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Francis P. O'Connell
Lehigh University

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By

FRANCIS P. O'CONNELL

A STUDY OF GAS-LIQUID CONTACTING BY HIGH SPEED THIN IMPELLERS

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By Francis P. O'Connell
Francis P. O'Connell

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I. INTRODUCTION

In general packed towers have been thought of as the usual means of carrying out gas absorptions. For some time, however, it has been appreciated that gas absorptions in tanks with agitation have certain advantages over towers in some cases. This was found especially true in the case of hydrogenations, aerations, chlorinations, and gas scrubbings, where the liquid film controlled (1,5). In such an instance, maximum turbulence of the liquid was consequently desirable, but this was not realizable in a tower where the liquid depended solely on gravity for its motion. In a mixer, on the other hand, the turbulence of the liquid could be increased considerably at the same time the gas bubbles were reduced in size, thus also increasing the interfacial surface of contact between the liquid and the gas. In addition to this it was found that the agitation of the liquid gave the bubbles a longer path through the liquid and hence a longer time of contact, resulting in a greater gas absorption efficiency per pass.

With these considerations in view there has been a limited amount of research work done on gas-liquid contacting. Practically all of this work has been done with the agitator shaft operating at less than 1000 r. p. m. The object of this work, however, was to determine how well gases and liquids could be brought into contact with each other by agitation with thin impellers at speeds as high as 7500 r. p. m. and with a minimum of power expended. This having been done, a comparison could be made with gas-liquid contacting done at the lower, more conventional speeds. This has been essentially accomplished.

Water and air were used as the liquid and gas respectively, and piano wires of varying length and number were used as impellers. The tank, baffles, and sparger, however, were not varied.

II. THEORY

There are two possible explanations offered for the fact that agitation reduces the size of bubbles of gas that has been introduced to a tank of agitated liquid. One is that the impellers cut the bubbles by passing through them. The other mechanism for reduction of bubble size is that the eddy currents due to turbulence behind the impellers break up the bubbles and at the same time reduce the liquid film resistance to mass transfer.

Before reduction of bubble size by this latter mechanism can be performed, there must first be turbulence, and this brings up the question of whether the agitation is turbulent or "viscous". In this work pure turbulence will be said to exist when the impellers throw out radially the liquid with which they come into contact in much the same manner as would a turbine, and pure "viscous" agitation will be said to exist when the impellers throw none of the liquid out radially.

Let us consider the relation between power consumed in agitation of a liquid and the impeller length, impeller speed, number of impellers, liquid density, and liquid viscosity, using the following nomenclature:

HP is the horse-power consumed.

L is the impeller length, where the other impeller dimensions remain constant.

N is the impeller shaft speed in r. p. m.

S is the number of impellers.

μ is the liquid viscosity.

ρ is the liquid density.

u is the speed of the liquid relative to the impellers.

m is the unit mass of the liquid.

g is the accelation due to gravity.

For this discussion the units of the above variables may be chosen arbitrarily.

Consider first the case of "viscous" agitation. Keeping all other variables constant HP is proportional to L^2, width of impellers remaining constant, since L^2 is proportional the volume of liquid swept by the impeller. Keeping other variables constant HP is proportional to N^2, since N^2 is proportional to u^2, which is proportional to the kinetic energy of the liquid. Also HP is proportional to μ, but ρ does not affect the power in purely "viscous" flow. Summing up the variation of power, then, for purely "viscous" agitation,

$$(1)\quad HP \propto N^2 L^2 \mu$$

Now consider the case of purely turbulent agitation. This time the liquid will be thrown out radially with a velocity that will be proportional to the shaft speed, N. Therefore, other variables being constant, HP is proportional N^2, since the kinetic energy of the liquid equals

$\frac{1}{2}mu^2$. However, the mass, m, of the liquid being thrown out is also proportional to N, and HP is proportional to N^3. Other variables being constant, HP is proportional to L^2, since L^2 is proportional to the volume swept, which is in turn proportional to m. Here too HP is also proportional to L^2 again, because L^2 is proportional to (impeller tip velocity)^2, which is proportional to u^2. Hence HP is proportional to L^4. The horse-power is not affected by μ for ideally turbulent flow, but it is proportional to ρ, since ρ determines the mass of the volume of liquid being swept. Summing up the variation of power for purely turbulent agitation,

$$(2)\quad HP \propto N^3 L^4 \rho$$

In actual cases the conditions are often somewhere between those represented by equations (1) and (2). In the general case the exponents of each of these variables have been found to be roughly the same proportion of the way between their respective extremes. Thus the general equation from (1) and (2) may be written:

$$(3)\quad HP \propto N^{3-a} L^{4-2a} \mu^{a} \rho^{1-a}, \text{ where } 0 \leq a \leq 1$$

In all cases it is assumed that HP is proportional to the number of impellers, S, and so equation (3) can be written

$$(4)\quad HP \propto N^{3-a} L^{4-2a} \mu^{a} \rho^{1-a} S$$

Agitation turbulence may be tested from experimental data by making a modified Reynolds number plot. If the liquid is completely turbulent, equation (4) may be written

$$(5)\quad HP \propto N^3L^4\rho S$$

Dividing both sides of equation (5) by $N^3L^4\rho S$, we get

$$(6)\quad \frac{HP}{N^3L^4\rho S} = \text{constant}$$

Therefore $\frac{HP}{N^3L^4\rho S}$ plotted as ordinate against the modified Reynolds number, $\frac{NL^2\rho}{\mu}$, as abscissa will give a horizontal straight line.

If there is ideal "viscous" agitation,

$$(7)\quad \frac{HP}{N^3L^4\rho S} \propto \frac{\mu}{NL^2\rho},$$

or $\frac{HP}{N^3L^4\rho S}$ will be inversely proportional to the modified Reynolds number. On log-log coordinates such a Reynolds number plot would have a slope of negative unity. Conditions of partial turbulence will give a slope, therefore, somewhere between minus one and zero. The above outlined method of testing for turbulence is used in this work.

In dealing with gas-liquid contacting the following nomenclature is used:

H is the hold-up, or increase in the height in feet of the liquid in the tank due to the presence of bubbles.

θ is the average contact time of the air per unit depth in seconds per foot and is equal to $\frac{h}{F}$.

