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RESEARCH STUDY FOR DETERMINATION OF LIQUID SURFACE PROFILE IN A CRYOGENIC TANK DURING GAS INJECTION

September 18 - December 18, 1967

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Quarterly Report #14, NAS8-11334
RESEARCH STUDY FOR DETERMINATION OF LIQUID SURFACE PROFILE IN A CRYOGENIC TANK DURING GAS INJECTION

Period Covered: September 18, 1967 - December 18, 1967

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NOMENCLATURE

A_v	void area of the partially filled horizontal pipe
E	fraction of the total amount of water initially present in the test section removed by the air stream within a given time
$E_{calculated}$	entrainment calculated from Equation (2)
E_{data}	entrainment found experimentally
H_v	distance from the liquid surface to the upper pipe surface
$\mathring{M}$	air mass flow rate, lbm/min.
N_{Re}	air Reynolds number, $N_{Re} = \frac{H_v \mathring{M}}{A_v \mu_a}$
t	time
μ	dynamic liquid viscosity
μ_a	dynamic viscosity of air

INTRODUCTION

This is the fourteenth Quarterly Progress Report for NAS8-11334, RESEARCH STUDY FOR DETERMINATION OF LIQUID SURFACE PROFILE IN A CRYOGENIC TANK DURING GAS INJECTION. The period covered is September 18, 1967 to December 18, 1967.

ANALYSIS OF PROGRESS

The primary effort during this report period was directed toward the development of preliminary correlation equations for the entrainment data previously obtained with test section two. These equations allow the prediction of entrainment as a function of time, liquid viscosity, and Reynolds number. Even though the correlation will require some refinement, it does show that entrainment can be predicted with a reasonable degree of accuracy for a given system.

The construction of test section four was completed this quarter and data for the 1/4-filled case were obtained. These data have not been fully evaluated but indications are that they behave in a manner similar to those data obtained with test section two.

PROGRESS

A preliminary system of correlation equations has been developed for the entrainment data obtained with test section two. The data for test section two are tabulated in Quarterly Progress Report #13. These data were analyzed in terms of the air mass flow rate (expressed as Reynolds Number N_{Re}), liquid viscosity μ (normalized with respect to the viscosity of water at standard conditions), initial liquid depth, and time duration t. In seeking the functional relationship

$$E = f(N_{Re}, \mu, t), \tag{1}$$

it was observed that plots of entrainment versus viscosity on log-log coordinates resulted in straight lines for different Reynolds numbers and time durations. Based on these plots, the correlation equation was assumed to be of the form

$$E = C_1 \mu^{C_2}, \qquad (2)$$

where C_1 and C_2 are constants for a given Reynolds Number and time, and μ is the dynamic liquid viscosity. Least-squares regression techniques were used in determining C_1 and C_2 as functions of Reynolds number and time.

For the 1/4-filled case, C_1 was found to be related to Reynolds number by the equation

$$\ln (C_1) = 0.622 \ln \left[\frac{N_{Re}}{10^6}\right] + 1.463. \qquad (3)$$

The equation for C_2 was determined to be

$$\ln (-C_2) = A \ln \left[\frac{N_{Re}}{10^6}\right] + B \qquad (4)$$

where

$$A = 0.1678\ t - 2.990 \qquad (5)$$

and

$$B = 0.3088\ t - 11.473. \qquad (6)$$

Substitution of C_1 and C_2 into equation (2), along with the corresponding value of liquid viscosity, yields the predicted value of entrainment.

A comparison of the experimental entrainment and the entrainment as predicted by equations (2) through (6), is shown in Figures 1 through 4 for the 1/4-filled case. Table 1 shows the range of error resulting from use of the prediction equations. The percent error was calculated using the relation

$$\text{percent error} = \frac{E_{data} - E_{calculated}}{E_{calculated}} \times 100 \qquad (7)$$

The correlation equations for the 1/2-filled case were developed in the same manner as in the 1/4-filled case. Again, equation (2) was used as the prediction equation where C_1 is defined by the relation

$$\ln (C_1) = 0.269 \ln \left[\frac{N_{Re}}{10^6}\right] + 0.631 \qquad (8)$$

and C_2 is determined by the equation

$$\ln (-C_2) = A \ln \left[\frac{N_{Re}}{10^6}\right] + B \,. \qquad (9)$$

The term B in equation (9) is a function of time as expressed by the equation

$$B = \frac{5.36}{t} - 13.6, \qquad (10)$$

and A is a constant

$$A = -3.19. \qquad (11)$$

Figures 5 through 8 show a comparison between the experimental and predicted entrainment for the 1/2-filled case. The range of error in the predicted results is presented in Table 2.

It is realized that considerable error exists between the experimental entrainment data and those values predicted by the equations presented herein. However, with the exception of the two-minute runs, it is felt that the system of equations gives reasonable accuracy. Additional work will be conducted on the correlation system next quarter in an effort to refine the present equations.

Construction of test section four was completed this quarter and acquisition of data for the 1/4-filled case was begun. A photograph of test section four is shown in Figure 9, and a schematic may be seen in Figure 10. The entrainment data for the 1/4-filled case are presented in Table 5. These data are also shown in Figures 11 through 14 as log-log plots of entrainment E versus viscosity μ for various times and Reynolds numbers. Analysis of these results has not been completed but observation of Figures 11 through 14 shows that these data behave similarly to previous data obtained with test section two. Note that the entrainment versus viscosity data plots as a straight line on log-log coordinates.

Plans for Next Quarter

The acquisition of data with test section four will be continued next quarter in an effort to make valid conclusions concerning the introduction of the T-section. In particular, the 1/2-filled case will be studied. Work will also continue on the correlation system in order to refine the equations presented in this report.

Table 1. Legend for Figures 1 through 4.

Experimental Values of Entrainment

	Reynolds Number
○	5.2×10^4
□	6.45×10^4
△	7.82×10^4
+	10.8×10^4

Values of Entrainment Calculated from Equation (2)

	Reynolds Number
— — — —	5.2×10^4
—— – ——	6.45×10^4
——— ———	7.82×10^4
————————	10.8×10^4

