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ENGINEERING AND INDUSTRIAL RESEARCH STATION

Quarterly Progress Report #15

NAS-8-11334

RESEARCH STUDY FOR DETERMINATION OF LIQUID SURFACE PROFILE

IN A CRYOGENIC TANK DURING GAS INJECTION

December 18, 1967 - March 17, 1968

COLLEGE OF ENGINEERING

MISSISSIPPI STATE UNIVERSITY

STATE COLLEGE, MISSISSIPPI

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Quarterly Report #15, NAS8-11334
RESEARCH STUDY FOR DETERMINATION OF LIQUID SURFACE PROFILE IN A CRYOGENIC TANK DURING GAS INJECTION

Period Covered: December 18, 1967 - March 17, 1968

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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
$\dot{M}$	air mass flow rate, lbm/min.
N_{Re}	air Reynolds number, $N_{Re} = \frac{H_v \dot{M}}{A_v \mu_a}$
t	time
μ	dynamic liquid viscosity
μ_a	dynamic viscosity of air

INTRODUCTION

This is the fifteenth 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 December 18, 1967 to March 17, 1968.

ANALYSIS OF PROGRESS

The primary effort during this report period was again directed toward the development of a correlation equation which sufficiently describes the entrainment-viscosity behavior observed with test section two. A preliminary correlation was presented in Quarterly Progress Report #14 which had as its basis the general relationship

$$E = C_1 \mu^{C_2} \tag{1}$$

Additional work has shown, however, that the relation

$$E = A + B \ln \mu \tag{2}$$

forms a much better basis for the correlation. Analysis of the data in terms of equation (2) is progressing satisfactorily.

Additional data have been obtained with test section four for the 1/2-filled case. Thes data along with previous data for the 1/4-filled case are in the process of evaluation.

PROGRESS

In Progress Report #14 a system of equations was proposed for correlating the entrainment data for test-section two (see Figure 1). These equations were based upon the general relationship

$$E = C_1 \mu^{C_2} \qquad (1)$$

where E is the fractional entrainment, μ is the dynamic liquid viscosity, and C_1 and C_2 are constants for a given time and Reynolds number. Further analysis of the data from test section two has shown however that a much better description of the data is provided by the general equation

$$E = A + B \ln \mu \quad . \qquad (2)$$

The terms A and B are constants which must be determined for each different value of Reynolds number and time.

The entrainment data for test section two are tabulated in Tables 3 and 4 of Progress Report #14. Least square regression analysis was used in order to fit an equation of the form of equation (2) to the data corresponding to each Reynolds number and time. Different values for the constants A and B were thus determined for each set of data. A comparison of the experimental data and the least square fit of the data is shown as plots of E versus $\ln \mu$ in Figures 2 through 9. It is apparent that the experimental data closely approximate a straight line on semi-log paper.

The results of the regression analysis are also shown in Tables 1 and 2 for the 1/4-Filled and 1/2-Filled cases, respectively. These tables present the values of A and B for each set of data and the percent error between the experimental data and its least square approximation.

The percent error shown in the tables was calculated by the relation

$$\text{Error} = \frac{E_{data} - E_{calculated}}{E_{calculated}} \times 100 \ .$$

The range of error for the 1/4-filled case is -12.67% to 14.11%, and for the 1/2-filled case is -8.65% to 9.79%. These error ranges are considerably less than those incurred in using equation (1), indicating that a favorable correlation system should develop from equation (2). Work on this correlation is proceeding rapidly.

Entrainment data for the 1/2-filled case have been obtained with test-section four (see Figure 1). These data are shown in Figures 14 through 17 as plots of E versus ln μ and are tabulated in Table 8. Previous data for the 1/4-filled case have also been replotted and are shown in Figures 10 through 13, and in Table 7. These data also approximate a straight line on semi-log coordinates. Analysis of the data for test-section four has not been completed but observation of Figures 10 through 17 shows a similarity between these data and the data previously obtained with test-section two.

PLANS FOR NEXT QUARTER

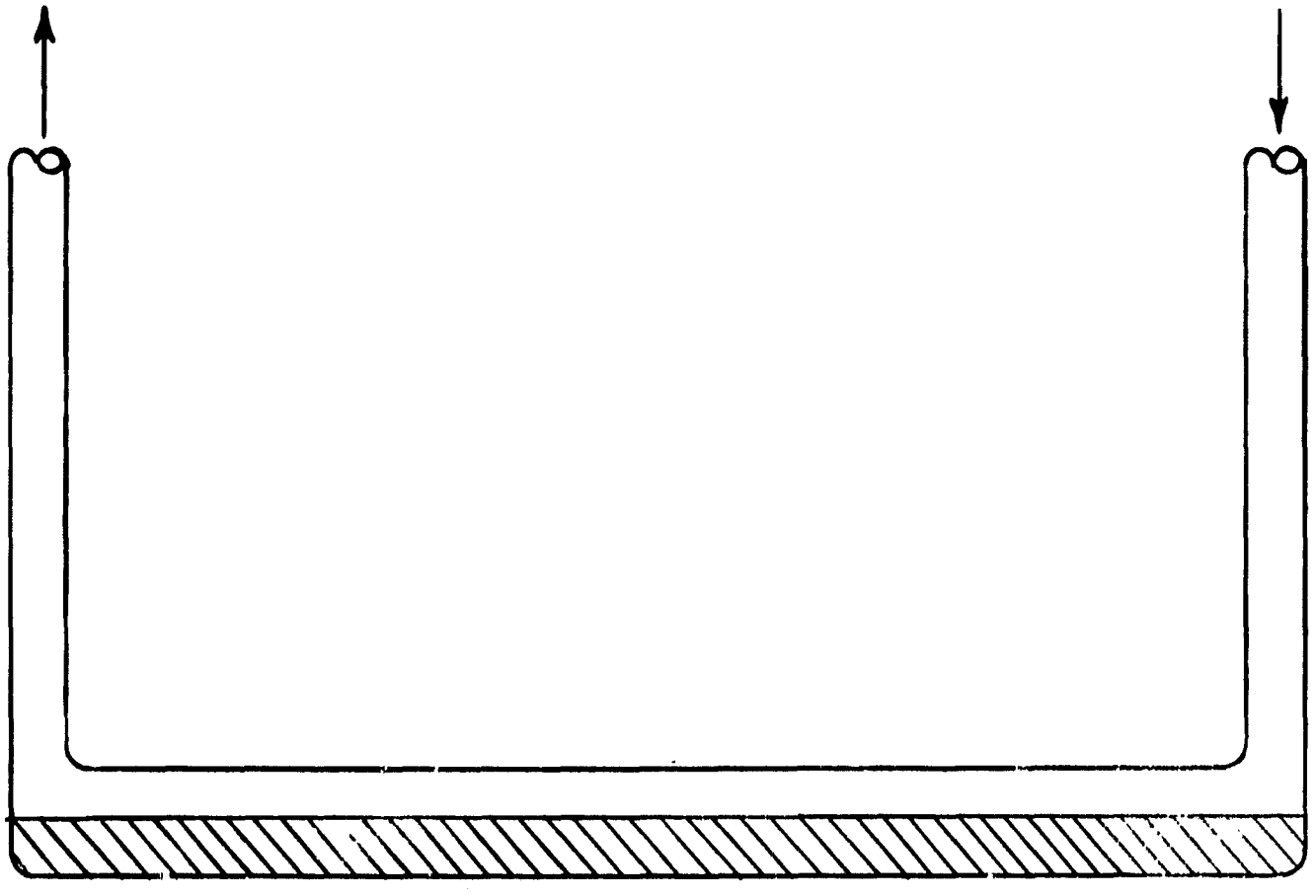
Analysis of the data obtained with test-section four will be conducted in an effort to make valid conclusions concerning the introduction of the T-Section into the system. The development of a correlation equation for the data from test-section two will also be completed.

Table 1. Values of A, B, Viscosity Range, and Range of Error for Given Values of Reynolds Number and Time Duration (1/4-Filled Case).

