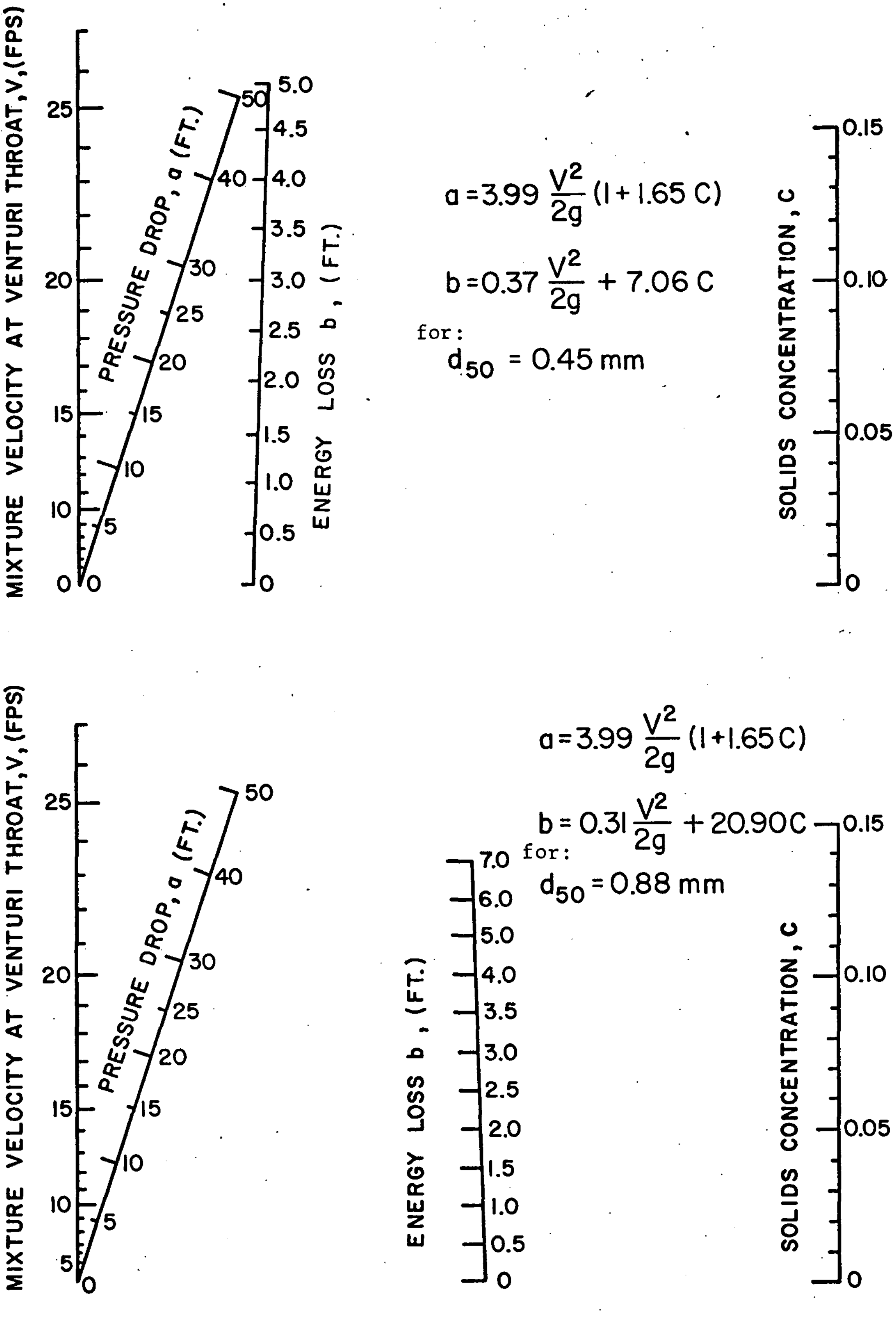


Fig. 19 Nomographic Relationship between Pressure Drop, Energy Loss, Velocity, and Concentration (Lehigh Experiments, 3 in.-Venturi)