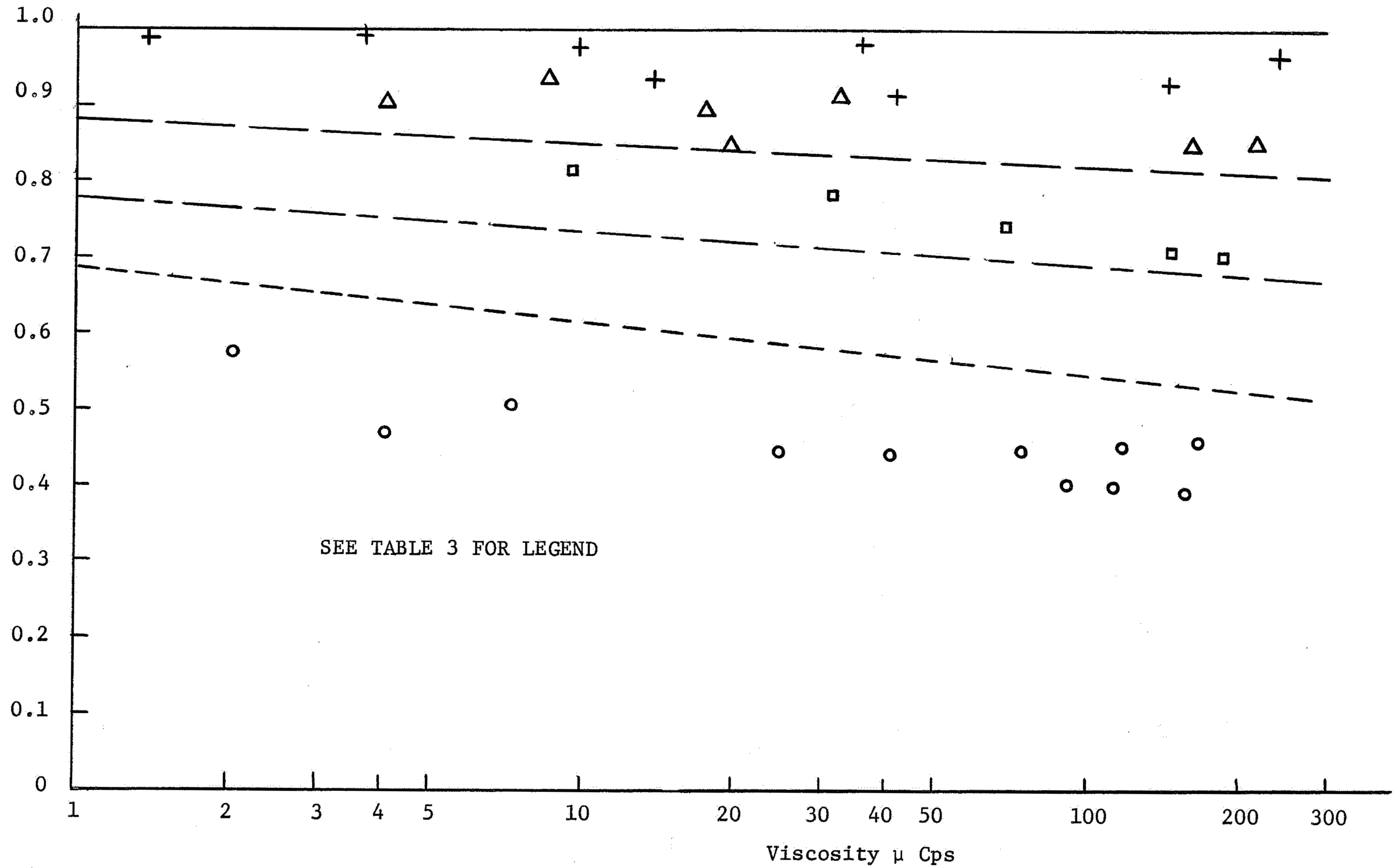

Figure 1. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

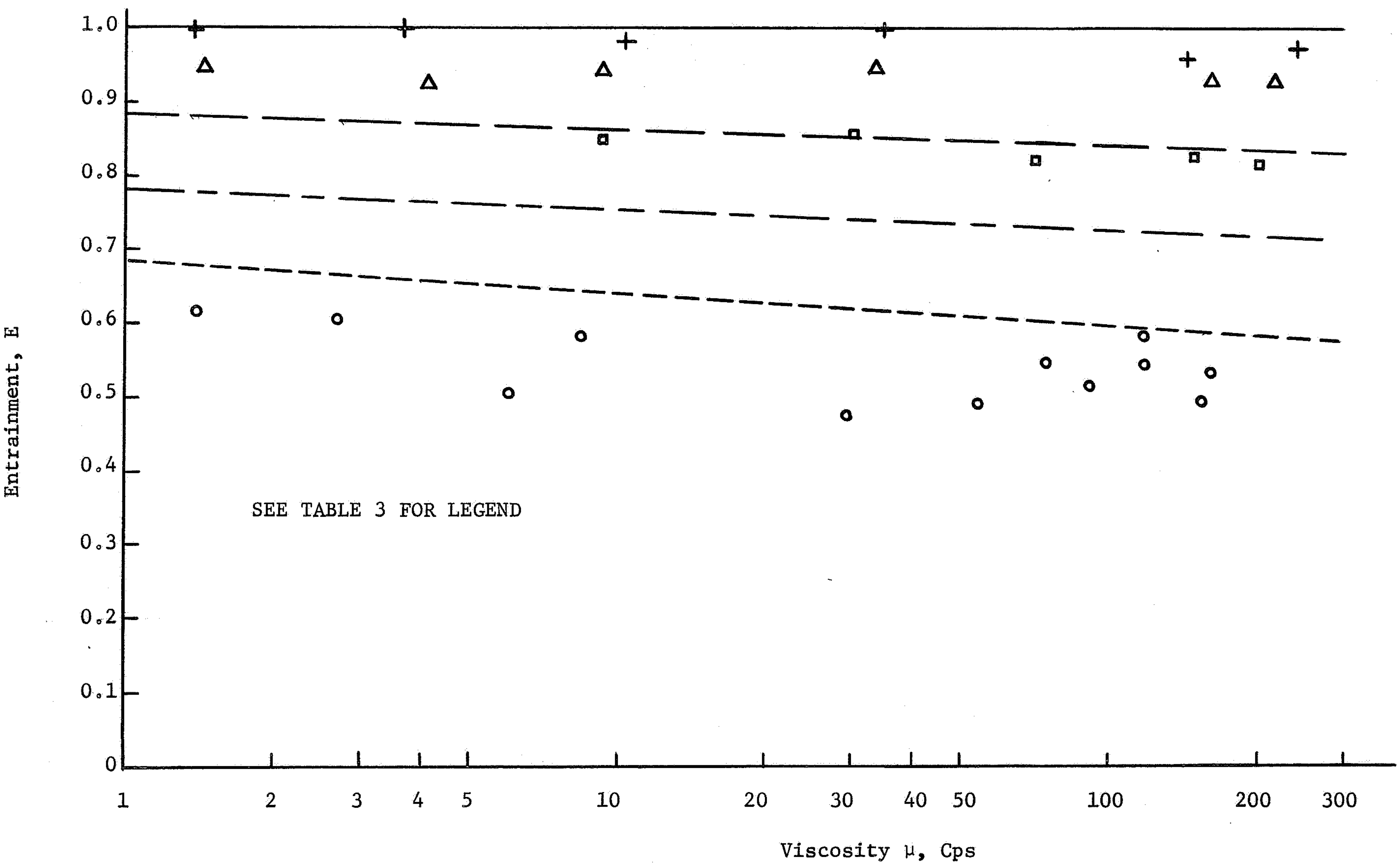

Figure 2. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

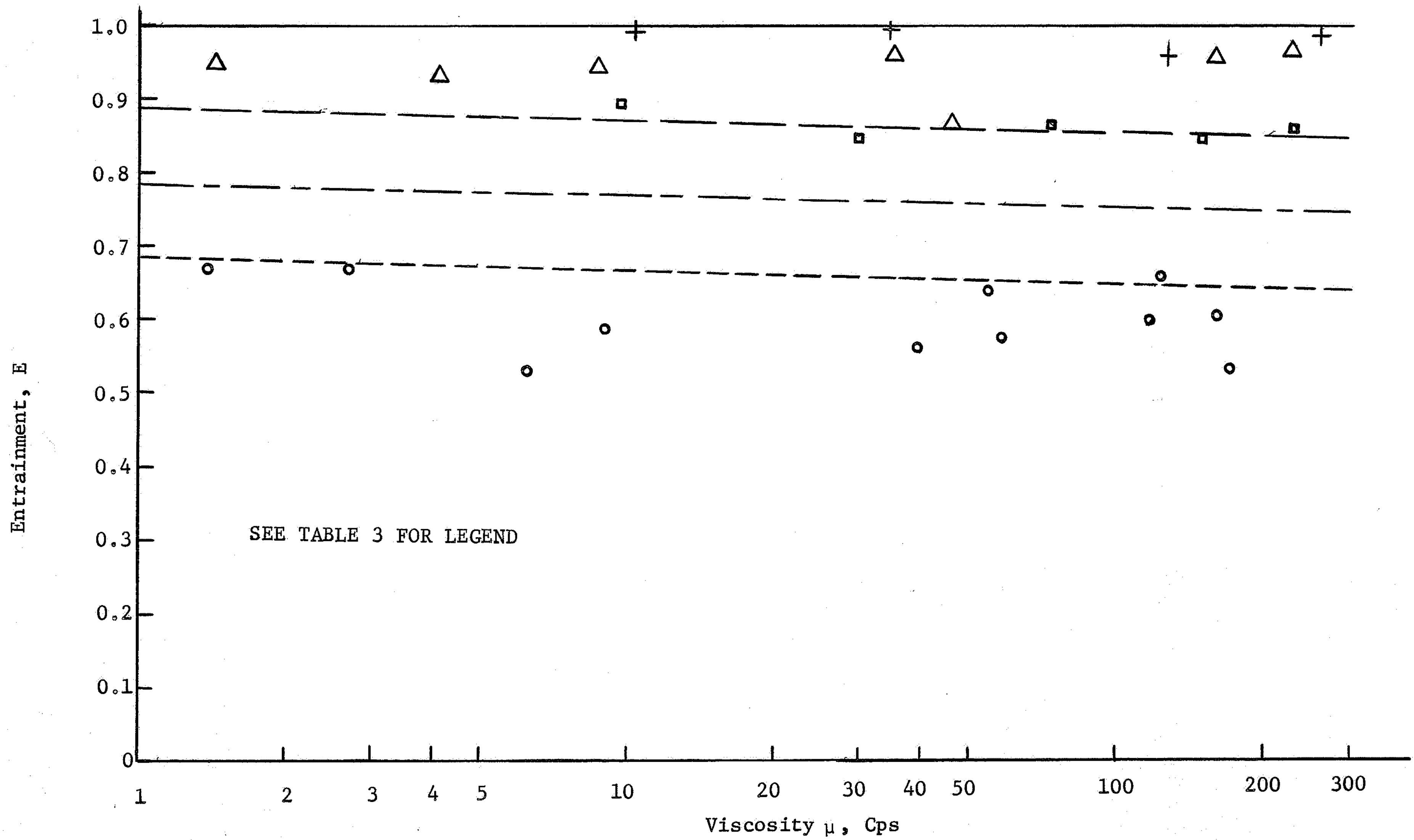