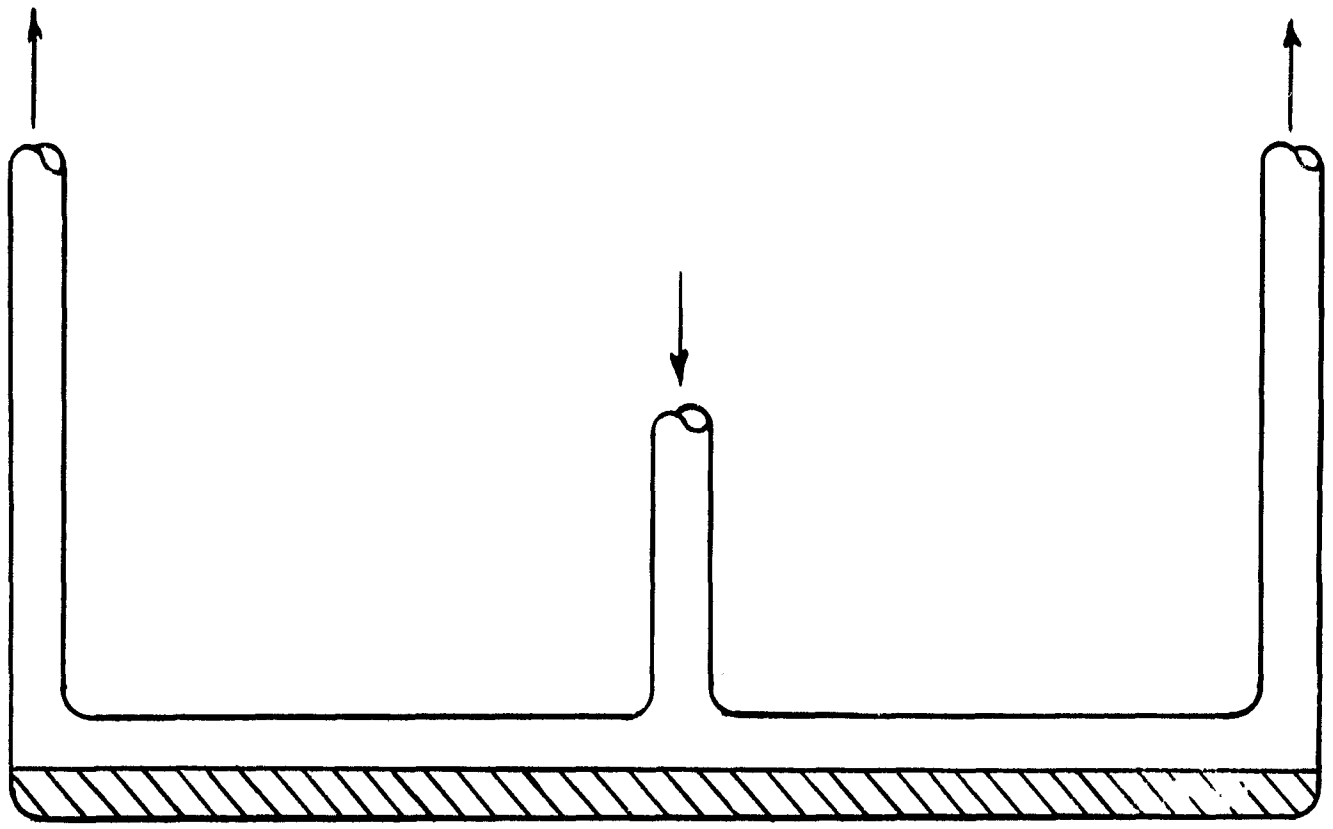
Data Set	Time Duration, Minutes	Flow Rate, LbM/Min	N_{Re} x 10^{-4}	Viscosity Range, cps	A	B	Error in E, %
1	0-2	11.20	5.20	1-164	0.552	-0.027	-9.08 to 10.93
2	0-2	13.90	6.45	1-185	0.914	-0.040	-0.73 to 1.49
3	0-2	16.83	7.82	1-216	0.945	-0.018	-4.65 to 3.68
4	0-2	23.23	10.80	1-238	0.987	-0.009	-3.87 to 2.78
5	0-5	11.20	5.20	1-160	0.593	-0.015	-12.46 to 11.49
6	0-5	13.90	6.45	1-200	0.878	-0.012	-0.74 to .31
7	0-5	16.83	7.82	1-2;6	0.943	-0.003	-1.52 to 1.16
8	0-5	23.23	10.80	1-238	1.00	-0.006	-1.37 to 1.60
9	0-10	11.20	5.20	1-170	0.835	-0.009	-10.46 to 11.40
10	0-10	13.90	6.45	1-230	0.904	-0.010	-2.16 to 1.35
11	0-10	16.83	7.82	1-228	0.933	-0.002	-7.67 to 2.31
12	0-10	23.23	10.80	1-265	1.00	-0.007	--1.71 to 1.05
13	0-15	11.20	5.20	1-185	0.653	-0.005	-12.67 to 14.11
14	0-15	13.90	6.45	1-230	0.864	-0.004	-2.26 to 1.42
15	0-15	16.83	7.82	1-228	0.971	-0.001	-0.166 to 0.36
16	0-15	23.23	10.80	1-265	1.00	-0.004	-0.24 to 0.41

Table 2. Values of A. B, Viscosity Range, and Range of Error for Given Values of Reynolds Number and Time Duration (1/2-Filled Case).

Data Set	Time Duration, Minutes,	Flow Rate, LbM/Min.	N_{Re} x 10^{-4}	Viscosity Range, cps	A	B	Error in E, %
1	0-2	10.10	5.55	1-297	0.827	-0.054	-10.27 to 8.27
2	0-2	12.60	6.94	1-222	0.966	-0.037	-5.12 to 3.15
3	0-2	15.10	8.31	1-224	1.00	-0.024	-1.32 to 2.09
4	0-2	20.40	11.20	1-240	0.985	-0.001	-2.89 to 1.41
5	0-5	10.10	5.55	1-297	0.834	-0.038	-8.13 to 8.25
6	0-5	12.60	6.94	1-222	0.948	-0.017	-4.66 to 2.83
7	0-5	15.10	8.31	1-224	1.00	-0.018	-3.99 to 2.85
8	0-5	20.40	11.20	1-246	1.00	-0.004	-0.79 to 0.48
9	0-10	10.10	5.55	1-312	0.817	-0.021	-8.35 to 8.64
10	0-10	12.60	6.94	1-224	0.964	-0.015	-4.46 to 2.48
11	0-10	15.10	8.31	1-228	0.991	-0.008	-3.24 to 1.92
12	0-10	20.40	11.20	1-240	1.00	-0.003	-1.36 to .668
13	0-15	10.10	5.55	1-312	0.814	-0.016	-8.65 to 9.79
14	0-15	12.60	6.94	1-224	0.951	-0.008	-4.91 to 3.63
15	0-15	15.10	8.31	1-228	0.987	-0.004	-2.71 to 2.13
16	0-15	20.40	11.20	1-240	1.00	-0.002	-0.504 to .39



Test Section Two



Test Section Four

Figure 1. Test Configurations

Table 3. Legend for Figures 2 through 5.

Experimental Values of Entrainment	
	Reynolds Number
o	5.20×10^4
□	6.45×10^4
△	7.82×10^4
+	10.8×10^4

Values of Entrainment Calculated from Equation (2) are Represented by a Solid Line for the Various Reynolds Numbers.

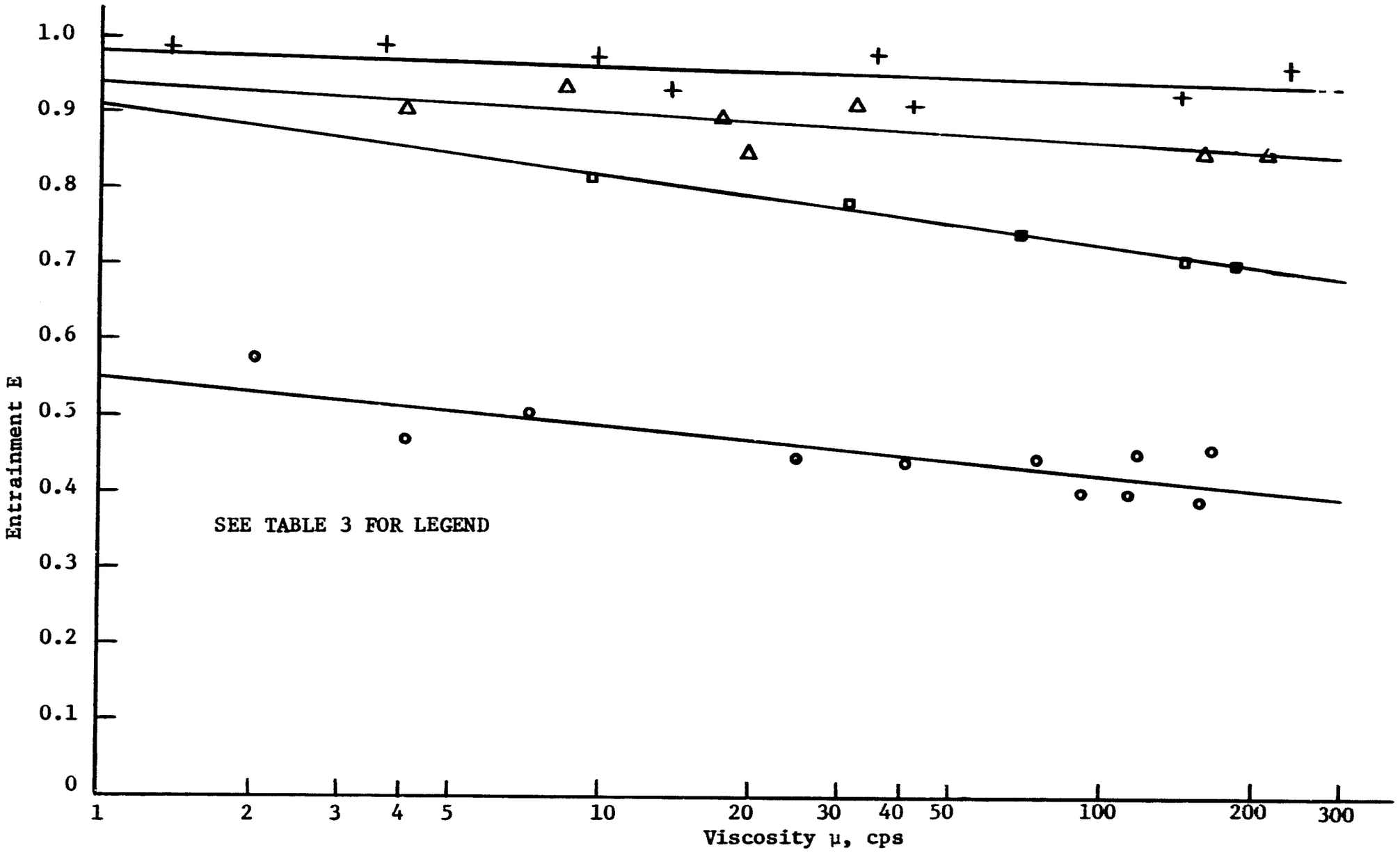


Figure 2. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-inch Diameter Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