HP is the horse-power consumed in the mixing.

V is the volume of the liquid in cubic feet.

F is the superficial gas velocity through the tank in feet per second, obtained by dividing the gas rate in cubic feet per second by the cross sectional area of the tank in square feet.

It has been found for given geometrical conditions that the average contact time, θ, is equal to $C(\frac{HP}{VF})^n$, where C and n are constants determined experimentally (5). The function, $\frac{HP}{VF}$, is known as the horse-power function, and is so grouped in effort to measure the horse-power required per unit quantity of gas-liquid contacting, which is in itself rather intangible. The average contact time, θ, is a measure of how well the gas and liquid are being brought into contact with each other. If θ is plotted as ordinate against $\frac{HP}{VF}$ as an abscissa on log-log coordinates, a straight line will result in which n will be the slope and C will be the ordinate intercept. Since n has been found to be essentially constant, the optimum conditions of agitation, so far as power requirements are concerned, are where C is a maximum, because there a minimum power consumption is required for a given contact time. It is for the investigation of these possibilities that this work has been done.

III. APPARATUS

The equipment used in this work was mounted on a steel frame. 2½ feet above the ground was a platform on which rested the mixing tank. This consisted of a Pyrex glass jar 1½ feet high and 9-9/16 inches inside diameter. In the tank were mounted sheet aluminum baffles 120 degrees apart extending toward the center of the tank four inches. In each of the baffles were cut four slots to allow that number of possible impellers to pass. Such extreme baffling was necessary to keep the liquid from vortexing out of the tank. The shaft was 3/4 inch steel. Four small parallel holes were drilled in the shaft at intervals of three inches starting two inches from the bottom of the tank. Straight pieces of piano wire .047 inches in diameter were bent at right angles about ¼ inch from one end and inserted into the holes as far as they would go for use as impellers. These impellers were cut to protrude from the shaft varying lengths; namely, 1¼, 1½, 1-3/4, 2, 2¼, 2½, 2-3/4, and 3 inches. The shaft was mounted on two bearings and driven from a 3/4 h. p., single phase, A. C. motor. The motor was mounted on the steel frame a few inches above and to one side of the mixing tank with its shaft facing the impeller shaft and perpendicular to it. On the motor shaft was a V-belt step pulley connected by a fractional horse-power V-belt to a step pulley on an auxiliary shaft mounted just above the frame and parallel to the motor shaft. The three drive ratios used with these step pulleys were 2.08, 1.22, and .813 respectively. The auxiliary shaft was connected to the impeller shaft by bevel gears having forty and twenty teeth and running at a drive ratio of 2.00. The motor ran at a no load speed of about 1800 r. p. m., and with these drive ratios it gave impeller shaft speeds of about 7500, 4500, and 2900 r. p. m. As a safety precaution a sheet iron shield was placed around the bevel gears and a shield made of wooden plank was placed on top of the frame, covering both the auxiliary shaft and the bevel gears. Wooden shields were also built on two sides of the frame in such a way as to protect the operator. The motor was started with a thirty ampere box switch and was connected with a voltmeter and ammeter. All of these electrical controls were mounted on one of the wooden side shields, which was used as a panel board. The voltmeter was used simply to check the line voltage from time to time, but it did not vary enough to show any effect on the ammeter readings.

The ammeter, however, was used to measure the power output of the impeller shaft and was calibrated by putting a prony brake on the impeller shaft and running tests on the machine at the three different drive ratios. For each load measured the ammeter was read. The speed of the impeller shaft was read by means of an electronic neon type stroboscope. Thus it was possible to plot ammeter readings against power output for each of the three drive ratios used. The ammeter was only graduated in half amperes and could only be read to the nearest .1 ampere, and since the current only varied from three amperes at no load to six amperes at full load, great care had to be taken in reading the ammeter. Even at best the accuracy was limited. The data taken in these calibrations are shown in Table I, and the calibration curve appears in Graph 1. The prony brake used was made of sheet iron bent in such a manner as to form a brake arm with a metal band on the end to hold the friction element, which consisted of clean, dry belt leather about $\frac{1}{2}$ inch wide and $\frac{1}{8}$ inch thick. The band was wrapped around a cast iron brake drum and tightened by means of a screw, which rejoined it to the brake arm. The brake was cooled and lubricated by a small stream of water trickling from a small copper tube on to the edge of the brake drum. At these high speeds the water caused considerable spray, and so a small wooden baffle had to be built to protect the operator and the motor. The stroboscope was protected by covering it with a transparent vinylite bag. For measurement of torque a string holding a weight pan was attached to the end of the brake arm and hung over a pulley. This way the torque could be balanced by placing weights on the pan.