Figure 3. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates.

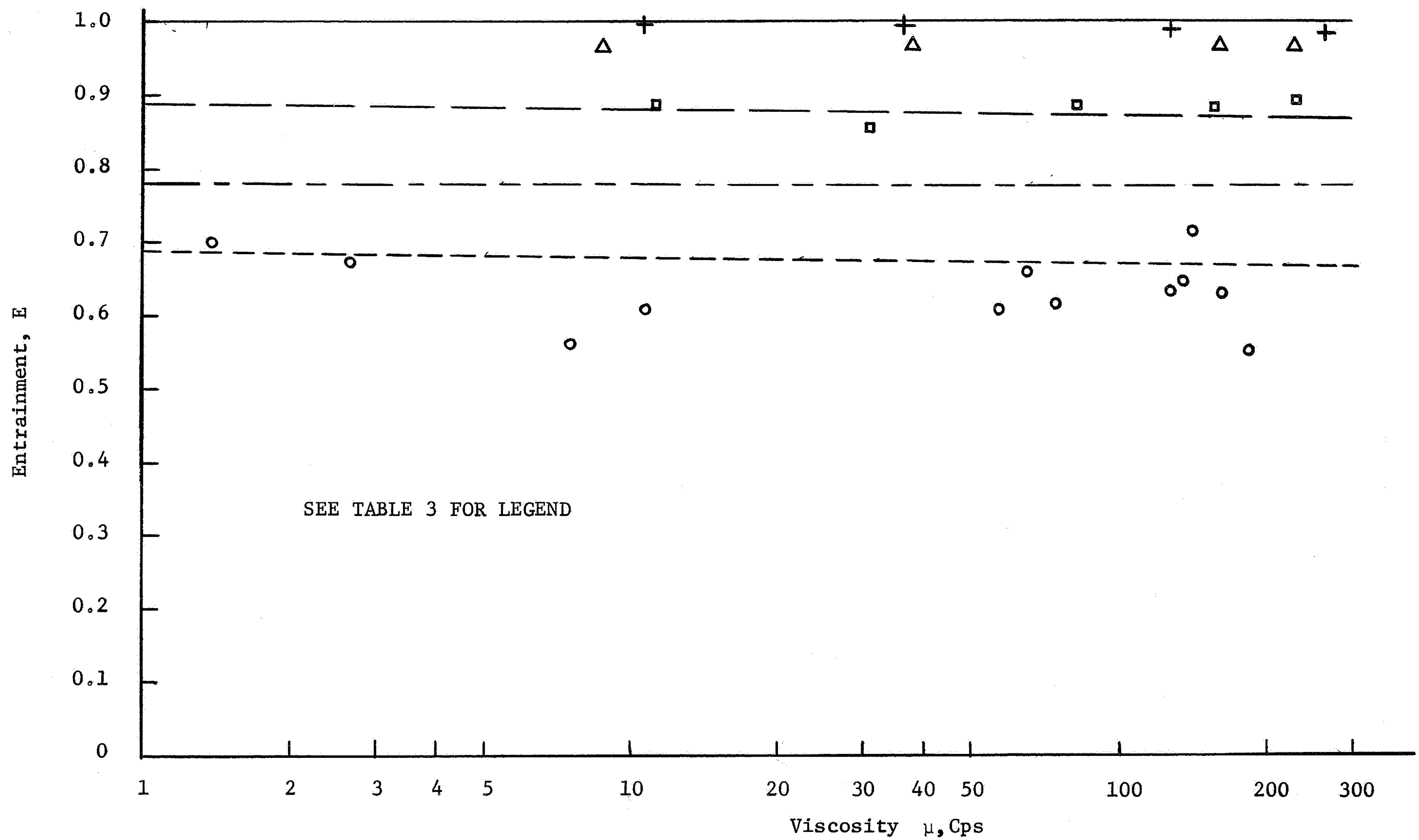

Figure 4. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Fifteen Minutes for Various Air Flow Rates.

Table 2. Legend for Figures 5 through 8.