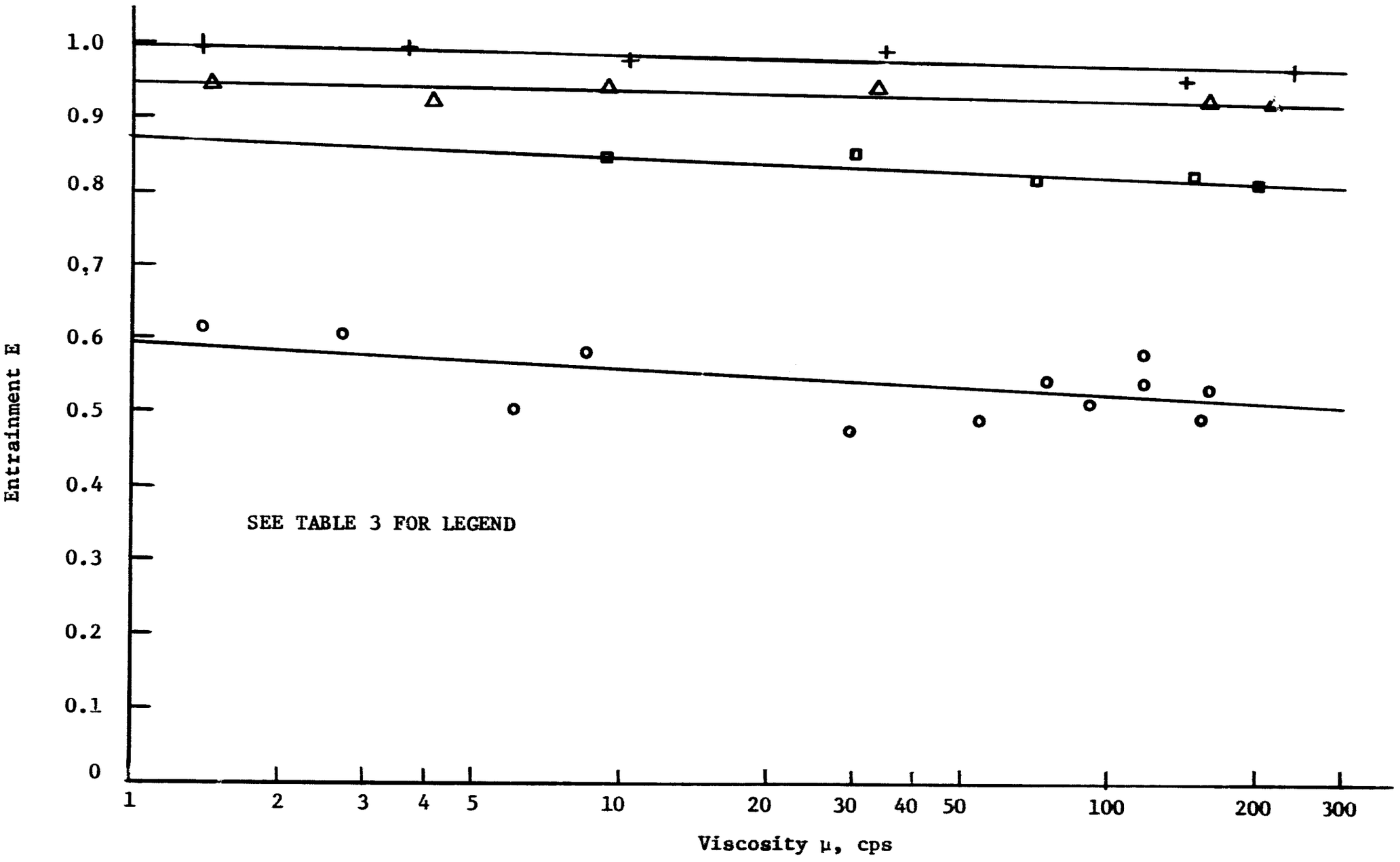


Figure 3. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

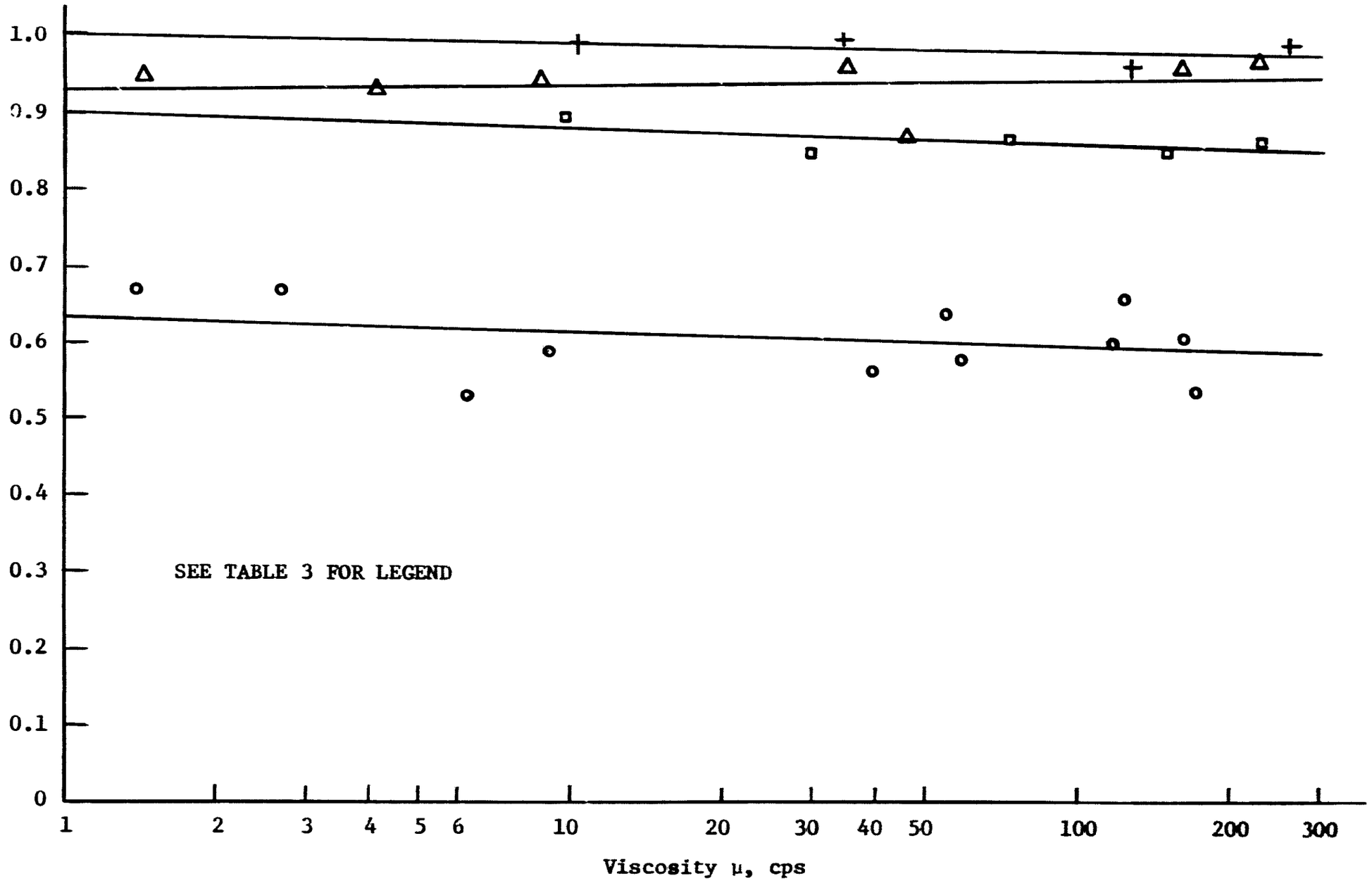


Figure 4. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal, Four-Inch Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates.

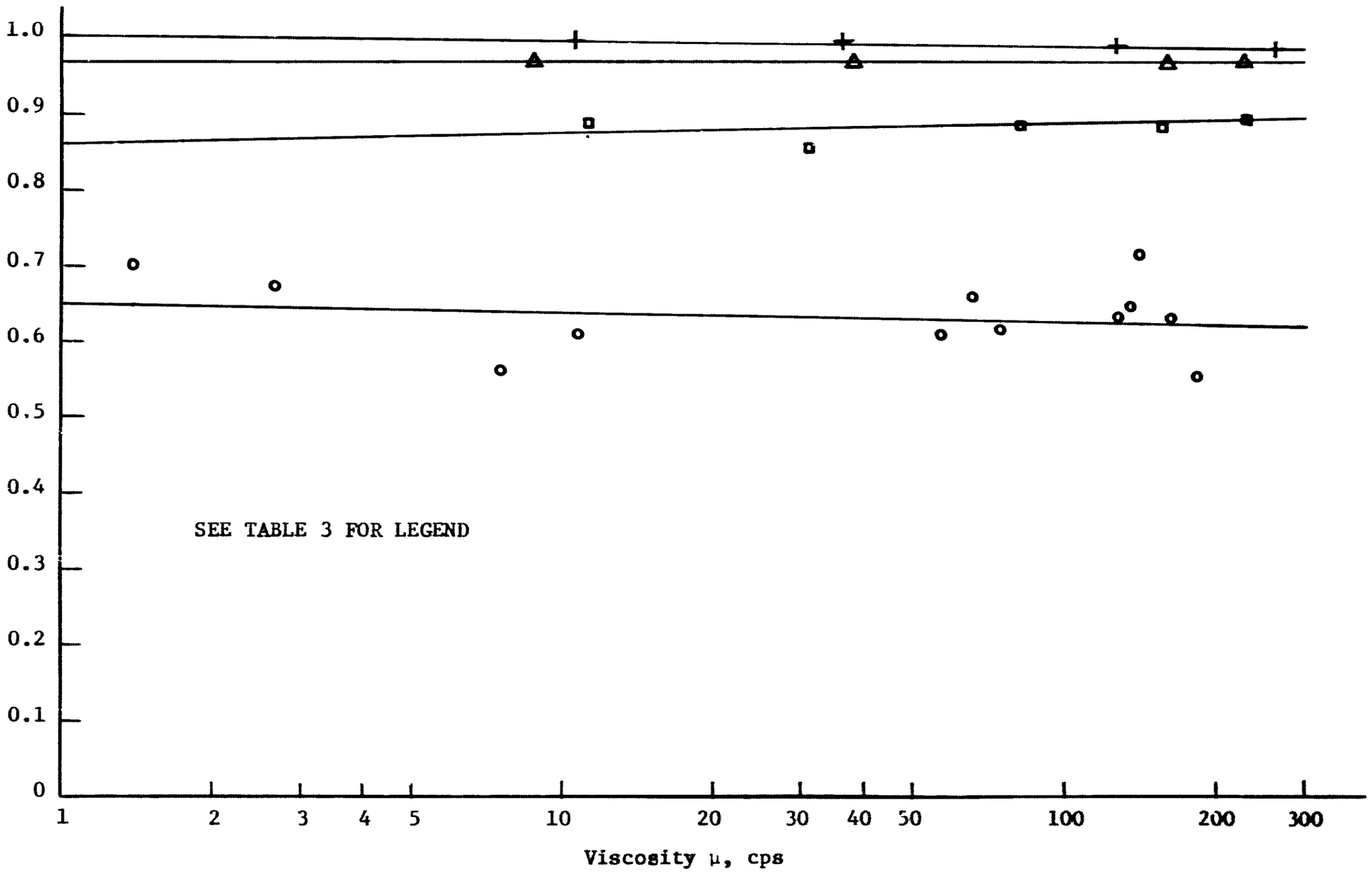


Figure 5. Entrainment versus Viscosity for Test Section Two (1/4-Filled, Five-Foot Horizontal Four-Inch Diameter Pipe) for an Average Time Interval of 15 Minutes for Various Air Flow Rates

Table 4. Legend for Figures 6 through 9.