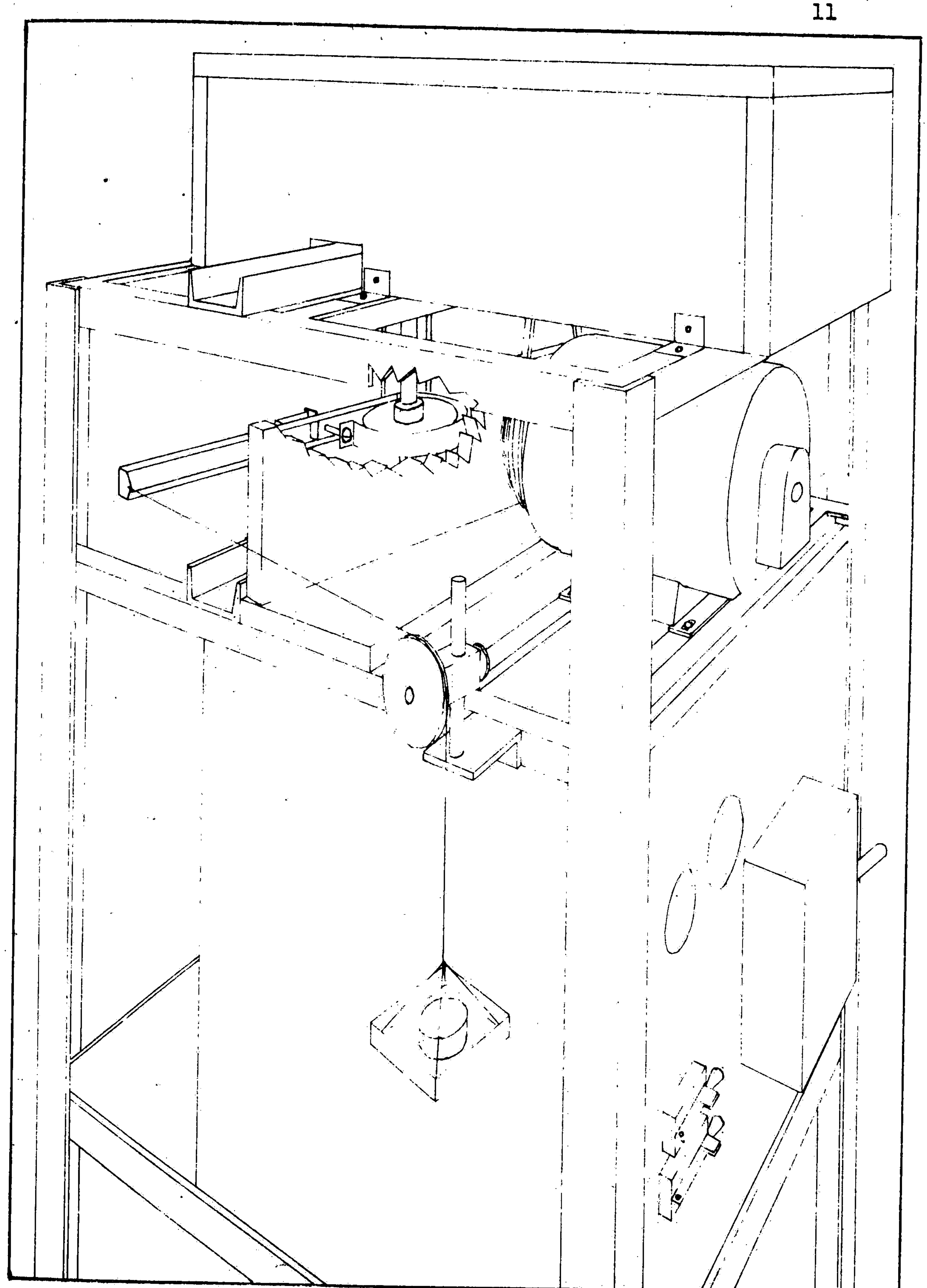
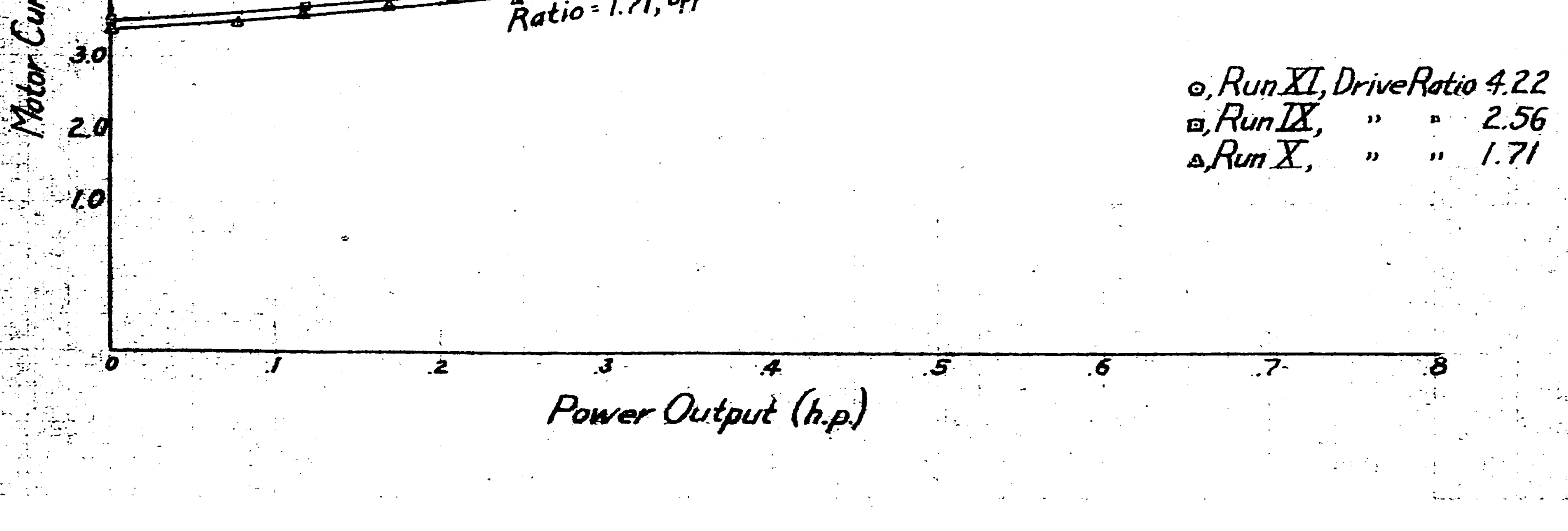
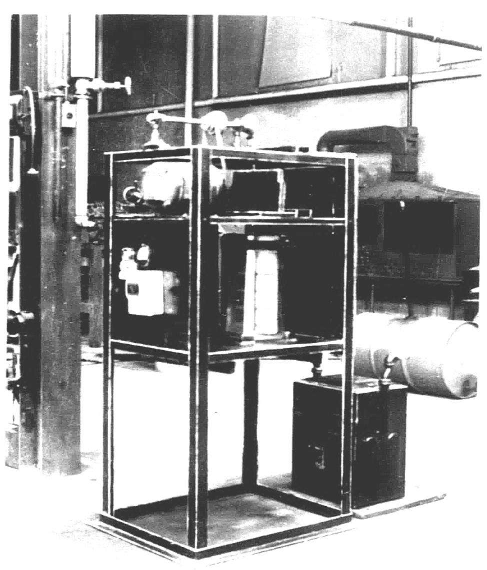


Fig. 1. Apparatus set up for calibration of the ammeter with a prony brake.