Experimental Values of Entrainment

	Reynolds Number
○	5.5×10^4
□	6.94×10^4
△	8.31×10^4
+	11.20×10^4

Values of Entrainment Calculated from Equation (2)

	Reynolds Number
— — — —	5.5×10^4
——— — ———	6.94×10^4
———— ————	8.31×10^4
————————	11.2×10^4

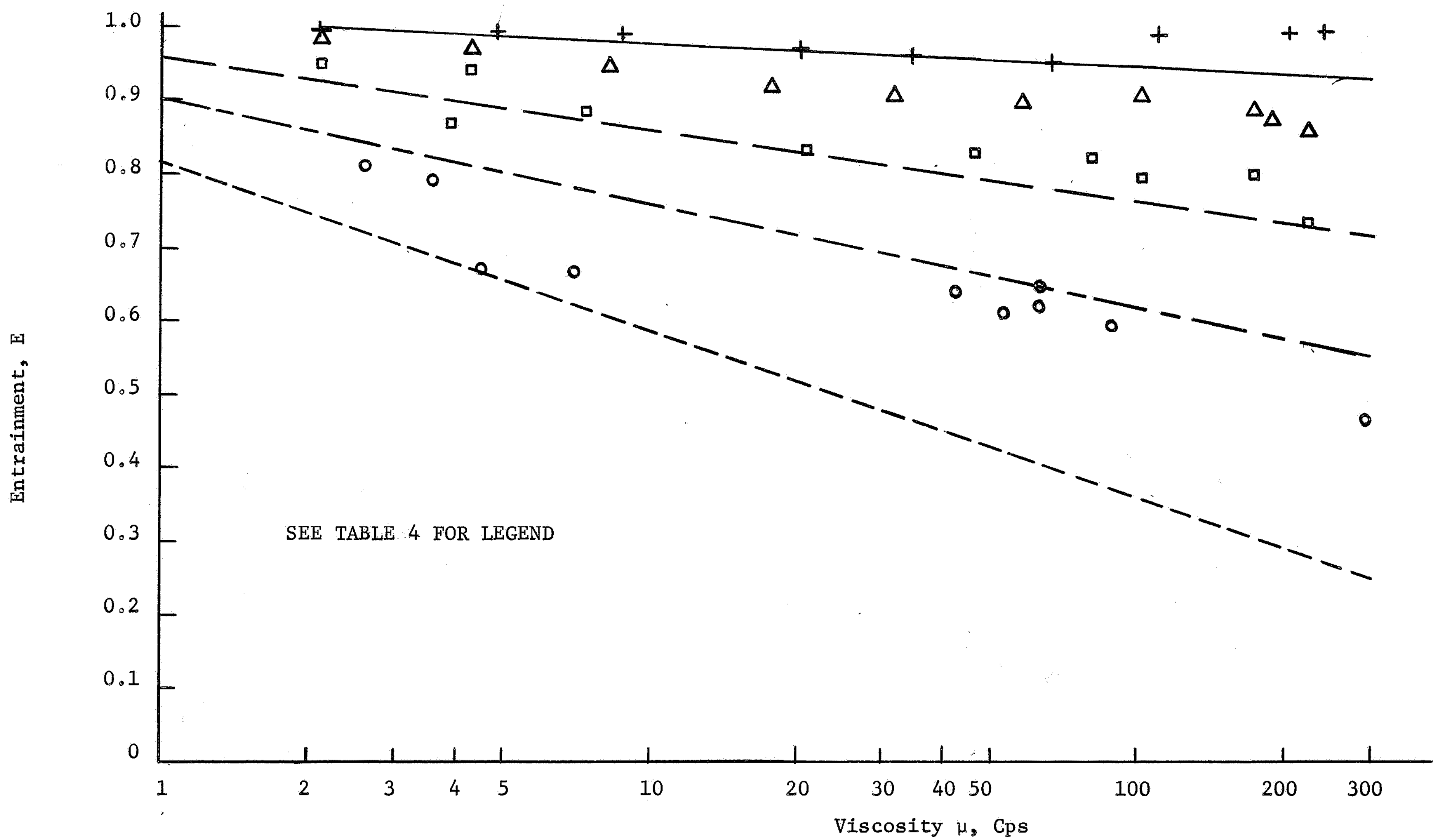

Figure 5. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