Experimental Values of Entrainment	
	Reynolds Number
o	5.50×10^4
□	6.94×10^4
Δ	8.31×10^4
+	11.20×10^4

Values of Entrainment Calculated from Equation (2) are Represented by a Solid Line for the Various Reynolds Numbers.

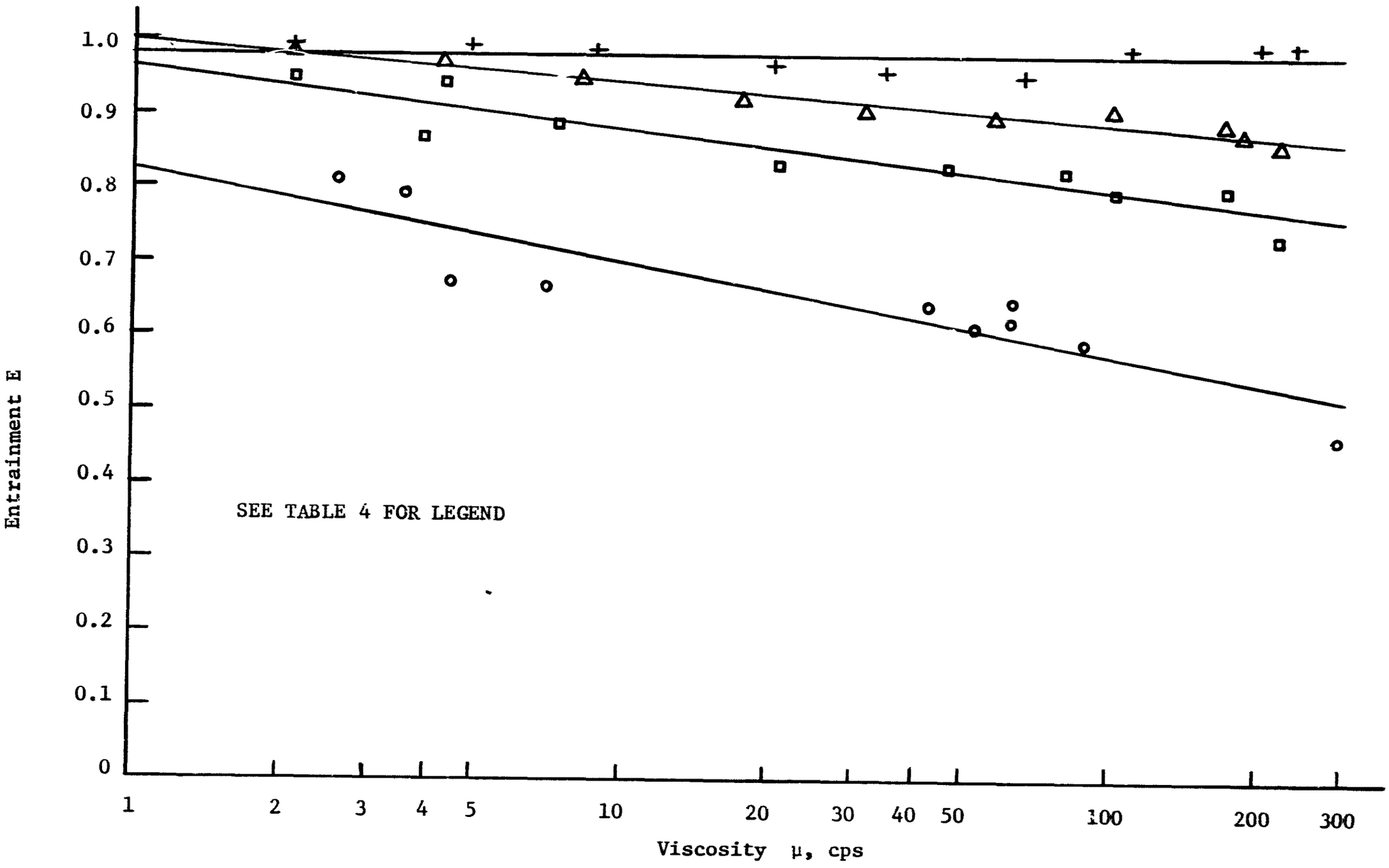


Figure 6. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Internal of Two Minutes for Various Air Flow Rates.