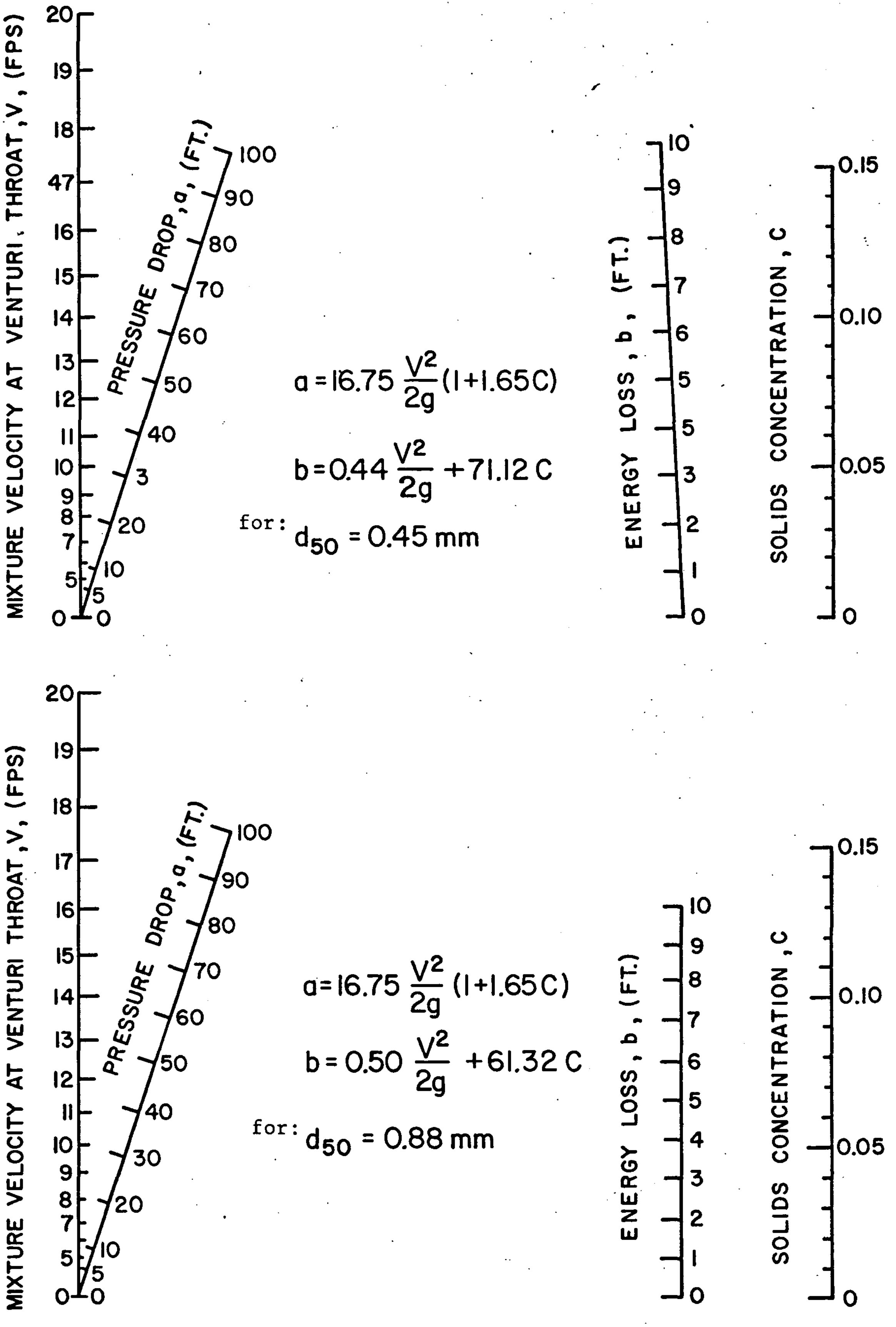
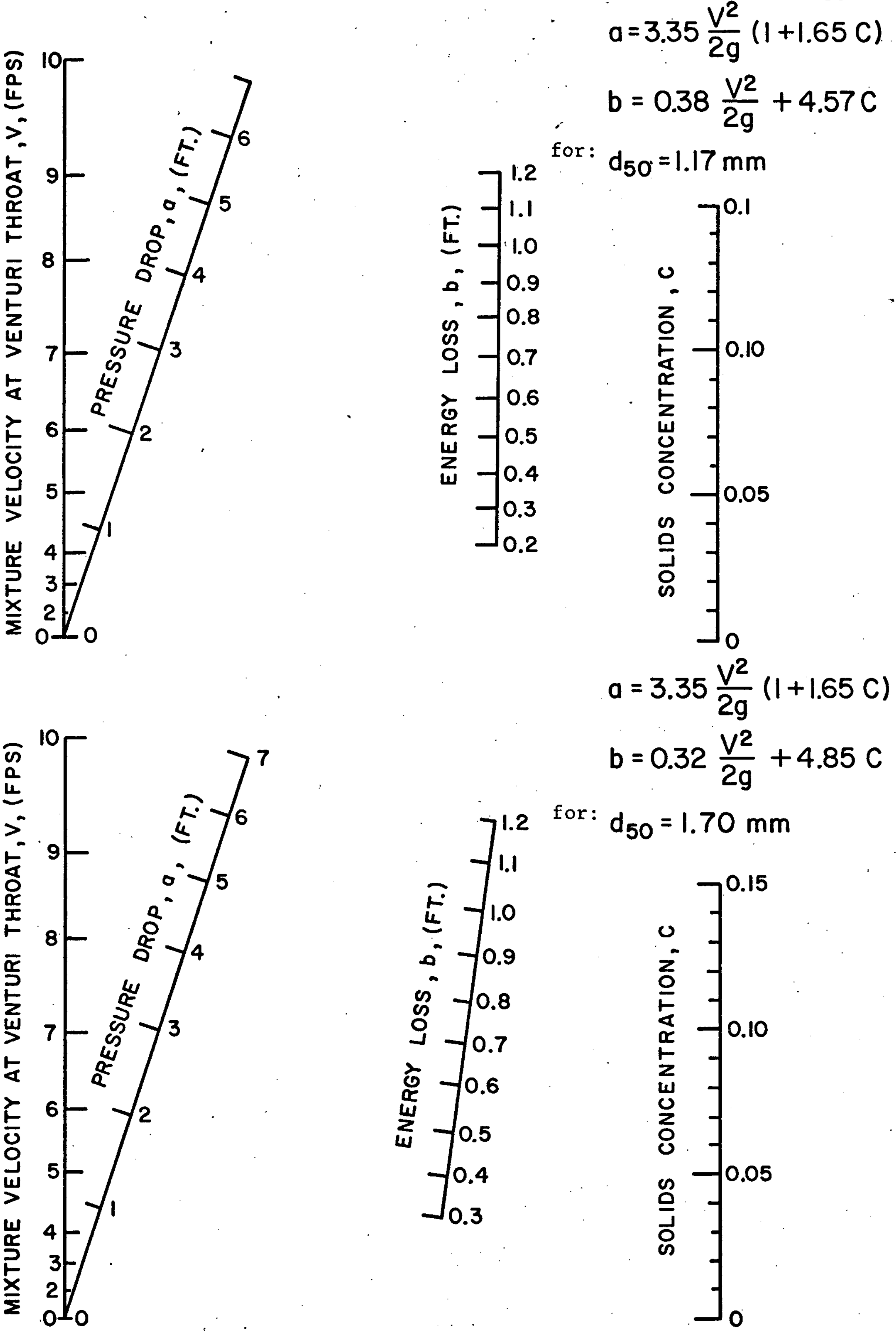