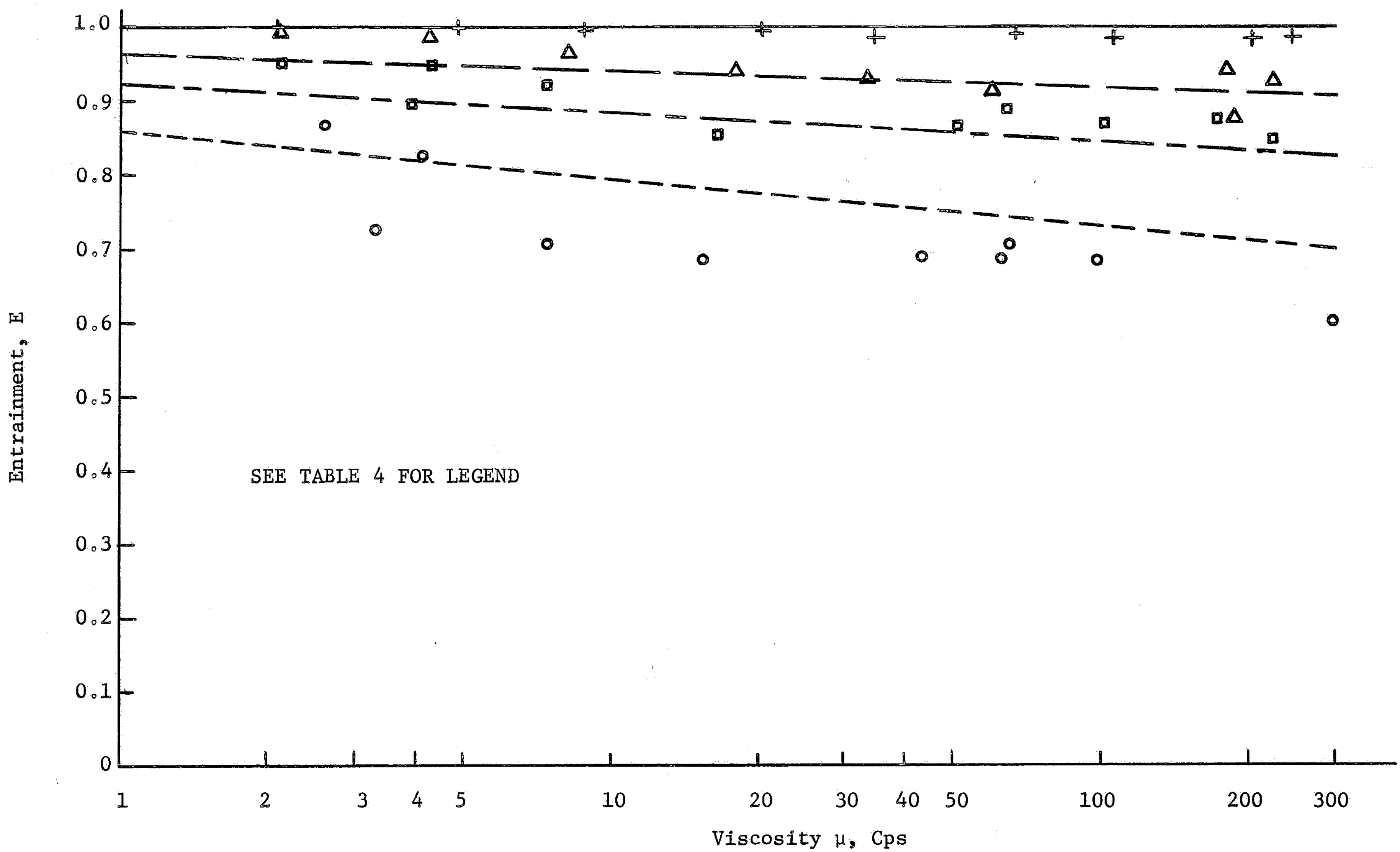

Figure 6. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

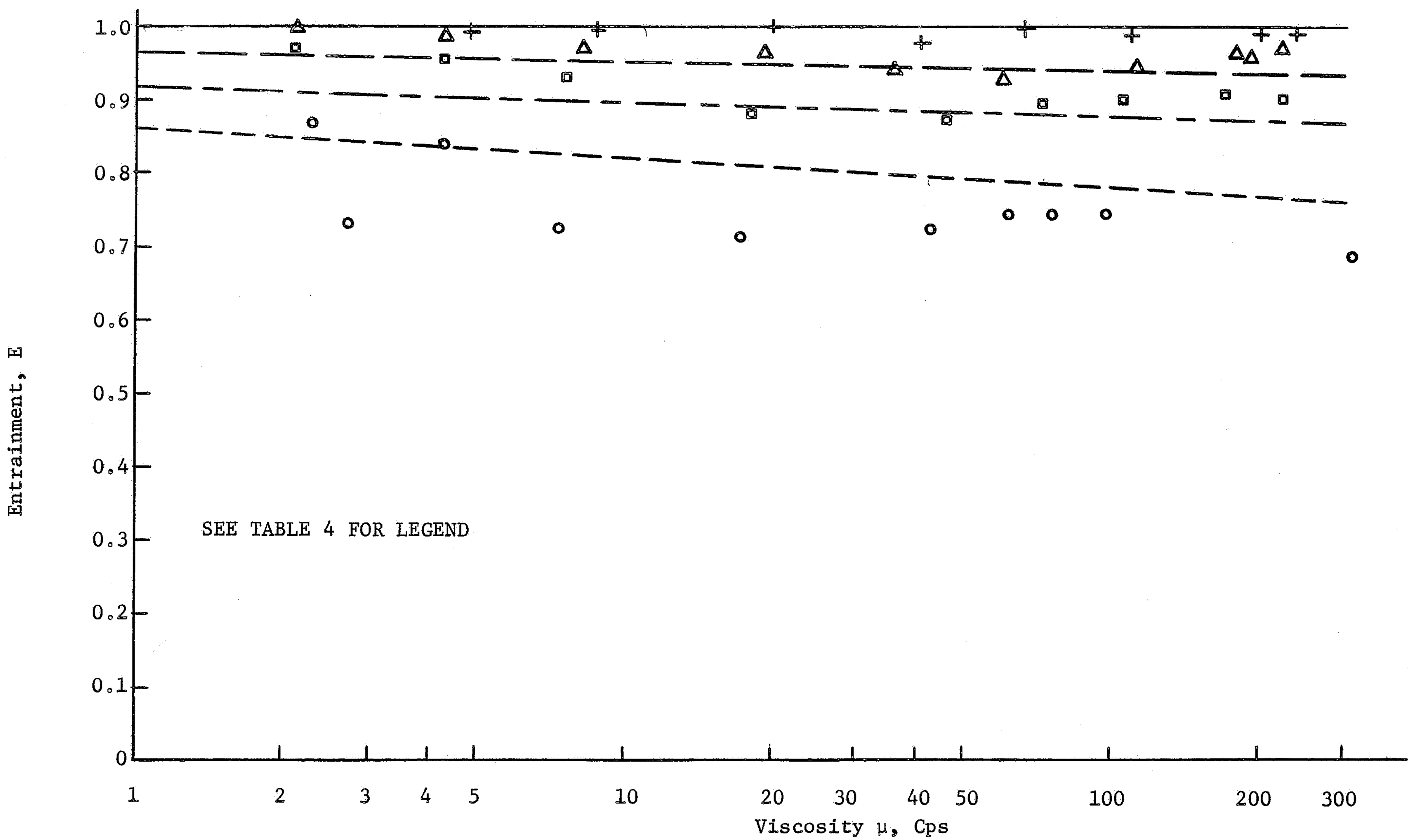

Figure 7. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates.

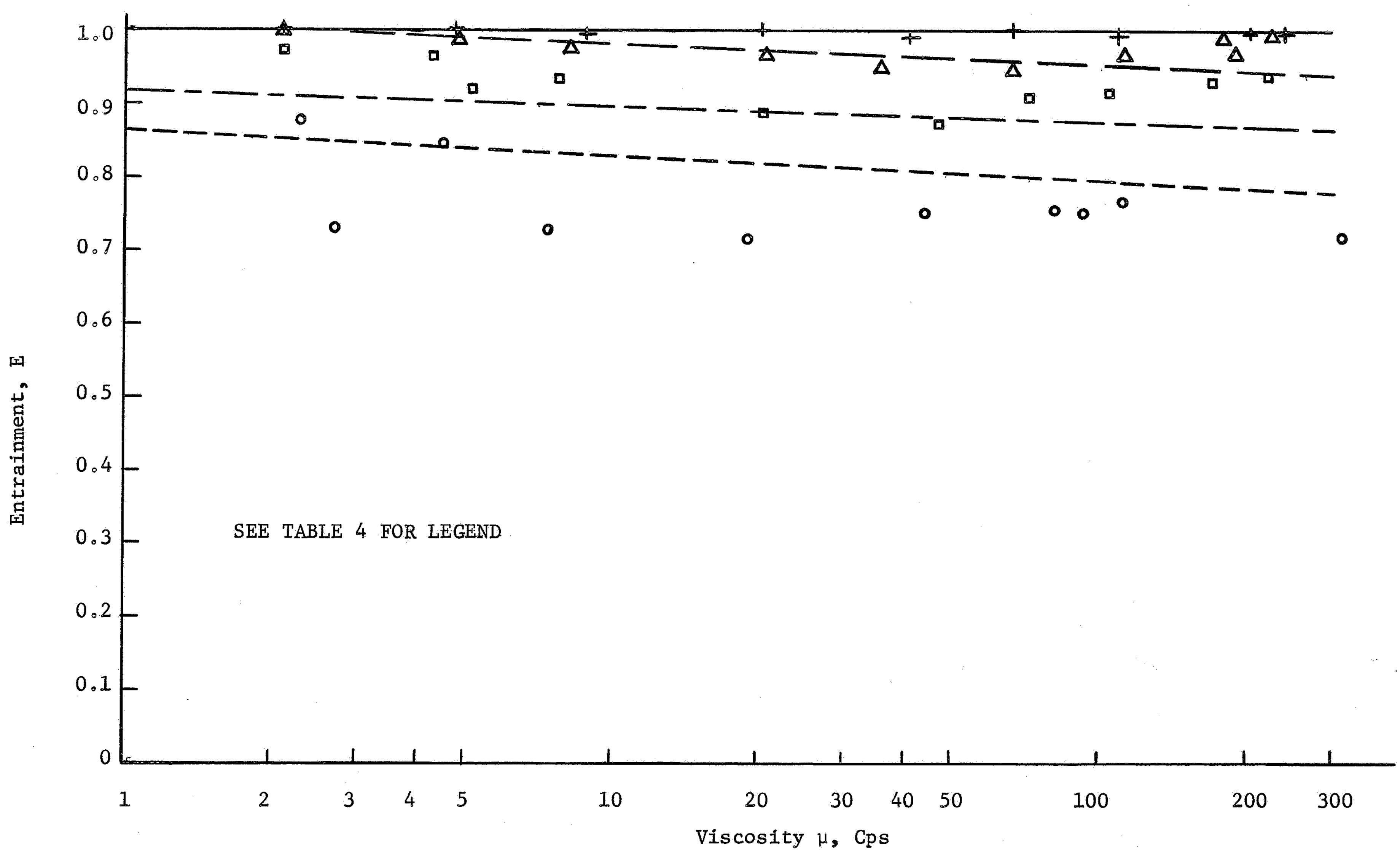

Figure 8. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Fifteen Minutes for Various Air Flow Rates.