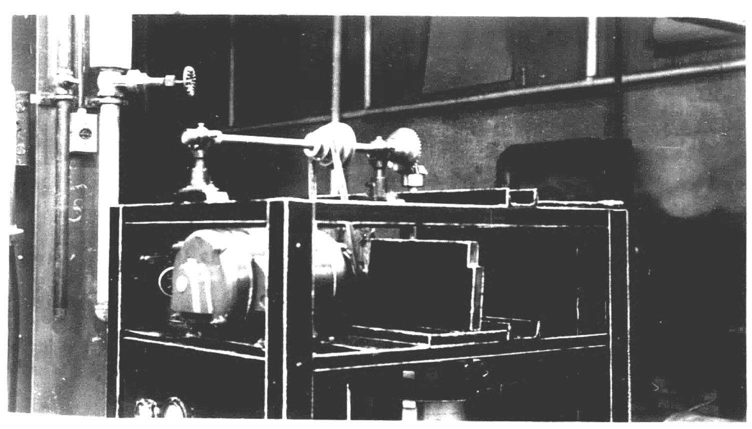
Graph 1. Calibration of Ammeter with Prony Brake for use as Dynamometer
Motor Current vs. Power Output of Impeller Shaft
Motor Warmed Up to 40°C Before Test



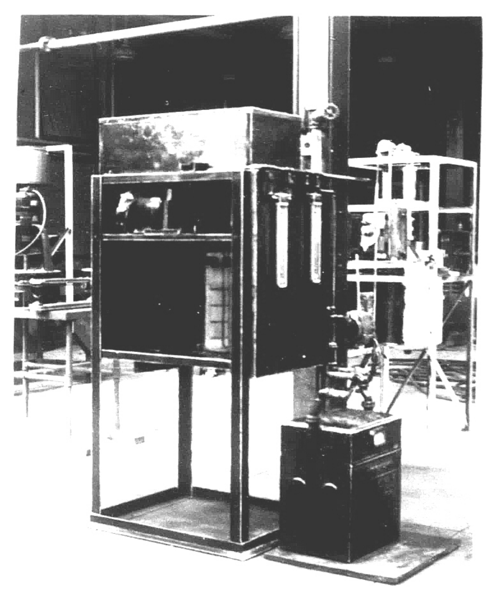
Air was run into the tank through copper tubing 3/8 inch outside diameter, which down along the inside wall of the tank and over underneath the impeller shaft. The end of the tube was sealed off, and a sparger was made directly under the center of the shaft by drilling a $\frac{1}{4}$ inch hole in the tubing. In series with the tubing and mounted on the side of the steel frame were two mercury manometers. One read the static pressure of the air, and the other read the drop across a capillary orifice. To calibrate this orifice a gas meter was placed in series with it, and air, which was supplied from a compressor, was run through the system. Then the gas meter was timed with a stop watch to get the rate of flow. The data taken in the calibration are shown in Table II, and the calibration curve is shown in Graph 2.



View showing machine with top shields removed.



Close-up showing drive mechanism with the shields removed.



View showing manometers and gas meter.

Fig. 2. Photographic Views of the Apparatus.

TABLE I

CALIBRATION OF THE AMMETER WITH A PRONY

BRAKE FOR USE AS A DYNAMOMETER

RUN IX

Speed Ratio: 2.56 (about 4500 r. p. m.)
Brake Arm: 1.094 feet
Brake Constant: .0002083
Weight of Pan and String: 27 grams

Current (amps.)	Line Voltage	r.p.m. of Shaft	Motor Temp. (°C)	Weights on Pan (g)	Weights Corrected (g)	Weights Corr. (lbs.)	Power Output (h.p.)
3.5	224	4540	38	NoLoad			0
3.7	222	4500		30	57	.1255	.1175
6.4	220	4150		360	387	.854	.738
3.9	224	4460		60	87	.1920	.2008
6.0	220	4140	40	330	357	.786	.687
4.0	226	4410		100	127	.280	.257
5.5	226	4100	42	300	337	.720	.614
4.1	225	4400	44	130	157	.346	.317
5.1	226	4240	44	260	287	.642	.566
4.4	228	4370	45	160	187	.412	.375
4.9	227	4300	45	230	257	.566	.507
4.6	227	4330	45	200	227	.500	.451

TABLE I (Continued)

RUN X

Speed Ratio: 1.71 (about 2900 r. p. m.)
Brake Arm: 1.094 feet
Brake Constant: .0002083
Weight of Pan and String: 27 grams

Current (amps.)	Line Voltage	r. p. m. of Shaft	Motor Temp. (°C)	Weights on Pan (g)	Weights Corrected (g)	Weights Corrected (lbs)	Power Output (h.p.)
3.4	228	2920	39	NoLoad			0
5.8	227	2770		530	557	1.226	.708
4.3	226	2841		260	287	.632	.388
3.5	226	2900		30	57	.1255	.0758
5.6	224	2765		500	527	1.161	.670
4.6	226	2822		330	357	.786	.462
3.6	227	2885	41	60	87	.1920	.1155
5.4	227	2784		460	487	1.074	.624
4.5	227	2828		300	327	.720	.424
3.7	229	2880		100	127	.280	.1680
5.2	227	2784		430	457	1.009	.586
4.1	228	2840		230	257	.566	.335
3.8	228	2869		130	157	.346	.207
5.0	229	2796		400	427	.941	.548
4.0	228	2850		200	227	.500	.297
3.8	228	2368		160	187	.412	.246
4.7	227	2808	45	360	387	.854	.500
3.4	230	2903	43	NoLoad			0

TABLE I (Continued)

RUN XI

Speed Ratio: 4.22 (about 7500 r. p. m.)
Brake Arm: 1.094 feet
Brake Constant: .0002083
Weight of Pan and String: 27 grams

Current (amps.)	Line Voltage	r. p. m. of Shaft	Motor Temp. (°C)	Weights on Pan (g)	Weights Corrected (g)	Weights Corrected (lbs.)	Power Output (h.p.)
4.0	225	7330	39	NoLoad			0
7.7	225	6800		220	247	.544	.770
4.4	225	7240		30	57	.1255	.1890
7.2	224	6860		200	227	.500	.715
4.8	225	7150		60	87	.1920	.286
6.2	225	6980		160	187	.412	.598
5.4	224	7070		110	137	.302	.445
5.9	224	7020		130	157	.346	.505
3.9	225	7300	42	NoLoad			0

Sample Calculations:

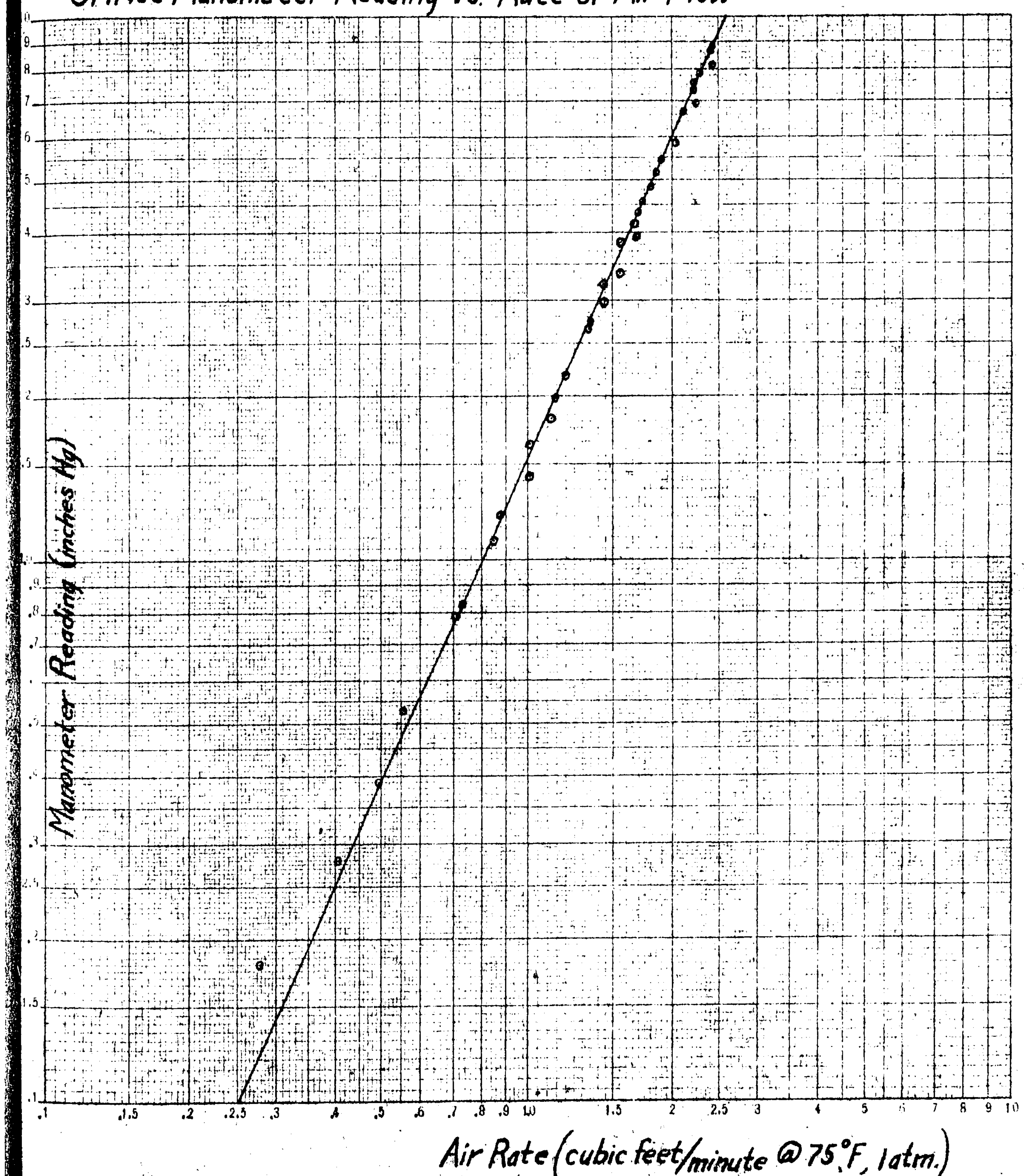
Take the second row data Run XI:

$$\text{Brake Constant} = \frac{6.28 \text{X} 1.094}{33,000} = .0002083$$

Power Output = .0002083X6800X.544 = .770 h. p.

Graph 2. Orifice Calibration

Orifice Manometer Reading vs. Rate of Air Flow



IRREGULAR

PAGINATION

TABLE II

CALIBRATION OF THE ORIFICE

Orifice Reading (in.Hg)	Line Pressure (in.Hg)	Gas Meter Reading (cu. ft.)	Time of Flow (min.)	Air Temp. (°F)	Air Rate (cu. ft./min., 1 atm., 75°F)
8.17	39.60	5.00	2.727	72.8	2.43
6.95	38.15	5.00	2.864	72.8	2.24
5.88	36.88	5.00	3.030	72.8	2.04
4.89	35.70	4.00	2.650	72.8	1.81
4.35	35.06	4.00	2.766	72.8	1.70
3.96	34.64	4.00	2.760	73.0	1.68
3.38	33.92	4.00	2.933	74.0	1.55
2.99	33.48	4.50	3.476	74.0	1.45
2.66	33.08	3.00	2.490	74.0	1.34
2.19	32.52	3.00	2.729	74.0	1.20
1.82	32.12	3.00	2.870	74.0	1.12
1.43	31.68	3.00	3.153	74.1	1.01
1.09	31.24	2.50	3.105	74.2	.849
.83	30.94	2.50	3.534	74.3	.733
.39	30.42	2.50	5.244	74.5	.495
.28	30.28	2.00	4.989	74.8	.406
.18	30.12	2.00	7.243	75.0	.278
.53	30.54	2.00	3.664	75.1	.556
.79	30.85	2.50	3.636	75.2	.710
1.21	31.35	2.50	2.996	75.2	.875
1.64	31.88	3.00	3.173	75.2	1.009
1.99	32.27	3.00	2.841	75.2	1.14
2.74	33.16	3.00	2.460	75.3	1.35
3.22	33.75	4.00	3.130	75.4	1.44
3.74	34.35	4.00	2.933	75.6	1.56
4.18	34.88	5.00	3.503	75.6	1.66
4.59	35.37	5.00	3.386	75.6	1.74
5.19	36.07	5.00	3.253	75.6	1.85
5.47	36.40	5.00	3.187	75.6	1.91
5.95	36.96	5.00	3.110	75.6	1.98
6.72	37.88	5.00	2.991	75.8	2.11
7.33	38.60	5.00	2.918	76.0	2.21
7.59	38.89	5.00	2.887	76.0	2.22
7.91	39.25	5.00	2.860	76.0	2.29
8.74	40.28	5.00	2.769	76.0	2.42
8.80	40.28	5.00	2.773	76.0	2.43