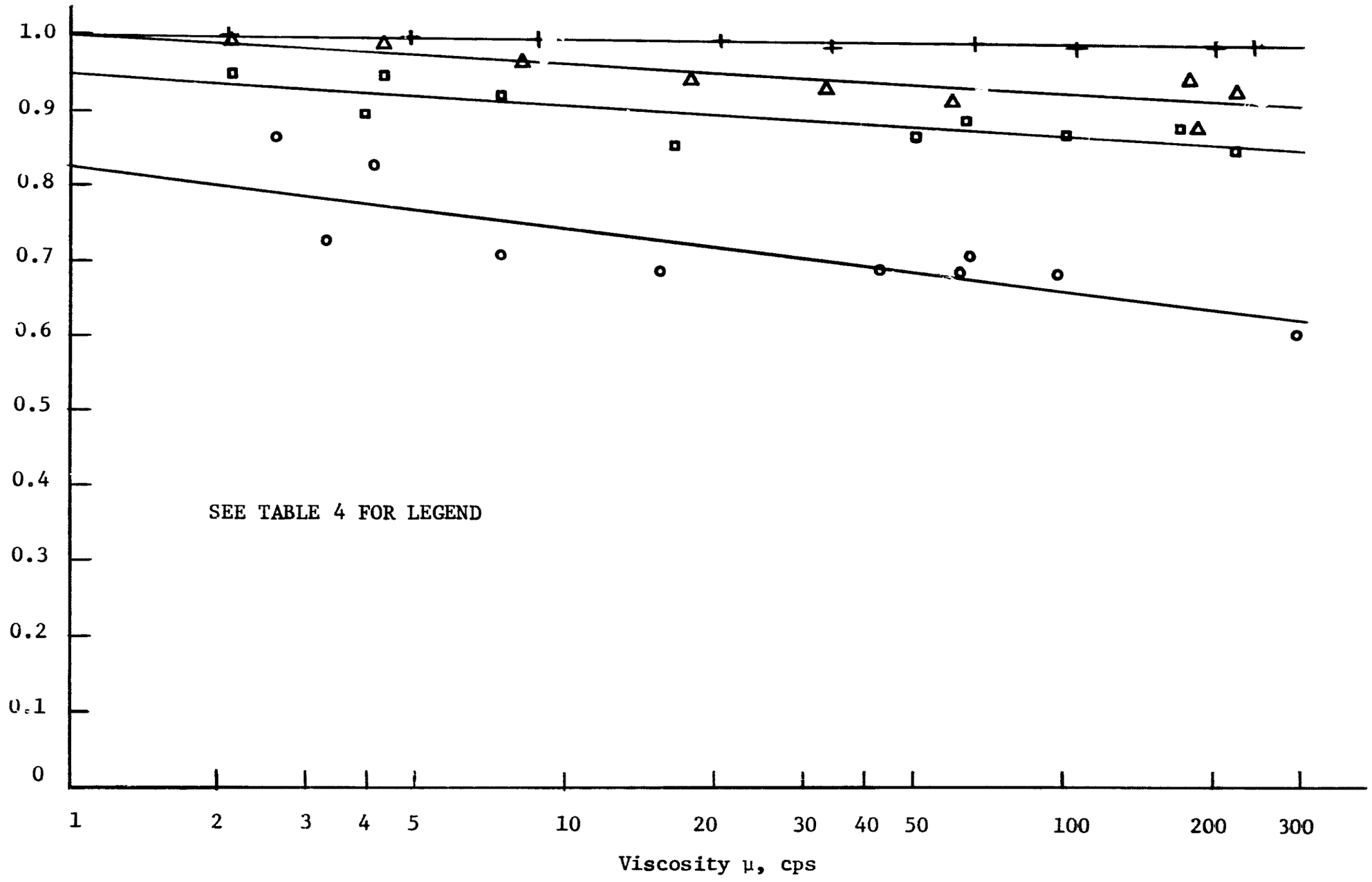


Figure 7. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

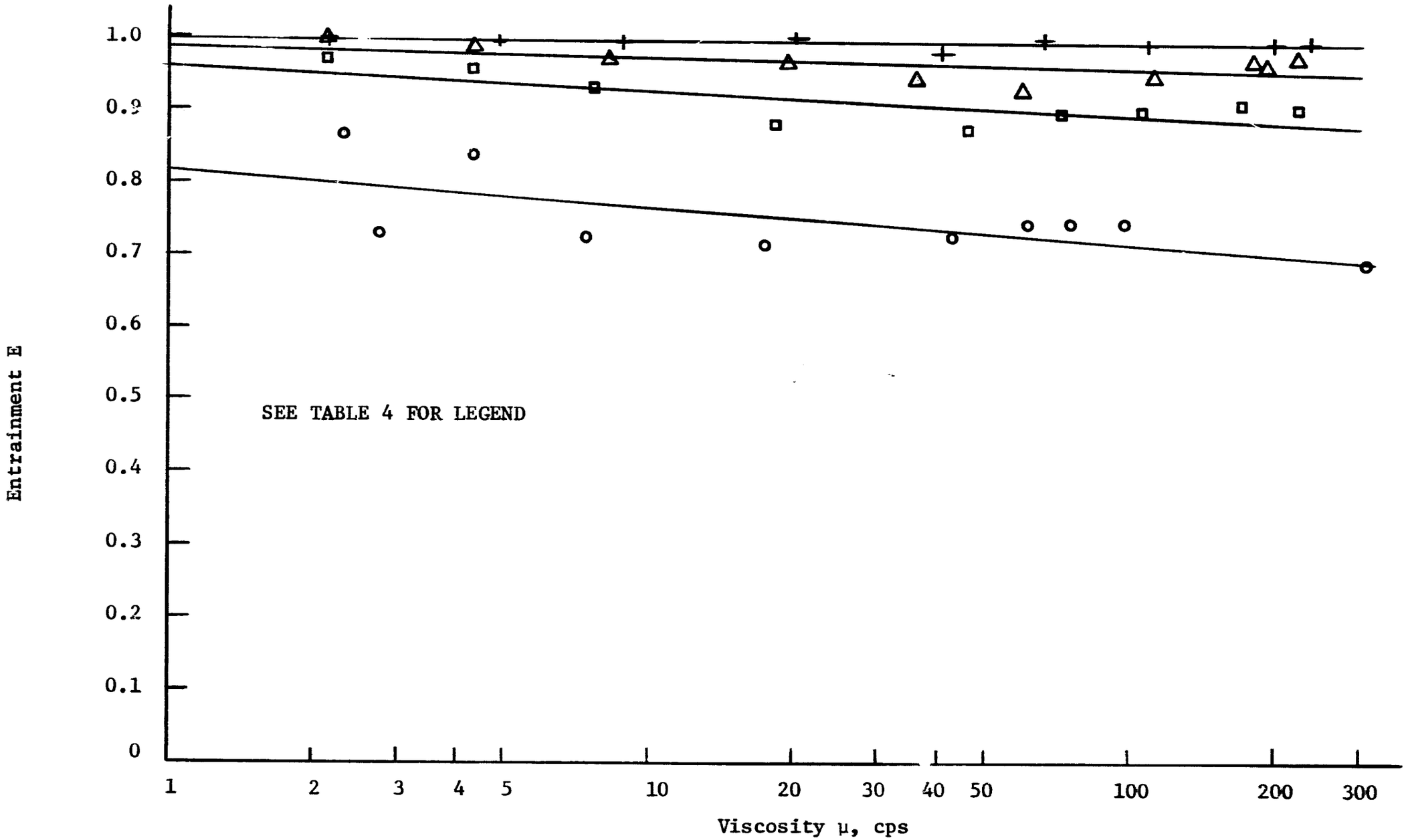


Figure 8. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates.

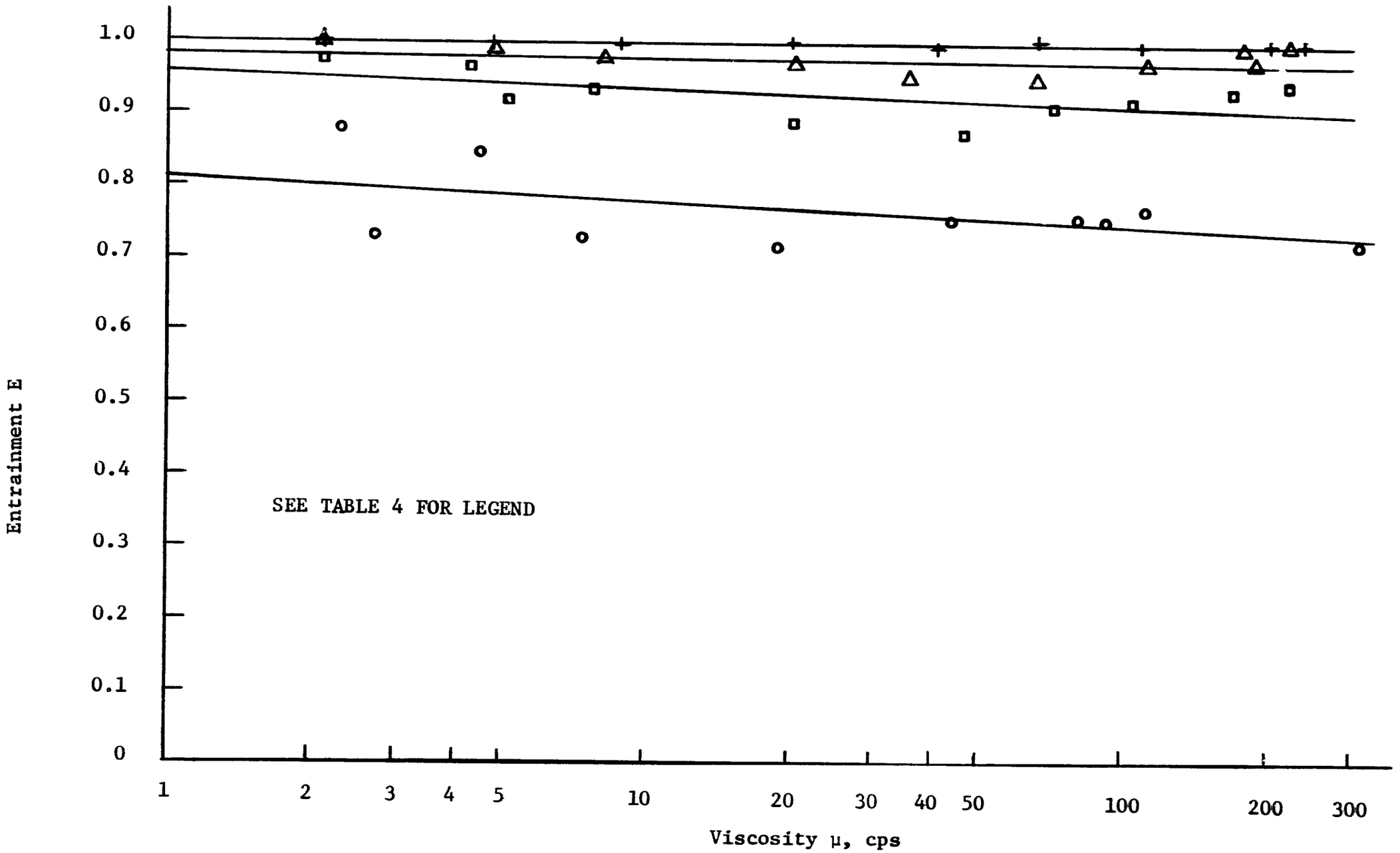


Figure 9. Entrainment versus Viscosity for Test Section Two (1/2-Filled, Five-Foot Horizontal, Four-Inch Diameter Pipe) for an Average Time Interval of 15 Minutes for Various Air Flow Rates.

Table 5. Legend for Figures 10 through 13.