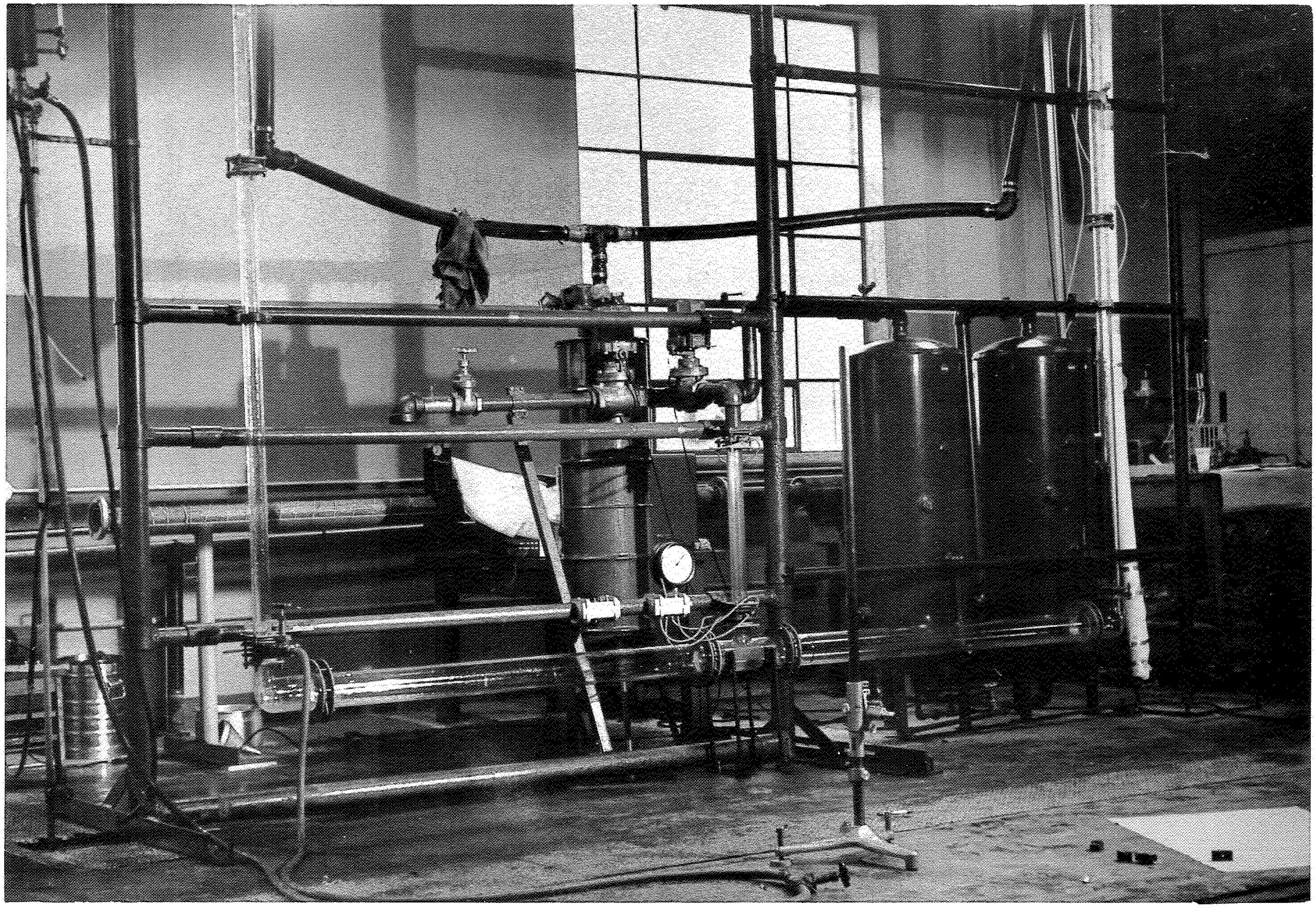

Figure 9. Photograph of Test Section Four.

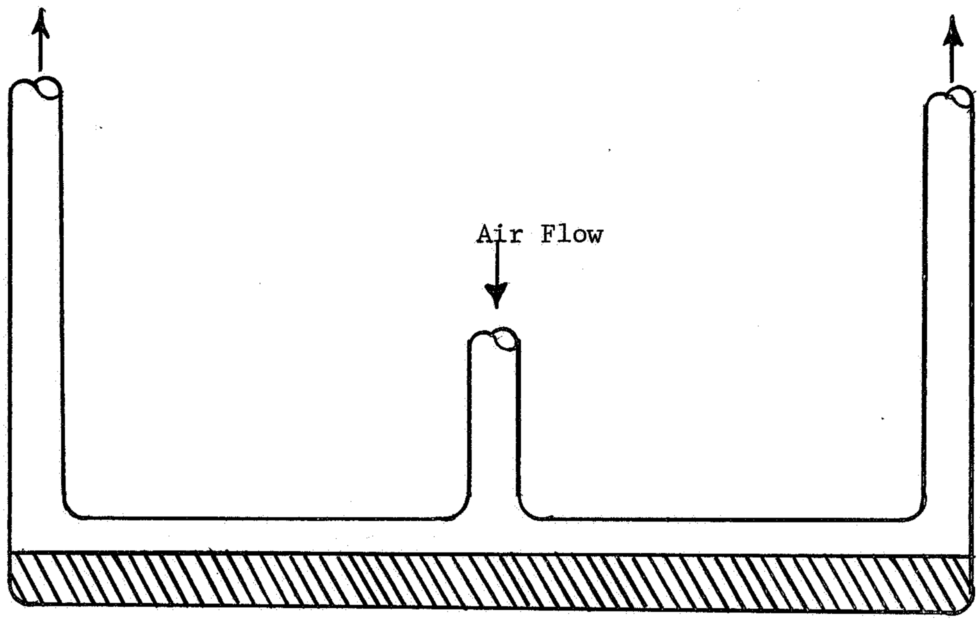

Figure 10. Test Section Four with Air Directed Vertically Downward into the Longitudinal Center of the Horizontal Pipe.