TABLE II (Continued)

Take the last row of data:

$$\text{Air Rate} = \frac{5.00 \times 40.28 \times (460-75)}{2.773 \times 29.92 \times (460-76)} = 2.43 \text{ cu. ft./min.}$$

@ 1 atm., 75°F

IV. PROCEDURE

The first tests were made without the addition of air in order to determine the nature of the agitation. The tank was first filled with water, and the desired number and size of impellers were inserted, always starting from the bottom of the shaft. The machine was started, and the shaft speed was read with the stroboscope, which was mounted on an adjustable stand. Then the motor current and voltage were read. From this data the power required for mixing at different speeds and different impeller numbers and lengths could be measured. The results are given in Table III and Graph 3.

The next series of tests were on gas-liquid contacting. The procedure was the same as in the previous tests, with the exception that varying rates of air were added for each condition. The air rates studied for each shaft speed, impeller length, and number of impellers were 0, .50, 1.00, 1.50, and 2.00 cubic feet per minute at one atmosphere and 75°F. The hold-up was also read by placing wax pencil marks on the outside of the tank in graduations of ½ inch. The results of these tests are shown in Table IV and Graphs 4 to 7.

Graph 3. Modified Reynolds Number Plot to Test for Turbulence

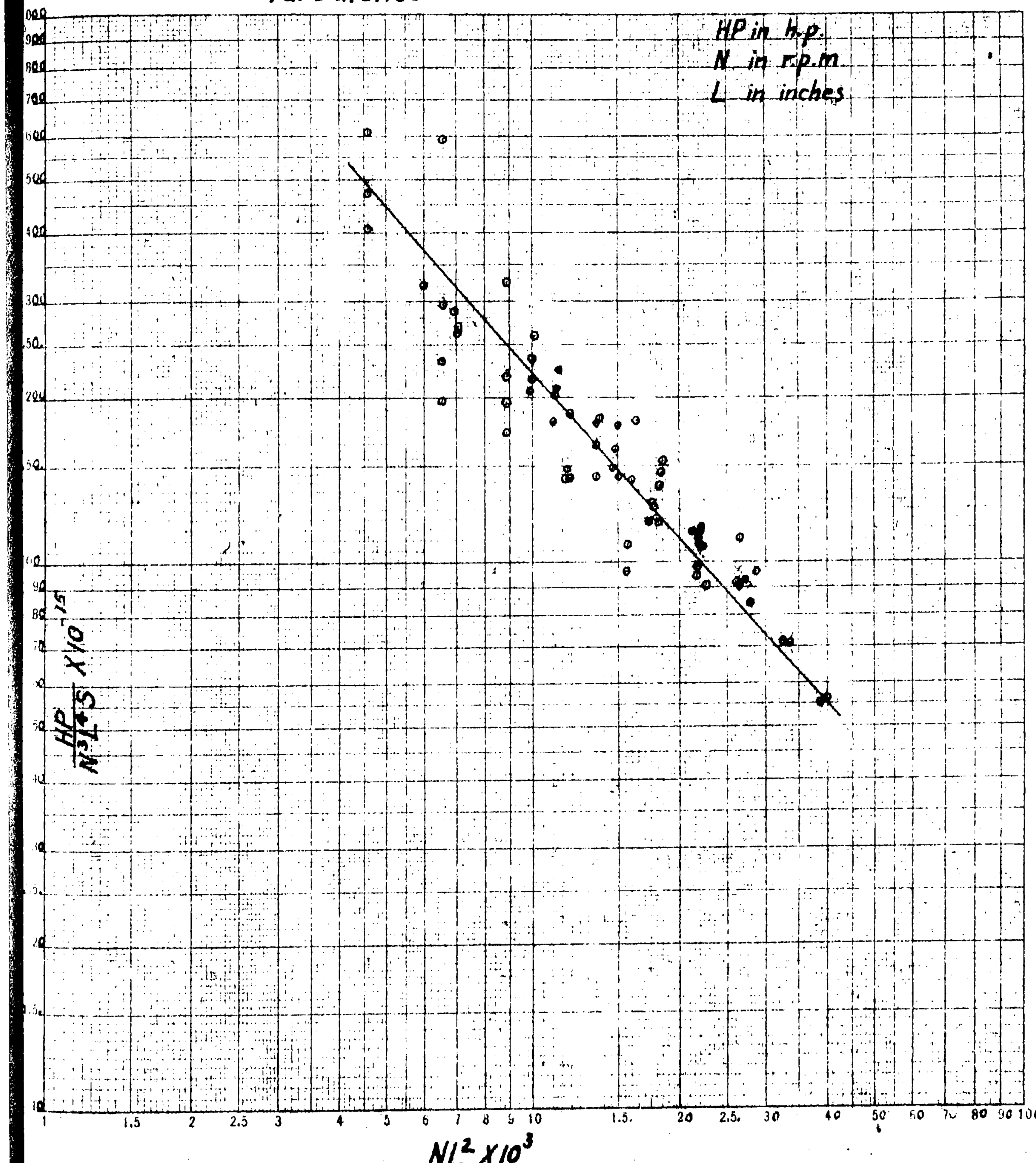


TABLE III

POWER REQUIRED FOR MIXING WITHOUT THE ADDITION OF AIR

Water Depth: 12 inches
No Air Added
Motor Warmed up to 40^{o}C before Starting

Impellers No.	Length (in.)	Line Voltage	Current (amps.)	r.p.m. of Shaft	Power Output (h.p.)	$\frac{HP}{N^3 L^4 S_5}$ X10^{-15}	NL^2 X10^3
Drive Ratio: 1.71 (approx. 2900 r. p. m.)							
1	1¼	230	3.5	2931	.075	1225	4.58
2	"	230	3.5	2921	.075	613	4.58
3	"	230	3.5	2920	.075	408	4.58
4	"	230	3.6	2920	.116	473	4.58
1	1½	230	3.5	2925	.075	593	6.58
2	"	230	3.5	2918	.075	297	6.56
3	"	230	3.5	2907	.075	198	6.54
4	"	230	3.6	2903	.116	234	6.54
1	1-3/4	230	3.5	2911	.075	325	8.90
2	"	230	3.55	2898	.100	219	8.87
3	"	227	3.6	2885	.116	173	8.84
4	"	227	3.7	2882	.175	196	8.83
Drive Ratio: 2.56 (approx. 4500 r. p. m.)							
1	1¼	227	3.6	4500	.060	270	7.04
2	"	229	3.7	4500	.117	264	7.04
3	"	230	3.9	4480	.212	321	7.00