Experimental Values of Entrainment	
	Reynolds Number
o	6.25×10^4
□	7.25×10^4

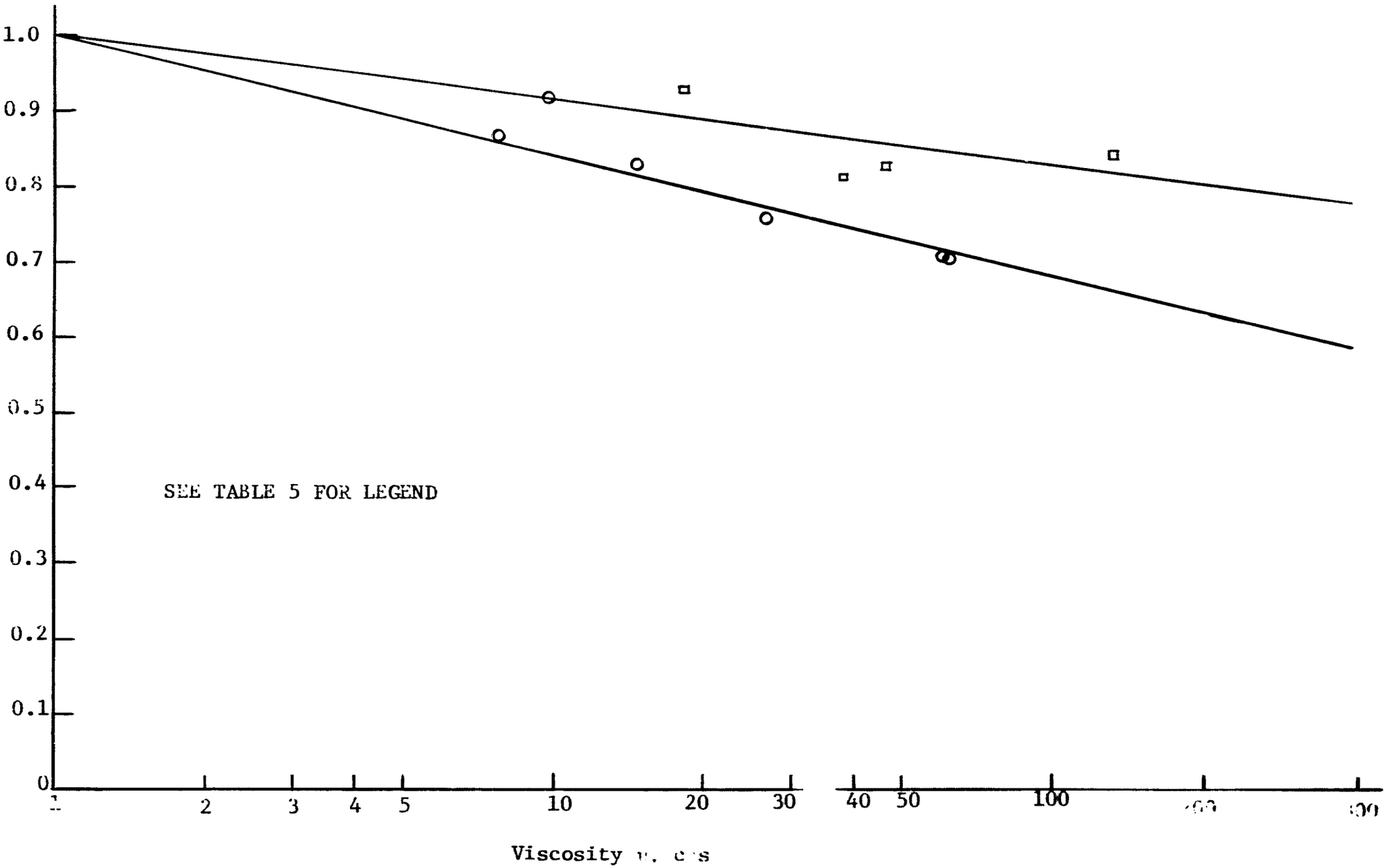


Figure 10. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

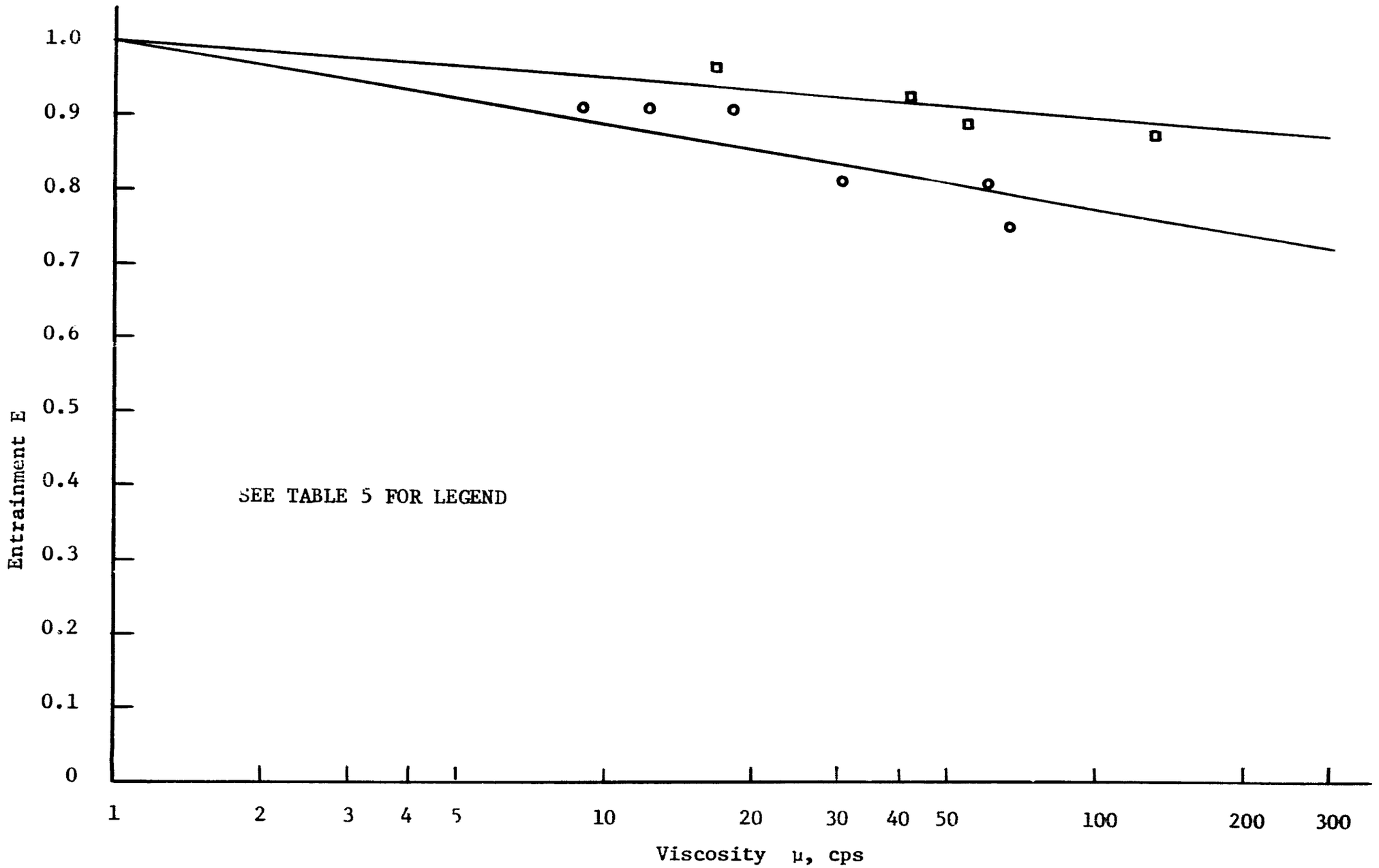


Figure 11. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizonta Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates.

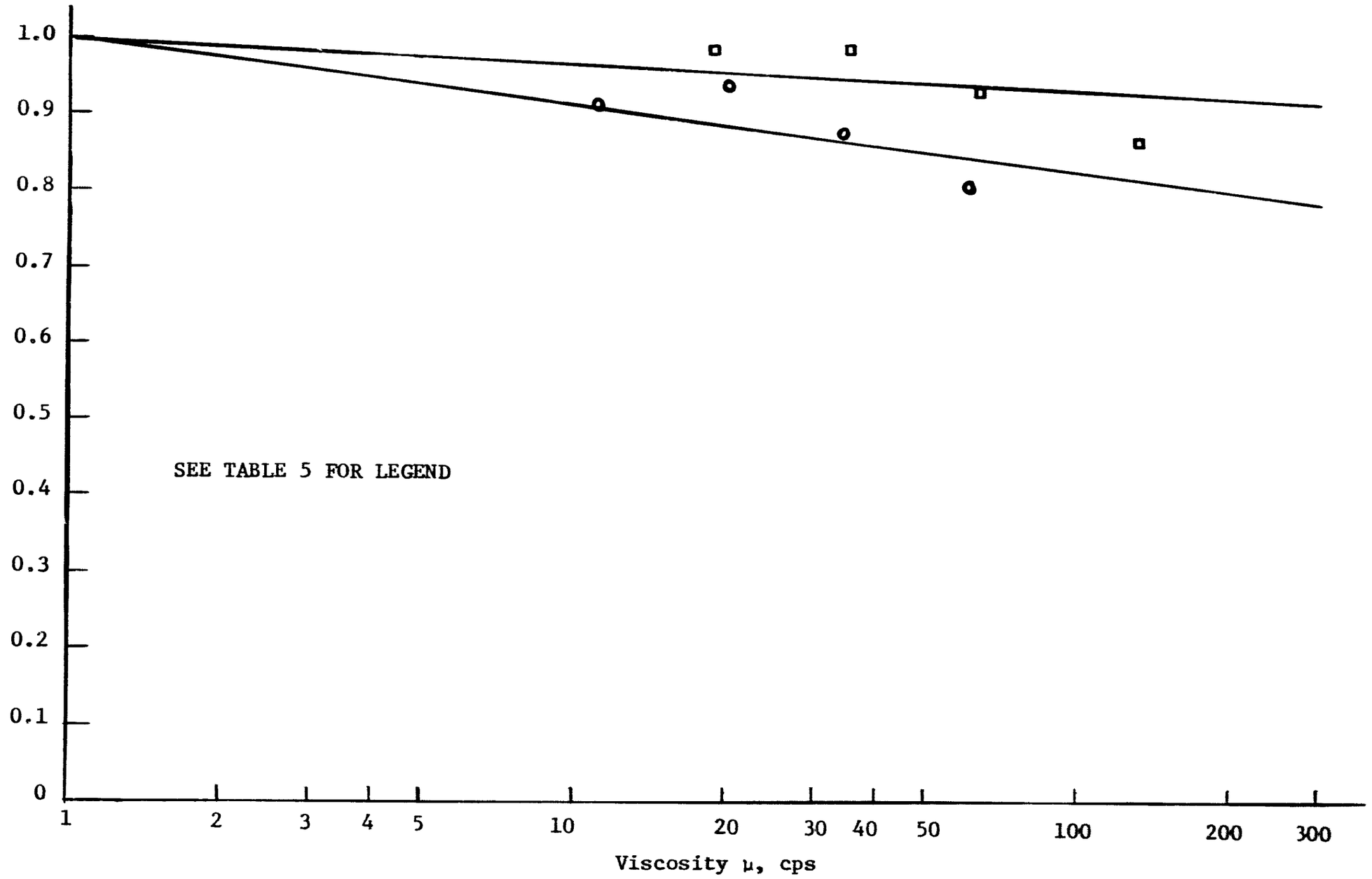


Figure 12. Entrainment versus Viscosity for Test Section Four (1/-4 Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates