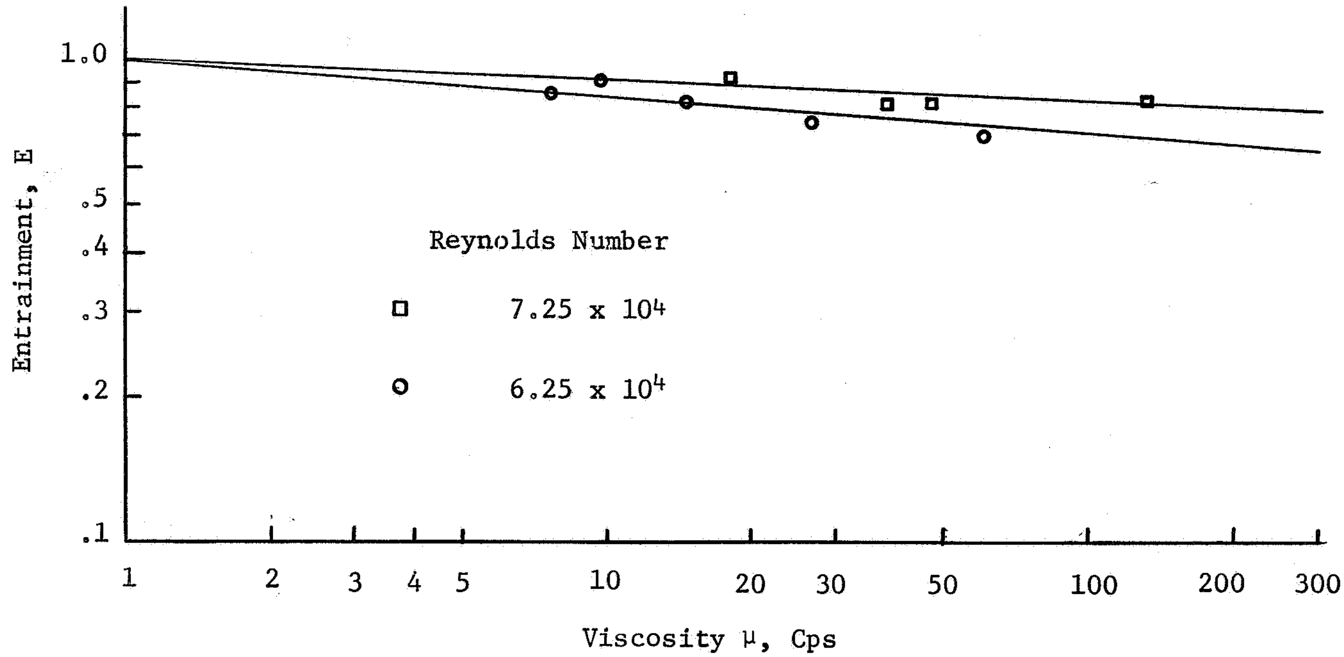

Figure 11. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

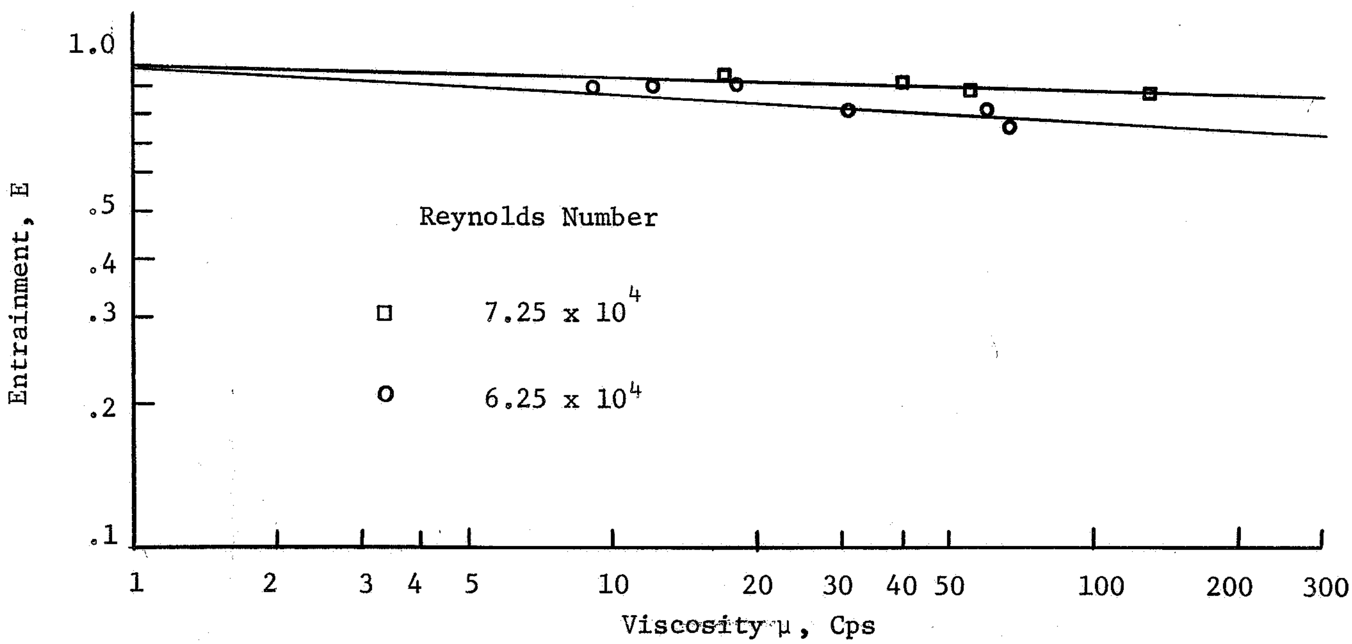

Figure 12. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

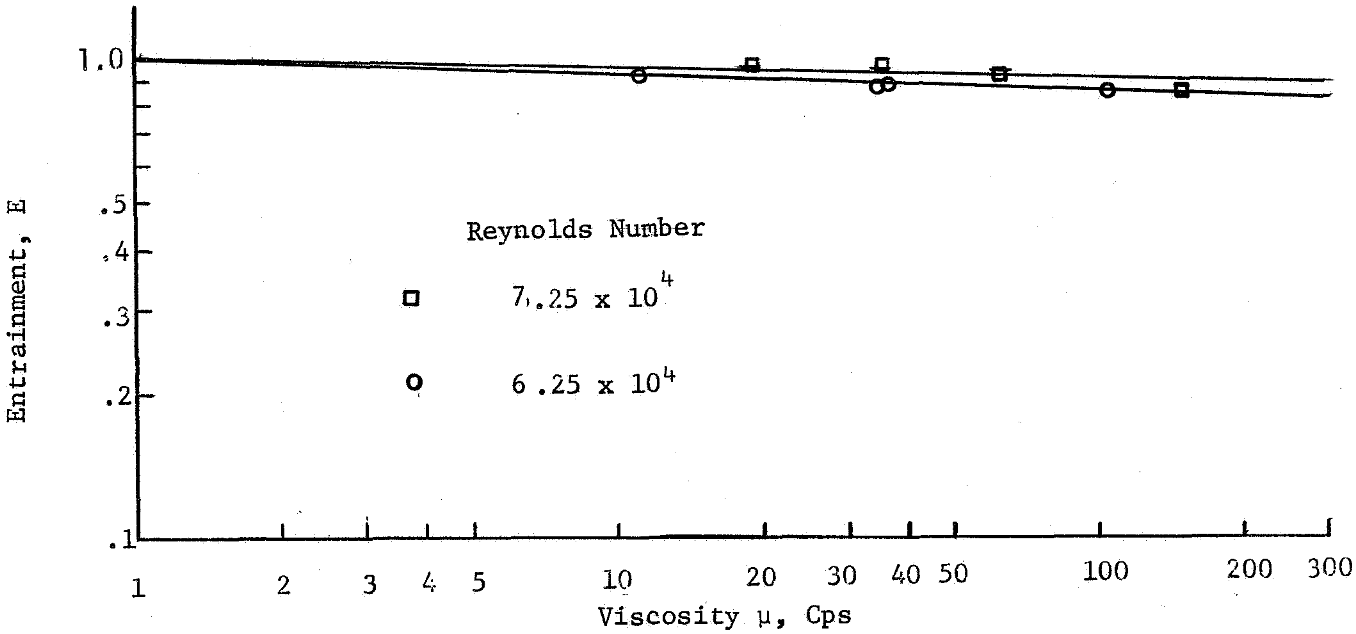

Figure 13. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates.