4	"	230	4.0	4460	.250	288	6.97
1	1½	229	3.7	4490	.117	256	10.10
2	"	226	3.9	4460	.212	236	10.02
3	"	226	4.1	4440	.288	217	10.00
4	"	226	4.3	4400	.355	206	9.90
1	1-3/4	228	3.8	4470	.165	184	13.68
2	"	228	4.2	4430	.325	180	13.55
3	"	228	4.6	4410	.440	164	13.49
4	"	230	4.9	4400	.510	144	13.44
Drive Ratio: 4.22 (approx. 7500 r. p. m.)							
1	1¼	230	4.5	7250	.210	225	11.32
2	"	230	5.0	7160	.375	209	11.20
3	"	231	5.8	7090	.530	203	11.09
4	"	230	6.4	7060	.625	181	11.02
1	1½	230	4.9	7240	.350	182	16.30
2	"	230	5.7	7120	.515	141	16.00
3	"	230	6.4	7000	.625	107.8	15.74
4	"	230	6.6	6950	.655	96.4	15.62
1	1-3/4	230	5.0	7150	.375	109.6	21.9
2	"	227	7.1	6930	.710	114	21.2

TABLE III (Continued)

Impellers No.	Impellers Length (in.)	Line Voltage	Current (amps.)	r.p.m. of Shaft	Power Output (h.p.)	$\frac{HP}{N^3L^4S}$ X10^{-15}	NL^2 X10^3
Drive Ratio: 1.71 (approx. 2900 r. p. m.)							
1	2	226	3.5	2993	.080	187	11.93
2	"	229	3.6	2976	.120	143	11.90
3	"	230	3.7	2960	.185	148	11.83
4	"	228	3.8	2936	.230	142	11.73
1	2¼	230	3.6	2975	.120	178	15.04
2	"	230	3.7	2957	.185	144	14.97
3	"	230	3.95	2927	.290	161	14.80
4	"	230	4.2	2895	.370	149	14.64
1	2½	230	3.65	2960	.155	153	18.50
2	"	233	3.95	2943	.290	146	18.40
3	"	234	4.3	2920	.400	138	18.24
4	"	235	4.5	2900	.450	118	18.10
1	2-3/4	232	3.65	2953	.155	106	22.3
2	"	231	4.0	2920	.330	116	22.1
3	"	231	4.5	2898	.450	108	21.9
4	"	231	4.9	2875	.535	98.6	21.7
1	3	232	3.8	2948	.230	111	26.5
2	"	230	4.2	2915	.370	92.0	26.2
Drive Ratio: 2.56, (approx. 4500 r. p. m.)							
1	2	225	3.8	4500	.175	120	18.00
2	"	225	4.3	4450	.355	126	17.79
3	"	224	5.0	4400	.530	129	17.59
4	"	226	5.6	4360	.630	119	17.41
1	2¼	224	3.9	4480	.210	91.2	22.6
2	"	225	4.7	4410	.465	105.7	22.3
3	"	224	5.8	4330	.660	113	21.9
4	"	224	6.5	4260	.750	94.6	21.6
1	2½	225	4.1	4450	.290	84.3	27.8
2	"	224	5.4	4360	.600	92.7	27.2
3	"	224	6.9	4240	.810	90.6	26.5
4	"	Motor Overloaded					
1	2-3/4	225	4.3	4440	.355	71.0	33.6
2	"	226	5.8	4320	.660	71.7	32.6
3	"	Motor Overloaded					
1	3	224	4.45	4440	.400	56.2	39.9
2	"	225	6.2	4300	.715	55.4	38.7
Drive Ratio: 4.22 (approx. 7500 r. p. m.)							
1	2	225	6.0	7160	.565	96.2	28.6

TABLE III (Continued)

Sample Calculations:

Take as an example the first row of data:

Power Output is read directly from the ammeter calibration curve.