Fig. 20 Nomographic Relationship between Pressure Drop, Energy Loss, Velocity, and Concentration (Lehigh Experiments, 4 in.-Venturi)



$$a = 3.35 \frac{V^2}{2g} (1 + 1.65\ C)$$

$$b = 0.38 \frac{V^2}{2g} + 4.57\ C$$

for: $d_{50} = 1.17$ mm

$$a = 3.35 \frac{V^2}{2g} (1 + 1.65\ C)$$

$$b = 0.32 \frac{V^2}{2g} + 4.85\ C$$

for: $d_{50} = 1.70$ mm

Fig. 21 Nomographic Relationship between Pressure Drop, Energy Loss, Velocity, and Concentration (University of California at Berkeley Experiments, 3 in.-Venturi)

TABLE I: LEHIGH EXPERIMENTS (3" VENTURI)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
	Clear Water						
I/1	163	--	--	3.40	--	0.33	--
I/2	192	--	--	4.81	--	0.46	--
I/3	232	--	--	7.30	--	0.67	--
I/4	268	--	--	9.71	--	0.87	--
I/5	342	--	--	15.68	--	1.36	--
I/6	368	--	--	18.18	--	1.53	--
I/7	445	--	--	26.90	--	2.18	--
I/8	486	--	--	32.30	--	2.53	--
I/9	553	--	--	41.25	--	3.13	--
I/10	603	--	--	51.10	--	3.76	--

TABLE I (Contd.)

SUMMARY OF RESULTS

Series/Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
	Sand No. 00 - d_{50} = 0.46 mm						
I-00/1	230	0.4	7.00	6.96	0.65	0.60	0.05
I-00/2	325	0.8	14.50	14.30	1.29	1.05	0.24
I-00/3	423	1.6	25.25	24.60	2.17	1.65	0.52
I-00/4	505	2.6	37.00	35.45	3.12	2.22	0.90
I-00/5	570	3.4	47.80	45.35	4.53	2.70	1.83
II-00/1	195	0.3	4.71	4.69	0.46	0.45	0.01
II-00/2	230	0.6	6.96	6.90	0.64	0.60	0.04
II-00/3	265	0.8	9.12	9.00	0.85	0.72	0.13
II-00/4	295	1.1	11.66	11.47	1.05	0.91	0.14
II-00/5	345	1.7	16.26	15.81	1.46	1.17	0.29
II-00/6	383	2.0	20.35	19.68	1.83	1.40	0.43
II-00/7	423	2.6	25.60	24.50	2.27	1.65	0.62
II-00/8	470	3.7	31.35	29.55	2.75	1.95	0.80
II-00/9	530	4.9	40.10	37.10	3.52	2.40	1.12
II-00/10	585	6.3	49.60	45.20	4.28	2.82	1.46
III-00/1	300	2.35	12.31	11.86	1.08	0.93	0.15
III-00/2	365	3.8	18.42	17.30	1.63	1.28	0.35
III-00/3	410	5.0	24.10	22.20	2.18	1.55	0.63
III-00/4	460	6.0	30.45	27.70	2.78	1.90	0.88
III-00/5	515	7.8	37.55	33.30	3.50	2.27	1.23
III-00/6	550	9.2	43.40	37.65	4.07	2.55	1.52
III-00/7	595	10.5	52.45	44.70	4.88	2.90	1.98
III-00/8	620	12.0	56.00	46.75	5.13	3.10	2.03
IV-00/1	310	4.15	13.66	12.79	1.28	0.98	0.30
IV-00/2	345	5.45	17.32	15.88	1.66	1.17	0.49
IV-00/3	400	6.9	22.55	20.25	2.35	1.50	0.85
IV-00/4	435	8.0	27.40	24.20	2.68	1.72	0.96
IV-00/5	470	9.5	32.65	28.25	3.26	1.95	1.31
IV-00/6	500	10.1	38.30	32.85	3.85	2.20	1.65
IV-00/7	530	11.7	43.00	36.00	4.32	2.40	1.92
IV-00/8	570	12.2	50.70	42.30	5.02	2.70	2.32

TABLE I (Contd.)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
	Sand No. 0 - d_{50} = 0.88 mm						
I-0/1	220	0.4	6.85	6.81	0.61	0.55	0.06
I-0/2	255	0.5	9.25	9.18	0.82	0.70	0.12
I-0/3	310	0.9	13.33	13.12	1.16	0.98	0.18
I-0/4	355	1.1	17.66	17.35	1.52	1.25	0.27
I-0/5	395	1.2	21.90	21.45	1.85	1.47	0.38
I-0/6	440	1.8	26.65	25.90	2.23	1.75	0.48
I-0/7	480	2.3	32.40	31.20	2.69	2.02	0.67
I-0/8	530	2.5	39.80	38.20	3.16	2.40	0.76
II-0/1	320	1.3	14.55	14.23	1.33	1.03	0.30
II-0/2	355	1.9	17.55	17.00	1.61	1.25	0.36
II-0/3	385	2.5	20.70	19.85	1.89	1.40	0.49
II-0/4	420	3.0	24.70	23.55	2.43	1.65	0.78
II-0/5	480	4.0	33.50	31.45	3.06	2.03	1.03
II-0/6	520	5.0	39.20	36.10	3.56	2.30	1.26
II-0/7	540	5.7	44.85	40.95	4.55	2.47	2.08
II-0/8	590	6.6	51.45	46.40	4.68	2.85	2.17
II-0/9	615	7.0	57.15	51.25	5.17	3.07	2.10
III-0/1	320	3.4	14.95	14.16	1.50	1.04	0.46
III-0/2	355	4.3	18.45	17.21	1.88	1.25	0.63
III-0/3	390	5.2	22.55	20.78	2.31	1.44	0.87
III-0/4	435	6.6	28.05	25.30	2.93	1.75	1.18
III-0/5	465	7.1	33.80	30.25	3.55	1.92	1.63
III-0/6	505	8.2	39.75	35.00	4.22	2.23	1.99
III-0/7	535	8.8	44.90	39.20	4.77	2.43	2.34
III-0/8	580	10.2	53.50	45.80	5.71	2.80	2.91
IV-0/1	325	5.5	14.92	13.67	1.81	1.06	0.75
IV-0/2	360	6.8	18.67	16.80	2.45	1.25	1.20
IV-0/3	395	8.0	22.92	20.15	2.69	1.47	1.22
IV-0/4	445	9.0	27.25	23.70	3.59	1.78	1.81
IV-0/5	480	10.8	35.85	30.45	4.44	2.03	2.41
IV-0/6	540	12.0	45.90	37.90	5.93	2.47	3.46
IV-0/7	605	14.0	57.10	46.40	7.25	2.98	4.27