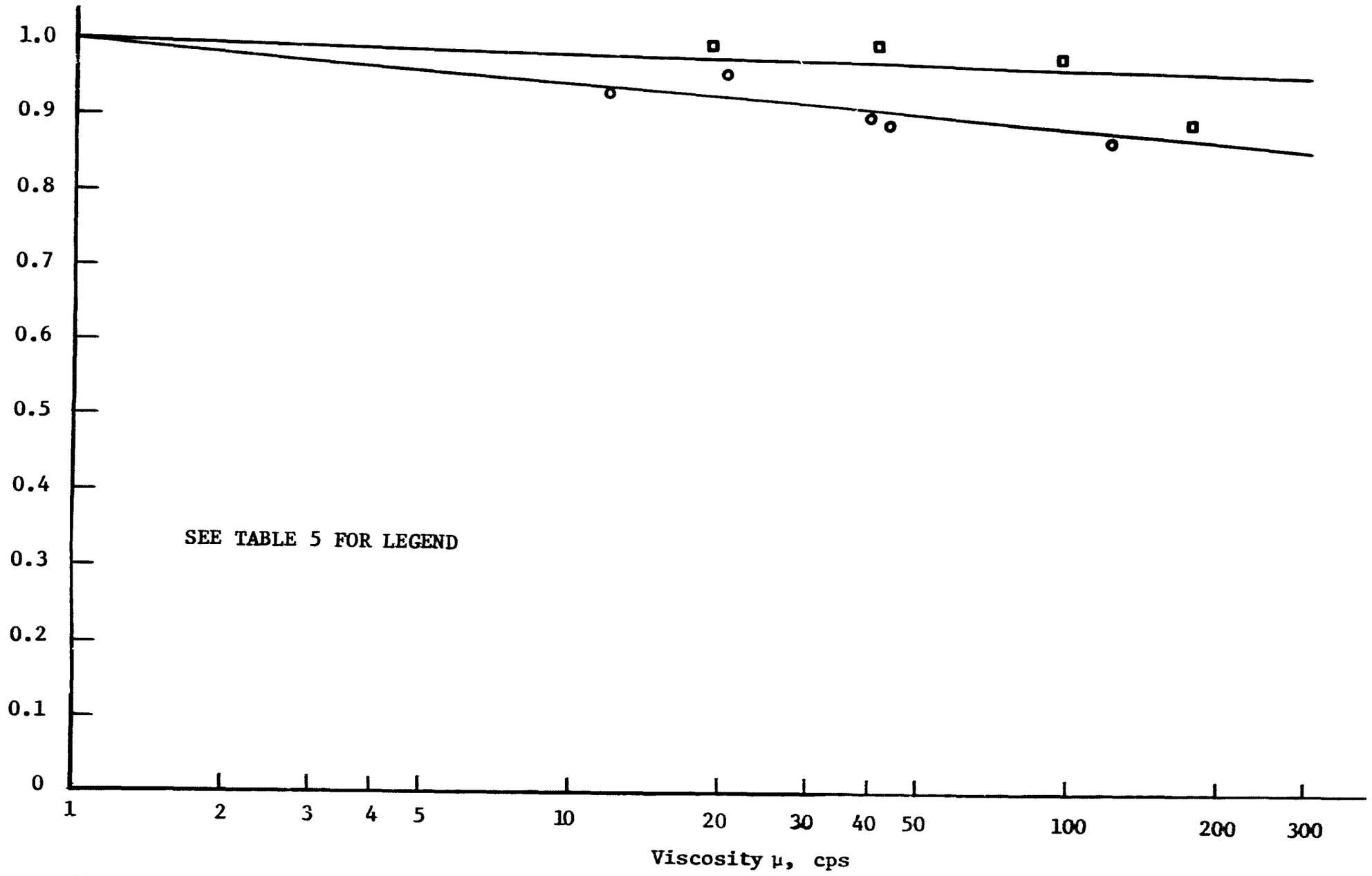


Figure 13. Entrainment versus Viscosity for Test Section Four (1/4-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of 15 Minutes for Various Air Flow Rates.

Table 6. Legend for Figures 14 through 17.

Experimental Values of Entrainment	
	Reynolds Number
o	5.76×10^4
□	7.03×10^4

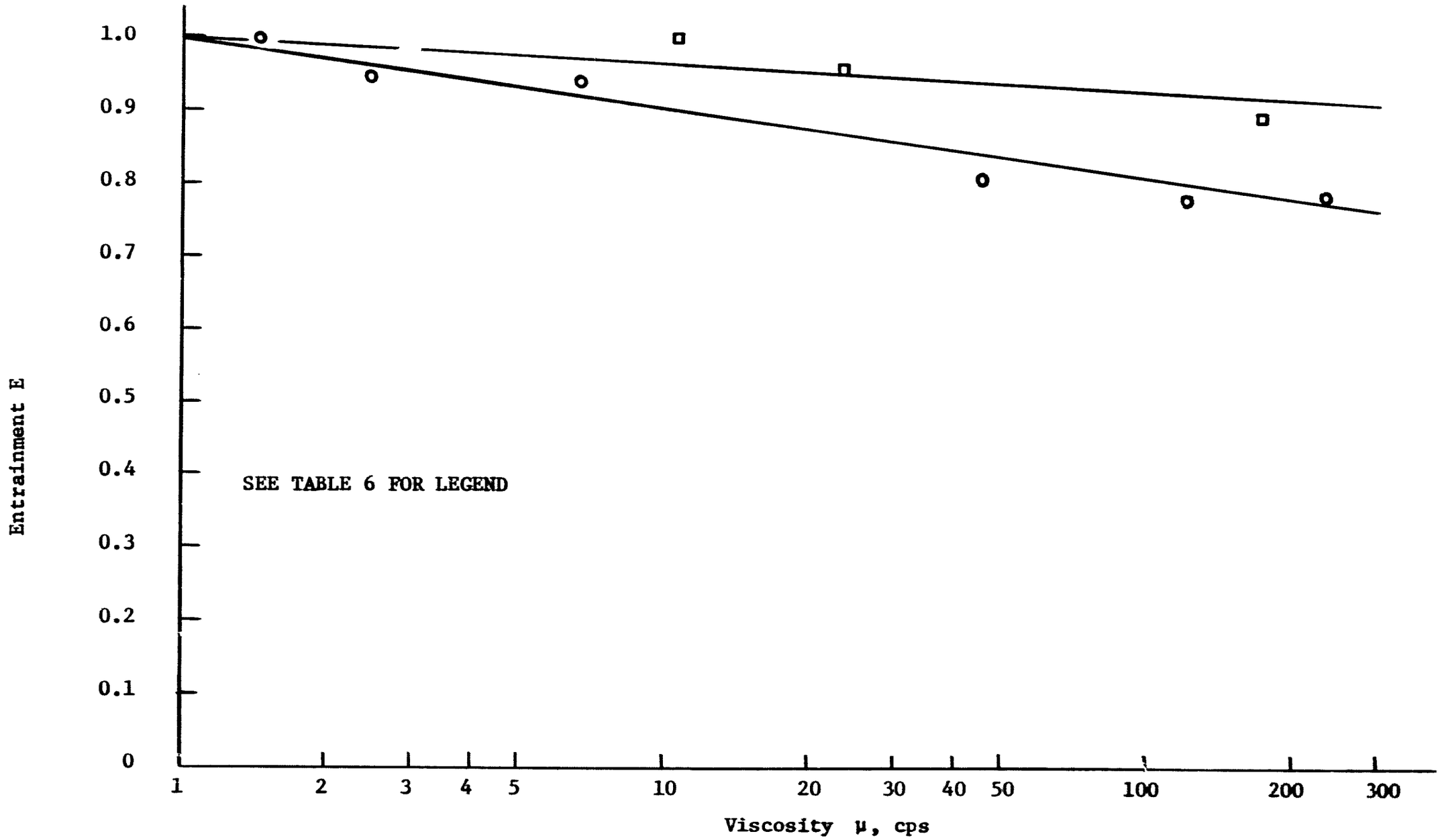


Figure 14. Entrainment versus Viscosity for Test Section Four (1/2-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Two Minutes for Various Air Flow Rates.

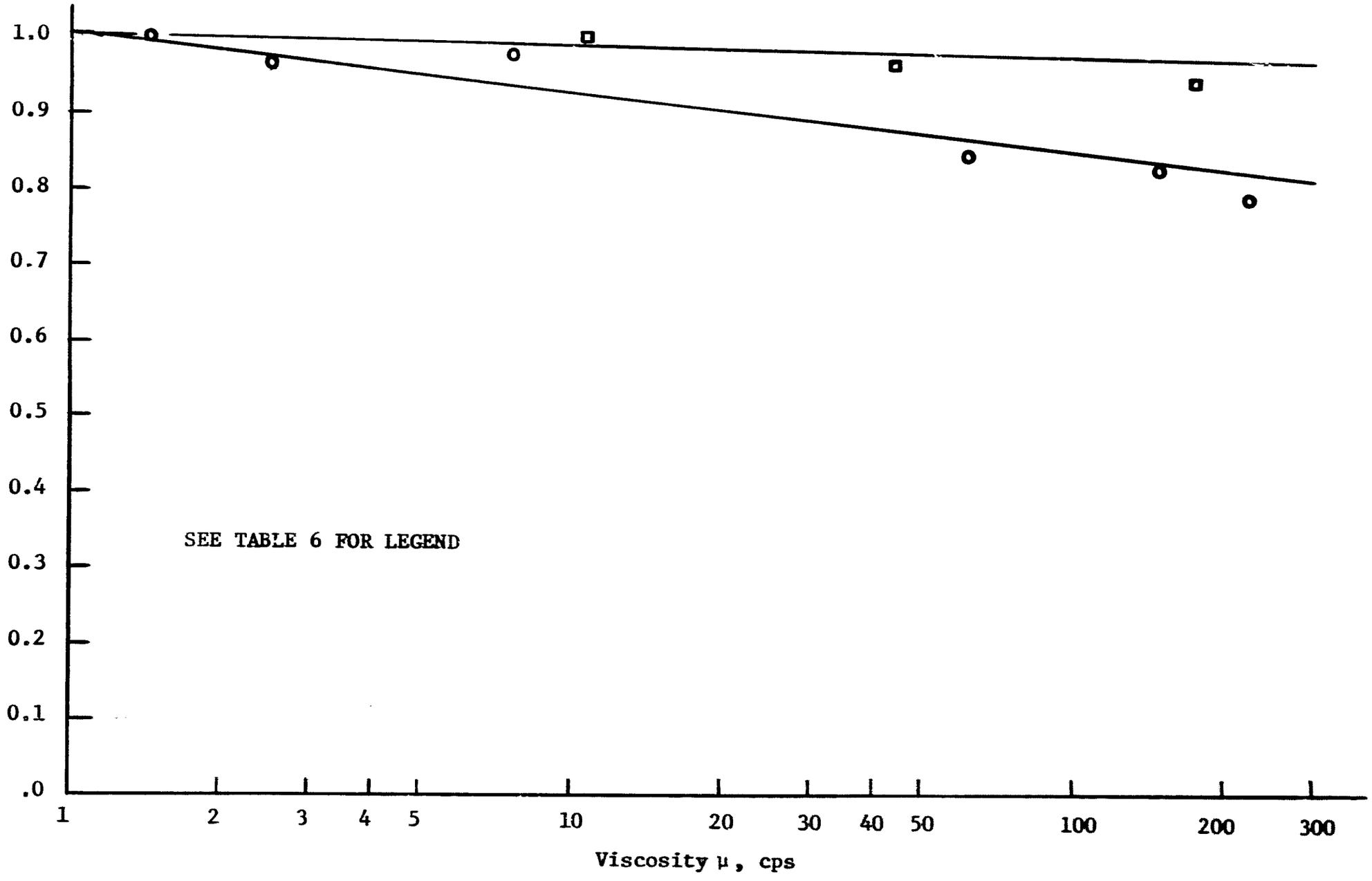


Figure 15. Entrainment versus Viscosity for Test Section Four (1/2-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Five Minutes for Various Air Flow Rates