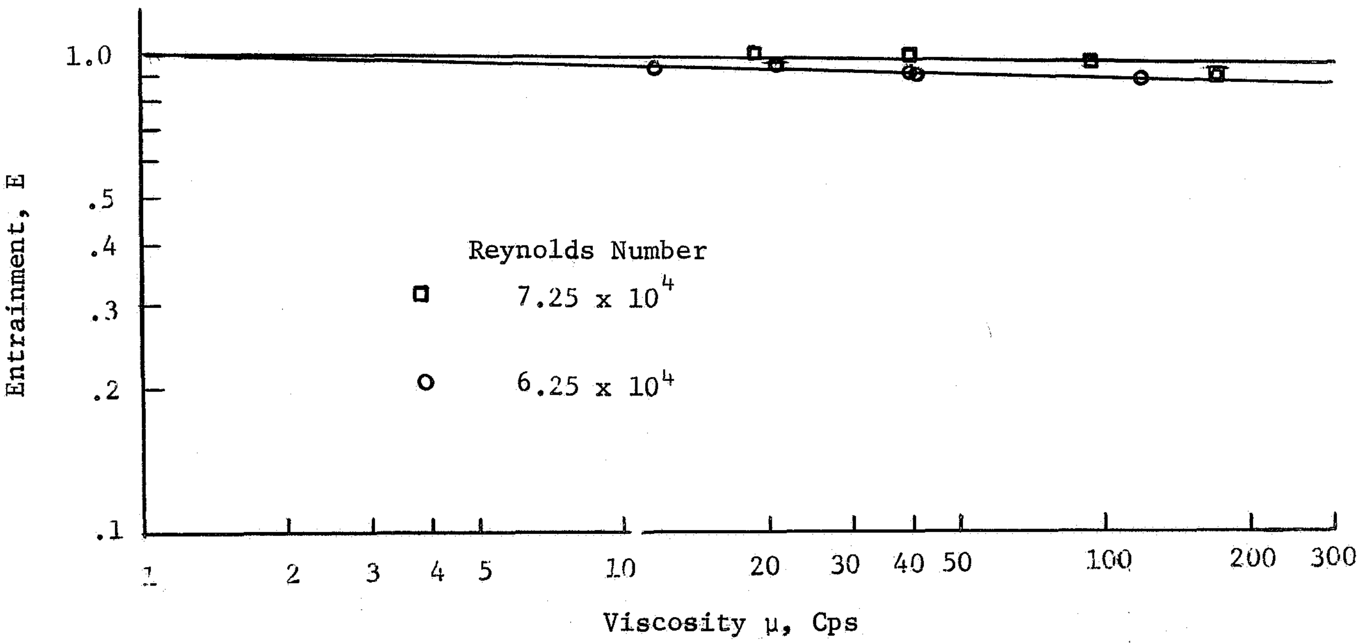

Figure 14. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Fifteen Minutes for Various Air Flow Rates.

Table 3. Deviation in Experimental and Calculated Values of Entrainment for 1/4-Filled Case.

Data Set	Time Duration, minutes	Flow Rate lb/min.	N_{Re} x 10^{-6}	Viscosity Range, cps	Error in E %
1	0-2	11.20	5.20	1-164	-26.73 to -12.80
2	0-2	13.90	6.45	1-185	3.72 to 10.91
3	0-2	16.83	7.82	1-216	-2.65 to 4.59
4	0-2	23.23	10.80	1-238	-12.96 to -6.99
5	0-5	11.20	5.20	1-160	-23.92 to -3.07
6	0-5	13.90	6.45	1-200	13.18 to 14.79
7	0-5	16.83	7.82	1-216	6.27 to 11.19
8	0-5	23.23	10.80	1-238	-9.13 to -6.29
9	0-10	11.20	5.20	1-170	-17.66 to 1.37
10	0-10	13.90	6.45	1-230	11.51 to 15.93
11	0-10	16.83	7.82	1-228	.54 to 12.93
12	0-10	23.23	10.80	1-265	-9.42 to -6.83
13	0-15	11.20	5.20	1-135	-18.07 to 2.09
14	0-15	13.90	6.45	1-230	10.76 to 16.19
15	0-15	16.83	7.82	1-228	10.23 to 11.52
16	0-15	23.23	10.80	1-265	-7.66 to -6.91

Table 4. Deviation in Experimental and Calculated Values of Entrainment for 1/2-Filled Case.

Data Set	Time Duration, minutes	Flow Rate, lb/min.	N_{Re} x 10^{-6}	Viscosity Range, cps	Error in E, %
1	0-2	10.10	5.55	1-297	4.08 to 61.43
2	0-2	12.60	6.94	1-222	7.10 to 38.62
3	0-2	15.10	8.31	1-224	6.11 to 19.13
4	0-2	20.40	11.20	1-240	-3.67 to 5.85
5	0-5	10.10	5.55	1-297	-14.50 to 3.63
6	0-5	12.60	6.94	1-222	-1.59 to 5.68
7	0-5	15.10	8.31	1-224	-4.26 to 4.27
8	0-5	20.40	11.20	1-246	-4.53 to -3.31
9	0-10	10.10	5.55	1-312	-13.74 to 2.34
10	0-10	12.60	6.94	1-224	-1.06 to 7.07
11	0-10	15.10	8.31	1-228	-1.43 to 3.43
12	0-10	20.40	11.20	1-240	-5.43 to -3.29
13	0-15	10.10	5.55	1-312	-14.04 to .55
14	0-15	12.60	6.94	1-224	-1.41 to 7.40
15	0-15	15.10	8.31	1-228	.14 to 5.43
16	0-15	20.40	11.20	1-240	-4.42 to -3.35

Table 5. Entrainment Data for Test Section Four, 1/4-Filled, for Various Entrapped Liquid Viscosities and Air Flow Rates.

Time, minutes	Upstream Air Pressures, inches Hg	Average Reynolds Number, x 10^{-4}	Liquid Viscosity, cps	Entrainment
		DATA SET 1		
0-2	23.0	6.25	7.74	.875
			9.70	.920
			14.8	.833
			26.9	.756
			60.6	.719
			62.0	.719
		DATA SET 2		
0-2	30.0	7.25	18.0	.929
			37.7	.814
			47.3	.829
			131.0	.845
		DATA SET 3		
0-5	23.0	6.25	9.05	.915
			12.3	.915
			18.4	.915
			30.4	.814
			60.6	.809
			67.0	.750
		DATA SET 4		
0-5	30.0	7.25	17.0	.963
			42.5	.926
			55.6	.894
			131.0	.878

Table 5 -- continued

Time, minutes	Upstream Air pressure, inches, Hg	Average Reynolds Number, x 10^{-4}	Liquid Viscosity cps	Entrainment
		DATA SET 5		
0-10	23.0	6.25	11.1	.919
			20.1	.940
			37.0	.880
			60.6	.809
		DATA SET 6		
0-10	30.0	7.25	19.0	.988
			35.6	.987
			63.6	.930
			131.0	.866
		DATA SET 7		
0-15	23.0	6.25	11.90	.938
			20.10	.959
			39.60	.900
			43.0	.890
			120.0	.870
		DATA SET 8		
0-15	30.0	7.25	19.0	1.0
			40.5	1.0
			95.0	.978
			173.0	.888