TABLE II: LEHIGH EXPERIMENTS (4" VENTURI)

SUMMARY OF RESULTS

Series/Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
			Clear Water				
I/1	163	--	--	4.44	--	1.20	--
I/2	192	--	--	6.40	--	1.68	--
I/3	232	--	--	9.48	--	2.47	--
I/4	268	--	--	12.71	--	3.23	--
I/5	342	--	--	20.45	--	5.11	--
I/6	368	--	--	23.75	--	5.86	--
I/7	445	--	--	35.00	--	8.26	--
I/8	486	--	--	41.85	--	10.04	--
I/9	553	--	--	53.50	--	12.50	--
I/10	603	--	--	66.65	--	15.25	--

TABLE II (Contd.)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
	Sand No. 00 - d_{50} = 0.46 mm						
I-00/1	230	0.4	9.25	9.20	2.30	2.05	0.25
I-00/2	325	0.8	19.00	18.75	4.81	4.08	0.73
I-00/3	423	1.6	32.91	32.05	8.79	7.10	1.69
I-00/4	505	2.6	48.45	46.40	13.17	10.30	2.87
I-00/5	570	3.4	62.05	58.87	16.75	13.00	3.75
II-00/1	195	0.3	6.12	6.08	1.62	1.47	0.15
II-00/2	230	0.6	9.88	9.81	2.46	2.05	0.41
II-00/3	265	0.8	12.00	11.85	3.45	2.75	0.70
II-00/4	295	1.1	15.17	14.90	4.29	3.40	0.89
II-00/5	345	1.7	21.35	20.75	6.17	4.70	1.47
II-00/6	383	2.0	26.85	25.95	7.84	5.80	2.04
II-00/7	423	2.6	33.45	32.10	9.91	7.10	2.81
II-00/8	470	3.7	41.00	38.60	13.70	8.80	4.90
II-00/9	530	4.9	52.65	48.70	15.30	11.20	4.10
II-00/10	585	6.3	65.55	59.80	19.00	13.80	5.20
III-00/1	300	2.35	16.05	15.45	4.72	3.50	1.22
III-00/2	365	3.8	24.15	22.70	7.57	5.25	2.32
III-00/3	410	5.0	31.75	29.30	10.12	6.60	3.52
III-00/4	460	6.0	40.40	36.80	12.88	8.45	4.43
III-00/5	515	7.8	49.35	43.80	15.80	10.60	5.20
III-00/6	550	9.2	57.20	49.65	18.20	12.20	6.00
III-00/7	595	10.5	69.15	58.90	21.65	14.20	7.45
III-00/8	620	12.0	73.45	61.35	22.75	15.50	7.25
IV-00/1	310	4.15	17.82	16.69	5.53	3.80	1.73
IV-00/2	345	5.45	22.50	20.55	7.31	4.70	2.61
IV-00/3	400	6.9	29.85	26.75	9.83	6.40	3.43
IV-00/4	435	8.0	36.10	31.85	12.03	7.55	4.48
IV-00/5	470	9.5	43.00	37.20	14.53	8.80	5.53
IV-00/6	500	10.1	50.55	43.40	16.95	10.00	6.95
IV-00/7	530	11.7	56.50	47.30	18.95	11.30	7.65
IV-00/8	570	12.2	67.20	56.00	22.30	13.00	9.30

TABLE II (Contd.)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
	Sand No. 0 - d_{50} = 0.88 mm						
I-0/1	220	0.4	8.79	8.73	2.25	1.88	0.37
I-0/2	255	0.5	12.03	11.95	3.09	2.53	0.56
I-0/3	310	0.9	17.45	17.20	4.44	3.80	0.64
I-0/4	355	1.1	22.90	22.50	5.90	4.96	0.94
I-0/5	395	1.2	28.10	27.55	7.43	6.20	1.23
I-0/6	440	1.8	34.50	33.50	9.10	7.75	1.35
I-0/7	480	2.3	41.90	40.35	11.41	9.25	2.16
I-0/8	530	2.5	51.30	49.25	13.70	11.30	2.40
II-0/1	320	1.3	18.85	18.43	5.78	4.40	1.74
II-0/2	355	1.9	22.70	22.00	7.06	4.98	2.08
II-0/3	385	2.5	26.85	25.75	8.74	5.85	2.89
II-0/4	420	3.0	32.25	30.70	11.04	7.00	4.04
II-0/5	480	4.0	43.45	40.75	14.80	9.22	5.58
II-0/6	520	5.0	50.90	47.00	17.00	10.80	6.20
II-0/7	540	5.7	57.30	52.35	18.80	11.75	7.05
II-0/8	590	6.6	67.30	60.70	22.05	14.10	7.95
II-0/9	615	7.0	74.60	66.95	24.55	15.35	9.20
III-0/1	320	3.4	19.40	18.38	6.38	4.04	2.34
III-0/2	355	4.3	24.05	22.45	8.00	5.00	3.00
III-0/3	390	5.2	29.35	27.05	9.94	6.05	3.89
III-0/4	435	6.6	36.50	32.90	12.88	7.55	5.33
III-0/5	465	7.1	43.95	39.35	16.18	8.65	7.53
III-0/6	505	8.2	52.00	45.85	19.24	10.25	8.99
III-0/7	535	8.8	59.00	51.50	22.30	11.50	10.80
III-0/8	580	10.2	69.00	59.05	26.65	13.60	13.05
IV-0/1	325	5.5	19.50	17.88	6.59	4.15	2.44
IV-0/2	360	6.8	23.50	21.50	8.05	5.12	2.93
IV-0/3	395	8.0	29.90	26.42	10.29	6.20	4.09
IV-0/4	445	9.0	35.80	31.20	12.88	7.90	4.98
IV-0/5	480	10.8	47.40	40.25	17.60	9.25	8.35
IV-0/6	540	12.8	60.40	49.90	22.85	11.75	11.10
IV-0/7	605	14.0	75.25	61.10	29.10	14.90	14.20