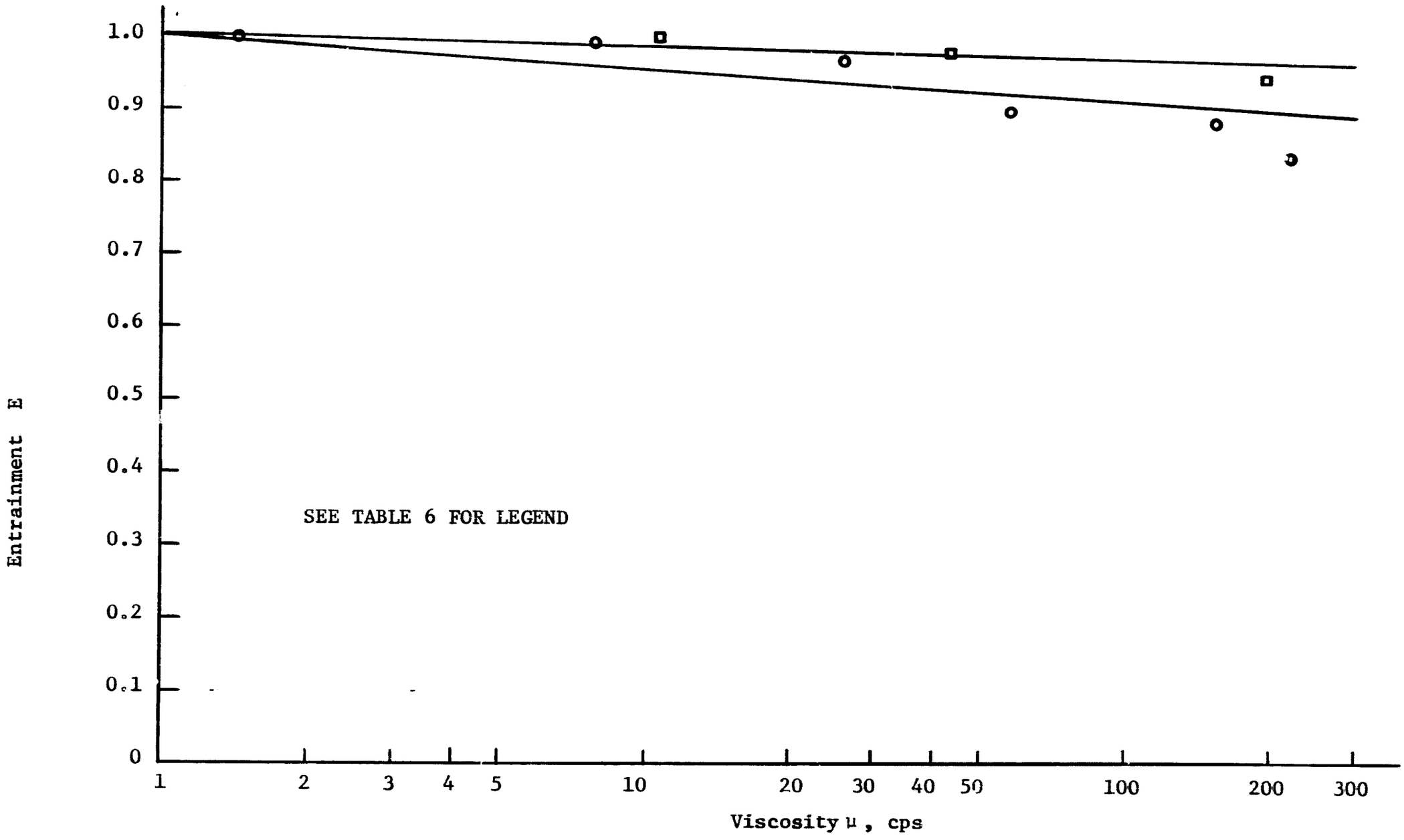


Figure 16. Entrainment versus Viscosity for Test Section Four (1/2-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of Ten Minutes for Various Air Flow Rates

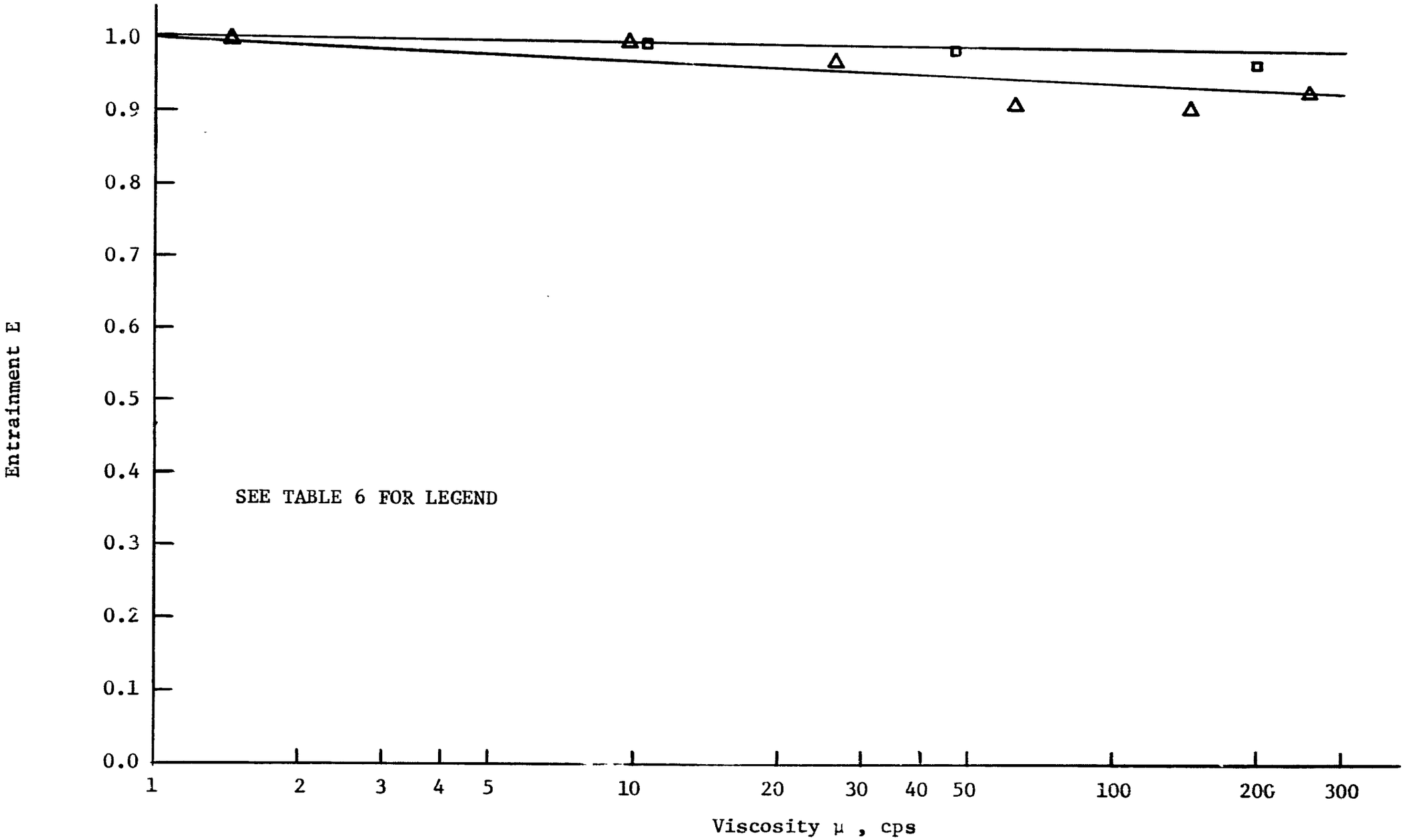


Figure 17. Entrainment versus Viscosity for Test Section Four (1/2-Filled, Four-Inch Diameter Horizontal Pipe) for an Average Time Interval of 15 Minutes for Various Air Flow Rates.

Table 7. 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
0-2	23.0	6.25	7.74	.875
			9.70	.920
			14.8	.833
			26.9	.756
			60.6	.719
			62.0	.719
0-2	30.0	7.25	18.0	.929
			37.7	.814
			47.3	.829
			131.0	.845
0-5	23.0	6.25	9.05	.915
			12.3	.915
			18.4	.915
			30.4	.814
			60.6	.809
			67.0	.750
0-5	30.0	7.25	17.0	.963
			42.5	.926
			55.6	.894
			131.0	.878
0-10	23.0	6.25	11.1	919
			20.1	.940
			37.0	.880
			60.6	.809
0-10	30.0	7.25	19.0	.988
			35.6	.987
			63.6	.930
			131.0	.866
0-15	23.0	6.25	11.90	.938
			20.10	.959
			39.60	.900
			43.0	.890
			120.0	.870

Table 7 -- continued

Time, minutes	Upstream Air Pressure, inches Hg	Average Reynolds Number x 10^{-4}	Liquid Viscosity, cps	Entrainment
0-15	30.0	7.25	19.0	1.0
			40.5	1.0
			95.0	.978
			173.0	.888

Table 8. Entrainment Data for Test Section Four, 1/2-Filled, for Various Entrapped Liquid Viscosities and Air Flow Rates.

Time, minutes	Upstream Air Pressure, inches Hg	Average Reynolds Number x 10^{-4}	Liquid Viscosity, cps	Entrainment
0-2	23.0	5.76	1.44	1.00
			2.46	0.944
			6.70	0.943
			45.7	0.808
			121.0	0.969
			238.0	0.785
0-2	30.0	7.03	1.07	1.0
			2.35	0.958
			172.2	0.888
0-5	23.0	5.76	1.42	1.00
			2.49	0.962
			7.6	0.975
			61.1	0.844
			147.0	0.782
			222.0	0.835
0-5	30.0	7.03	1.07	1.00
			42.0	0.963
			173.5	0.943
0-10	23.0	5.76	1.42	1.0
			2.64	0.968
			58.2	0.892
			154.0	0.882
			221.0	0.902
0-10	30.0	7.03	1.07	1.0
			43.6	0.980
			197.8	0.967
0-15	23.0	5.76	1.415	1.00
			2.64	0.972
			62.20	0.910
			143.0	0.904
			253.0	0.929

Table 8 -- continued

Time, minutes	Upstream Air Pressure, inches Hg	Average Reynolds Number x 10^{-4}	Liquid Viscosity, cps	Entrainment
0-15	30.0	7.03	1.07	1.00
			46.8	0.987
			199.0	0.969