TABLE III: UNIVERSITY OF CALIFORNIA AT BERKELEY EXPERIMENTS (3" VENTURI)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
			Clear Water				
1/1	250	0.0	--	7.02	--	--	--
1/2	233	0.0	--	5.84	--	--	--
1/3	206	0.0	--	4.72	--	--	--
1/4	188	0.0	--	3.58	--	--	--
1/5	161	0.0	--	2.43	--	--	--
			Sand No. 2 d_{50} = 1.15 mm				
2/1	245	0.3	7.21	7.21	--	--	--
2/2	225	0.5	6.13	6.06	--	--	--
2/3	204	0.7	4.89	4.82	--	--	--
2/4	182	1.1	3.74	3.68	--	--	--
2/5	157	1.25	2.46	2.43	--	--	--
3/1	242	4.3	7.15	6.70	--	--	--
3/2	218	5.3	5.90	5.44	--	--	--
3/3	199	5.7	4.66	4.26	--	--	--
3/4	172	5.9	3.48	3.18	--	--	--
3/5	147	5.9	2.00	1.87	--	--	--
4/1	220	14.1	6.37	5.22	--	--	--
4/2	201	13.6	5.22	4.30	--	--	--
4/3	183	13.0	4.40	3.31	--	--	--
4/4	165	13.0	2.79	2.33	--	--	--
4/5	146	12.0	1.38	1.15	--	--	--
5/1	212	17.0	5.97	4.70	--	--	--
5/2	194	16.6	4.86	3.84	--	--	--
5/3	177	15.9	3.74	2.98	--	--	--
5/4	162	14.7	2.59	2.10	--	--	--
5/5	144	12.4	1.25	1.05	--	--	--
6/1	238	5.4	7.09	6.53	--	--	--
6/2	218	6.0	5.88	5.31	--	--	--
6/3	200	6.3	4.65	4.23	--	--	--

TABLE III (Contd.)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
101/1	159	0	2.40	2.40	0.23	0.23	0
101/2	185	0	3.54	3.54	0.33	0.33	0
101/3	210	0	4.66	4.66	0.43	0.43	0
101/4	236	0	5.88	5.88	0.53	0.53	0
101/5	249	0	6.56	6.56	0.59	0.59	0
102/1	160	3.1	2.43	2.33	0.46	0.23	0.23
102/2	180	3.0	3.61	3.45	0.49	0.30	0.19
102/3	198	2.8	4.83	4.63	0.56	0.39	0.17
102/4	226	2.5	6.05	5.81	0.66	0.49	0.17
102/5	241	2.3	6.70	6.47	0.69	0.56	0.13
103/1	155	7.1	1.97	1.77	0.76	0.20	0.56
103/2	172	7.4	3.38	3.06	0.80	0.27	0.53
103/3	197	7.6	4.60	4.10	0.85	0.36	0.49
103/4	216	7.4	5.81	5.22	0.92	0.46	0.42
103/5	229	7.2	6.74	6.04	0.99	0.49	0.50
104/1	151	9.3	1.70	1.51	0.52	0.20	0.32
104/2	170	10.6	3.21	2.75	0.92	0.26	0.66
104/3	190	10.7	4.44	3.81	0.99	0.36	0.63
104/4	211	10.5	5.68	4.89	1.12	0.43	0.69
104/5	218	10.1	6.76	5.85	1.18	0.49	0.69
105/1	151	11.9	1.58	1.15	0.43	0.20	0.23
105/2	164	13.7	2.23	2.26	0.95	0.23	0.72
105/3	183	14.4	3.87	3.25	1.08	0.33	0.75
105/4	201	14.6	5.12	4.16	1.12	0.39	0.73
105/5	220	15.0	6.43	5.19	1.31	0.46	0.85
110/1	164	0	2.42	2.42	0.23	0.23	0
110/2	236	0	5.85	5.85	0.53	0.53	0
110/4	228	2.3	6.07	5.87	0.62	0.49	0.13
110/5	159	3.0	2.33	2.23	0.49	0.23	0.26
111/1	153	8.8	1.81	1.58	0.62	0.16	0.46
111/2	215	9.4	5 61	5.02	1.05	0.46	0.59
111/4	206	13.4	5.31	4.40	1.18	0.43	0.75
111/5	154	11.2	1.48	1.25	0.49	0.20	0.29

TABLE III (Contd.)

SUMMARY OF RESULTS

Series/Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
121/1	158	1.6	2.46	2.39	0.30	0.23	0.07
121/2	185	1.3	3.74	3.07	0.43	0.33	0.10
121/3	208	1.2	4.89	4.82	0.53	0.43	0.10
121/4	229	0.9	6.06	6.04	0.59	0.53	0.06
122/3	197	6.0	4.66	4.23	0.76	0.36	0.40
122/4	216	5.4	5.90	5.47	0.82	0.46	0.36
123/1	235	8.2	6.95	6.16	1.11	0.53	0.58
123/2	215	8.5	5.70	5.02	0.98	0.46	0.53
123/3	193	8.8	4.56	4.00	0.95	0.36	0.59
123/4	174	8.8	3.25	2.85	0.85	0.30	0.55
123/5	155	8.2	1.81	1.58	0.53	0.20	0.33
124/1	146	10.0	1.61	1.61	0.53	0.16	0.37
124/2	166	11.5	3.02	2.52	0.95	0.26	0.69
124/3	185	11.6	4.40	4.40	1.02	0.33	0.69
124/4	209	11.4	5.61	5.61	1.12	0.43	0.69
124/5	226	11.3	6.83	6.83	1.22	0.49	0.73
125/1	228	13.6	6.83	5.61	1.31	0.49	0.82
125/2	204	13.6	5.32	4.40	1.18	0.53	0.65
125/3	200	13.0	4.07	3.38	1.08	0.39	0.69
125/4	165	12.6	2.89	2.40	0.99	0.26	0.73
125/5	147	11.2	1.48	1.22	0.49	0.16	0.33
126/1	219	14.9	6.41	5.16	1.33	0.46	0.87
126/2	199	14.7	5.19	4.17	1.18	0.39	0.79
126/3	181	14.2	3.97	3.25	1.15	0.33	0.78
126/4	163	13.4	2.79	2.27	1.02	0.23	0.79
126/5	146	11.8	1.41	1.18	0.46	0.16	0.30
127/1	217	15.8	6.20	4.96	1.35	0.46	0.89
127/2	199	15.5	5.11	4.10	1.25	0.39	0.86
127/3	183	15.2	4.10	3.31	1.15	0.33	0.78
127/4	167	14.8	3.12	2.49	0.89	0.26	0.63
127/5	155	13.8	2.07	1.67	0.85	0.20	0.65

TABLE III (Contd.)

SUMMARY OF RESULTS

Series / Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
128/1	234	5.6	7.10	6.80	0.89	0.53	0.36
128/2	225	5.7	5.78	5.32	0.85	0.49	0.36
128/3	208	6.2	4.60	4.17	0.79	0.43	0.36
128/4	182	6.4	3.55	3.12	0.72	0.33	0.39
128/5	154	6.2	1.93	1.77	0.65	0.20	0.45
129/1	243	2.8	7.19	6.90	0.76	0.56	0.20
129/2	229	3.1	6.00	5.68	0.72	0.53	0.19
129/3	206	3.6	4.79	4.50	0.59	0.43	0.16
129/4	182	3.8	3.61	3.41	0.56	0.33	0.23
129/5	154	3.7	2.20	2.07	0.56	0.20	0.36
Sand No. 1 d_{50} = 1.70 mm							
201/1	247	3.6	6.75	6.40	0.75	0.59	0.16
201/2	230	3.4	5.84	5.50	0.69	0.52	0.17
201/3	214	3.5	4.69	4.46	0.59	0.46	0.13
201/4	193	3.8	3.51	3.31	0.49	0.36	0.13
202/1	237	7.8	6.58	5.96	1.02	0.56	0.46
202/2	225	7.6	5.70	4.92	0.89	0.49	0.40
202/3	209	7.1	4.36	3.90	0.79	0.43	0.36
202/4	189	6.7	3.11	2.78	0.72	0.33	0.39
202/5	166	5.6	1.74	1.57	0.46	0.26	0.20
203/1	234	9.0	6.50	5.64	1.05	0.53	0.52
204/1	234	9.8	6.42	5.45	1.08	0.53	0.55
204/2	217	9.5	5.21	4.49	0.99	0.46	0.53
204/3	200	9.2	4.03	3.51	0.85	0.39	0.46
204/4	181	8.8	2.76	2.40	0.76	0.33	0.43
204/5	170	7.6	1.48	1.32	0.43	0.26	0.17
205/1	214	11.3	6.04	5.05	1.12	0.49	0.63
205/2	209	11.0	4.95	4.17	0.99	0.43	0.56
205/3	195	10.6	3.81	3.25	0.89	0.36	0.53
205/4	179	9.8	2.72	2.33	0.76	0.30	0.46
205/5	162	7.9	1.13	1.15	0.43	0.28	0.15

TABLE III (Contd.)

SUMMARY OF RESULTS

Series/Run	Q	C	a	a_m	b	b_o	$b-b_o$
	gpm	%	ft.	ft.	ft.	ft.	ft.
206/1	247	2.44	7.28	7.08	0.72	0.59	0.13
206/2	233	2.8	5.96	5.76	0.62	0.53	0.09
206/3	210	2.9	4.89	4.73	0.58	0.43	0.15
206/4	186	2.9	3.54	3.44	0.46	0.33	0.13
206/5	180	2.8	2.43	2.36	0.39	0.23	0.16
207/1	234	7.0	6.75	6.00	0.95	0.53	0.42
207/2	234	5.7	6.82	6.20	0.89	0.53	0.36
207/3	225	5.6	5.63	5.15	0.75	0.49	0.26
207/4	200	5.7	4.46	4.07	0.69	0.39	0.30
207/5	179	5.6	3.25	2.95	0.66	0.30	0.36
207/6	157	4.9	2.85	2.66	0.56	0.23	0.33
208/1	241	1.4	7.11	7.00	0.66	0.56	0.10
208/2	225	1.3	6.13	6.00	0.59	0.49	0.10
208/3	204	1.7	4.82	4.72	0.49	0.39	0.10
208/4	181	1.9	3.74	3.64	0.40	0.30	0.10
208/5	157	2.1	2.62	2.56	0.30	0.20	0.10

TABLE IV: COMPUTATION OF FLOWRATE AND CONCENTRATION

Sand No. 00 - $d_{50} = 0.46$ mm.

Series/Run	Q_L	Q_F	$\frac{Q_F - Q_L}{Q_L}$	Q	C_L	C_{cor}	C_s	$\frac{C_s - C_L}{C_L}$	C	s_m
	gpm	gpm	%	gpm	%	%	%	%	%	
I-00/1	225	230	2.1	230	0.4	0.4	0.4	0	0.4	1.007
I-00/2	325	325	0	325	0.8	0.8	0.75	0	0.8	1.013
I-00/3	422	423	0.2	423	1.5	1.5	1.6	6.6	1.6	1.026
I-00/4	500	506	1.2	505	2.3	2.7	2.6	13.0	2.6	1.043
I-00/5	568	572	0.7	570	2.9	3.2	3.4	17.0	3.4	1.054
II-00/1	190	196	3.1	195	0.3	0.3	(0.3)	0	0.3	1.005
II-00/2	225	231	2.6	230	0.6	0.7	(0.6)	2.0	0.6	1.008
II-00/3	260	267	2.7	265	0.8	0.9	(0.8)	4.0	0.8	1.013
II-00/4	290	298	2.7	295	1.0	1.1	1.06	6.0	1.1	1.018
II-00/5	342	347	1.4	345	1.5	1.7	(1.6)	6.0	1.7	1.028
II-00/6	380	383	0.8	383	1.9	2.0	1.98	4.1	2.0	1.033
II-00/7	420	423	0.7	423	2.4	2.6	(2.6)	8.0	2.6	1.043
II-00/8	465	472	1.5	470	3.2	3.7	(3.6)	11.0	3.7	1.061
II-00/9	515	534	3.6	530	4.0	5.0	(4.6)	14.0	4.9	1.081
II-00/10	565	587	3.8	585	4.6	6.5	5.4	17.5	6.3	1.097
III-00/1	295	302	2.3	300	2.1	2.4	(2.3)	9.0	2.35	1.039
III-00/2	360	365	1.4	365	3.25	3.75	3.85	18.5	3.8	1.063
III-00/3	405	414	2.2	410	4.2	4.9	(5.1)	23.0	5.0	1.083
III-00/4	450	463	2.8	460	4.7	6.0	(6.0)	27.0	6.0	1.099
III-00/5	490	516	5.2	515	5.7	7.9	7.55	32.5	7.8	1.129
III-00/6	520	551	5.8	550	6.4	9.3	(9.1)	42.0	9.2	1.152
III-00/7	565	596	5.2	595	6.9	10.5	10.55	53.0	10.5	1.173
III-00/8	585	620	5.7	620	7.2	12.2	(11.5)	60.0	12.0	1.198

TABLE IV: COMPUTATION OF FLOWRATE AND CONCENTRATION
(Contd.)

Sand No. 00 - $d_{50} = 0.46$ mm.

Series/Run	Q_L	Q_F	$\frac{Q_F-Q_L}{Q_L}$	Q	C_L	C_{cor}	C_s	$\frac{C_s-C_L}{C_L}$	C	s_m
	gpm	gpm	%	gpm	%	%	%	%	%	
IV-00/1	305	312	2.3	310	3.6	4.0	4.3	19.4	4.15	1.069
IV-00/2	340	347	2.0	345	4.75	5.3	(5.65)	19.5	5.45	1.091
IV-00/3	380	401	5.4	400	5.7	6.9	(6.8)	19.5	6.9	1.114
IV-00/4	415	436	5.0	435	6.6	7.9	(8.0)	19.5	8.0	1.132
IV-00/5	445	472	5.9	470	7.3	9.7	9.1	19.8	9.5	1.156
IV-00/6	480	503	4.7	500	7.8	10.1	(10.1)	30.0	10.1	1.165
IV-00/7	505	534	5.6	530	8.2	11.5	11.9	45.0	11.7	1.193
IV-00/8	540	574	6.1	570	8.1	12.0	(12.6)	55.0	12.2	1.199

TABLE IV: COMPUTATION OF FLOWRATE AND CONCENTRATION (Contd.)

Sand No. 0 - d_{50} = 0.88 mm.

Series/Run	Q_L	Q_F	$\frac{Q_F-Q_L}{Q_L}$	Q	C_L	C_{cor}	C_s	$\frac{C_s-C_L}{C_L}$	C	s_m
	gpm	gpm	%	gpm	%	%	%	%	%	
I-0/1	218	222	1.8	220	0.3	0.5	--	--	0.4	1.007
I-0/2	250	258	3.2	255	0.4	0.6			0.5	1.008
I-0/3	305	312	2.3	310	0.8	1.0			0.9	1.015
I-0/4	345	356	2.9	355	0.8	1.3			1.1	1.018
I-0/5	385	396	2.8	395	0.8	1.3			1.2	1.020
I-0/6	425	440	3.5	440	1.0	2.0			1.8	1.030
I-0/7	465	481	3.4	480	1.5	2.5			2.3	1.038
I-0/8	525	534	1.7	530	1.7	2.5			2.5	1.042
II-0/1	315	320	1.6	320	1.15	1.35	--	--	1.3	1.021
II-0/2	345	356	3.2	355	1.5	2.1			1.9	1.031
II-0/3	370	387	4.6	385	1.8	2.8			2.5	1.042
II-0/4	405	423	4.5	420	2.3	3.3			3.0	1.050
II-0/5	465	481	3.5	480	3.1	4.3			4.0	1.066
II-0/6	500	520	4.0	520	3.4	5.4			5.0	1.083
II-0/7	525	543	3.4	540	4.0	6.0			5.7	1.094
II-0/8	570	592	3.9	590	4.4	6.8			6.6	1.109
II-0/9	600	618	3.0	615	4.8	7.0			7.0	1.115
III-0/1	310	320	3.2	320	2.85	3.5	--	--	3.4	1.056
III-0/2	345	356	3.2	355	3.7	4.4			4.3	1.071
III-0/3	380	392	3.2	390	4.3	5.3			5.2	1.086
III-0/4	422	436	3.3	435	5.3	6.8			6.6	1.109
III-0/5	455	467	2.7	465	5.85	7.25			7.1	1.117
III-0/6	490	506	3.3	505	6.7	8.4			8.2	1.135
III-0/7	515	538	4.5	535	7.0	9.0			8.8	1.145
III-0/8	560	583	4.1	580	7.5	10.5			10.2	1.169

TABLE IV: COMPUTATION OF FLOWRATE AND CONCENTRATION (Contd.)

Sand No. 0 - d_{50} = 0.88 mm.

Series/Run	Q_L	Q_F	$\frac{Q_F-Q_L}{Q_L}$	Q	C_L	C_{cor}	C_s	$\frac{C_s-C_L}{C_L}$	C	s_m
	gpm	gpm	%	gpm	%	%	%	%	%	
IV-0/1	305	325	8.0	325	4.7	5.7	--	--	5.5	1.091
IV-0/2	340	360	5.9	360	5.9	7.0			6.8	1.112
IV-0/3	370	396	4.3	395	7.0	8.0			8.0	1.132
IV-0/4	420	445	6.0	445	8.25	9.25			9.0	1.149
IV-0/5	455	481	5.7	480	8.8	11.0			10.8	1.178
IV-0/6	500	542	8.0	540	9.8	13.0			12.8	1.211
IV-0/7	555	608	7.5	605	10.7	14.0			14.0	1.231

APPENDIX

COMPUTATIONAL PROCEDURES

The Foxboro Magnetic Flowmeter readings were checked against the readings of a Prandtl tube placed in the pipeline for flow rates up to 600 gpm. Since the flowmeter operates on the basis of magnetic flux transmitted and recorded across the flow, the mixture flow rate in a two-phase flow is recorded just as done in the case of a clear-water flow. Thus, the flowmeter is a reliable device for measurement of the flow rate for solid-liquid mixture flows.

The Loop System consists essentially of two identical vertical pipe sections with opposite flow directions, namely the "riser" and the "downcomer". Mixture flow rate, Q_m, and the concentration, C, are determined with the theory advanced by Einstein et al. (1966). A computer (CDC 6400) program was developed to expedite the solution for both types of sand.

It was noted that the flowmeter readings were systematically higher than the ones given by the loop, and that this discrepancy increased with larger flow rates and larger solids concentrations, although never exceeding 8 percent. Further, it was discovered that the concentrations evaluated by using a sediment sampling device quite similar to a Pitot-tube were also larger than those given by the loop. The discrepancy increased with flow rate and solids concentration to magnitudes as much as 50%. Since the flowmeter and the sediment sampler were considered to be the more reliable measuring devices, a method of correction of the loop reading was applied, as explained in the following. First, the loop readings were corrected for the flow rate according to the flowmeter readings, in effect adjusting the sum of the two head readings from the riser and the downcomer. It was observed that the corresponding correction of head differences most consistently corrected the concentration readings. The sediment sampling device was clogged and damaged when using the coarser sand so that the same method of correction was assumed applicable to the coarser sand concentrations.

The correction values are those used in the analysis. Table IV is a tabulation of the flow rate and the concentration readings and corresponding corrections. The numbers in parantheses () are those interpolated between sampled runs.

BIBLIOGRAPHY

Einstein, H. A. and W. H. Graf (1966): "Loop System for Measuring Sand-Water Mixtures", Journal of the Hydraulics Division, ASCE, Vol. 92, No. HY1, Proc. Paper 4608, January, pp. 1-12.

Graf, W. H. (1967): "A Modified Venturimeter for Measuring Two-Phase Flow-or-Particle Dynamics and the Venturimeter", Journal of Hydraulic Research, Vol. 5, No. 3, pp. 161-187.

Olson, R. B. (1967): "Essentials of Engineering Fluid Mechanics", International Textbook Company, Scranton, Pennsylvania.

LIST OF SYMBOLS

A_1, A_2	cross sectional area of the Venturimeter at the entrance and at the throat, respectively, in sq ft
a	pressure drop due to mixture flow, in ft of water column
a_m	pressure drop due to mixture flow, in ft of mixture column
b, b_o	energy loss of the mixture and of the clear water, respectively, in ft of water column
C	solids concentration, in percent by volume
C_{cor}	corrected concentration, reading from the loop system, in percent by volume
C_m	coefficient, given in Eq. (6)
C_L	concentration reading from the loop system, uncorrected, in percent by volume
C_s	concentration computed from sediment sampling devices, in percent by volume
c_V	coefficient of flow for a Venturimeter, given by Eq. (2)
g	gravitational acceleration, 32.2 ft/sec^2
k	coefficient, given in Eq. (8)
n	exponent, given in Eq. (7)
Q	flow rate, in gpm
Q_F	mixture flow rate recorded by the magnetic flowmeter, in gpm
Q_m	mixture flow rate, in gpm
Q_L	mixture flow rate obtained from the loop system, uncorrected, in gpm

s_m	density of the mixture determined according to the equation $s_m = 1.00\ (1-C) + 2.65C$
Δp	the pressure drop, in lb/sq ft
V	mixture velocity at the throat of the Venturimeter, in fps
γ, γ_s, γ_m	specific weights of the water, sand, and mixture, respectively, in lb/cu ft