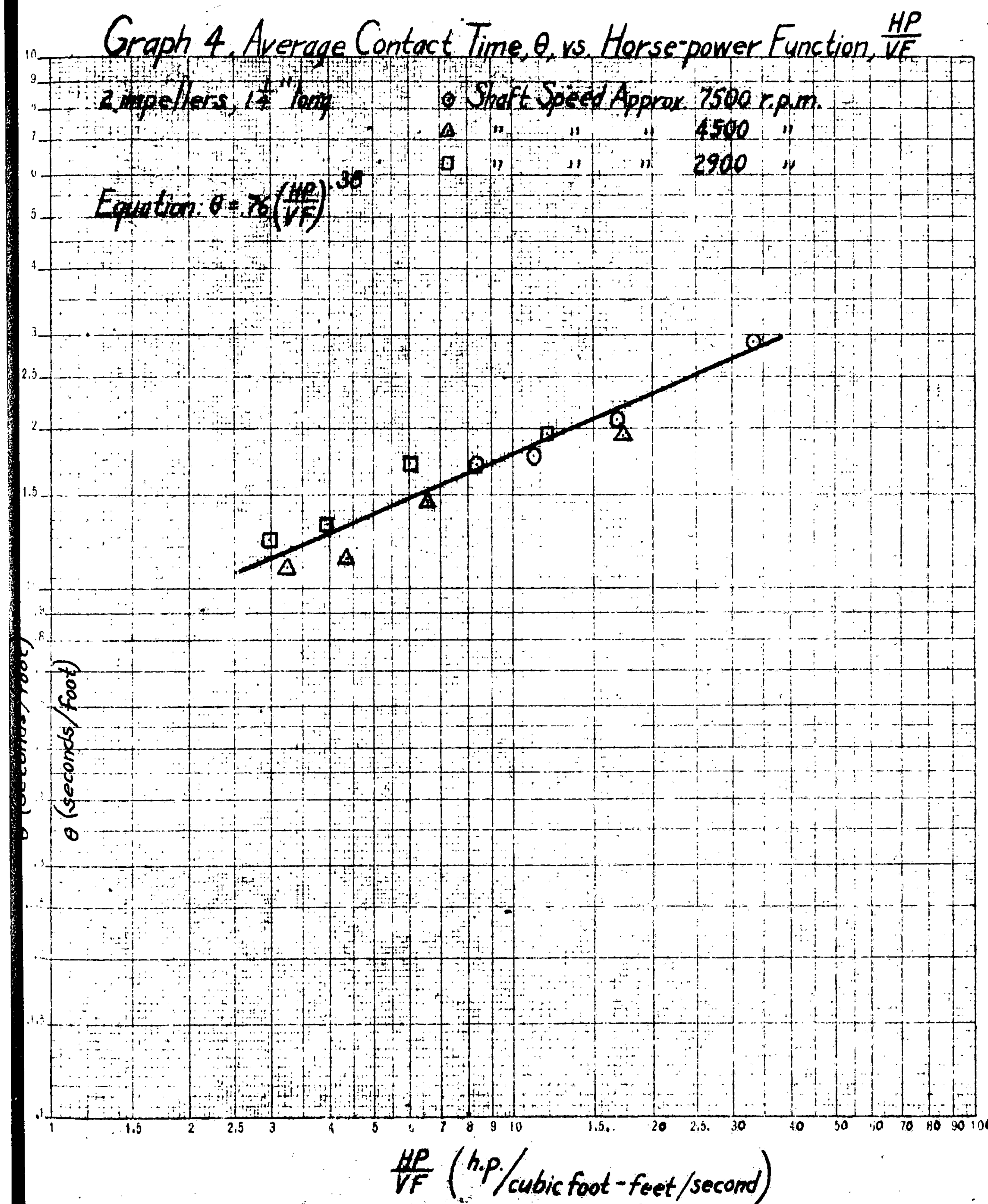
$$\frac{HP}{N^3L^4S} = \frac{.075}{2931^3 X 1.25^4 X 1} = 1225X10^{-15}$$

$$NL^2 = 2931 X 1.25^2 = 4.58X10^3$$

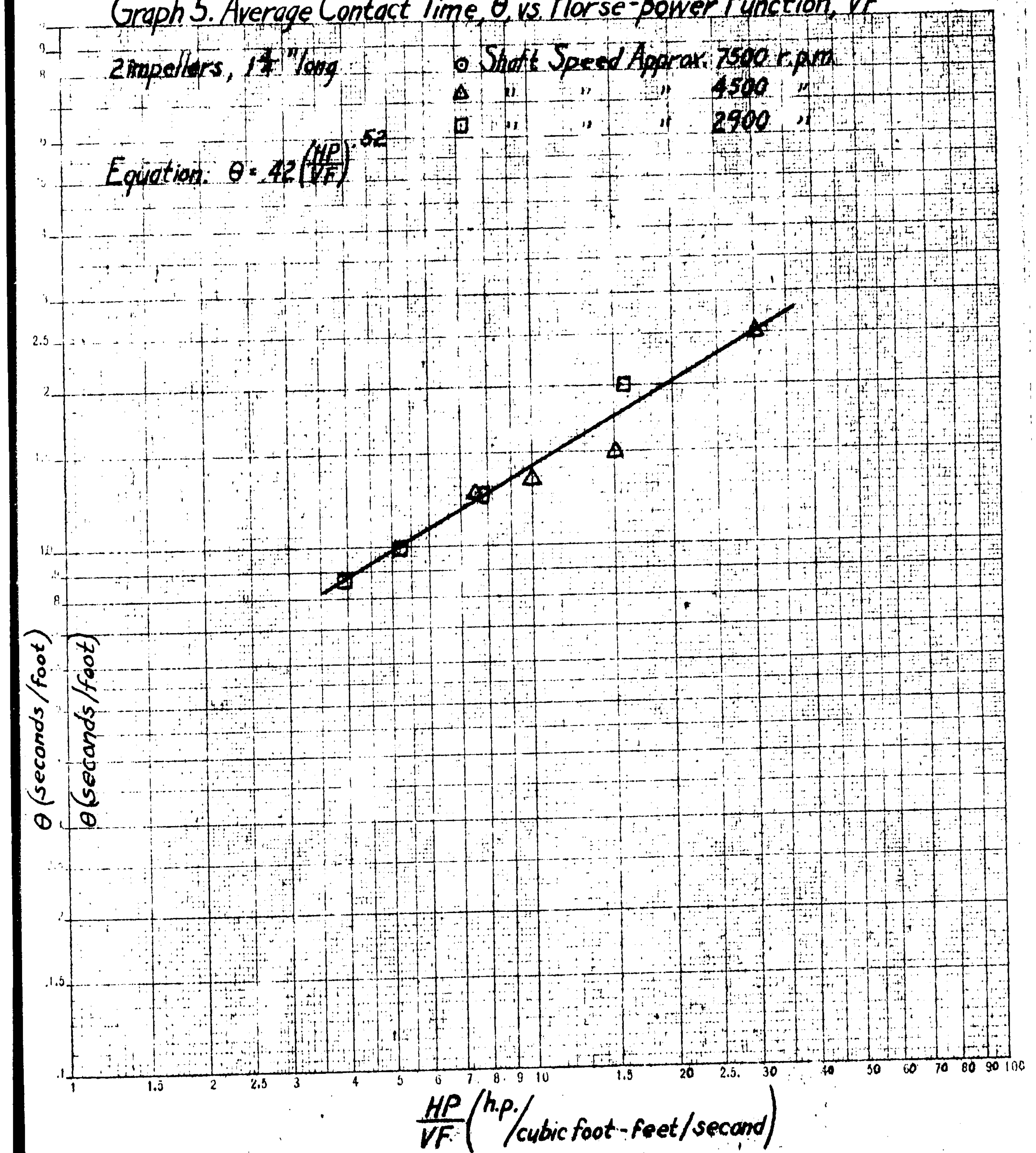
where HP is in h. p.

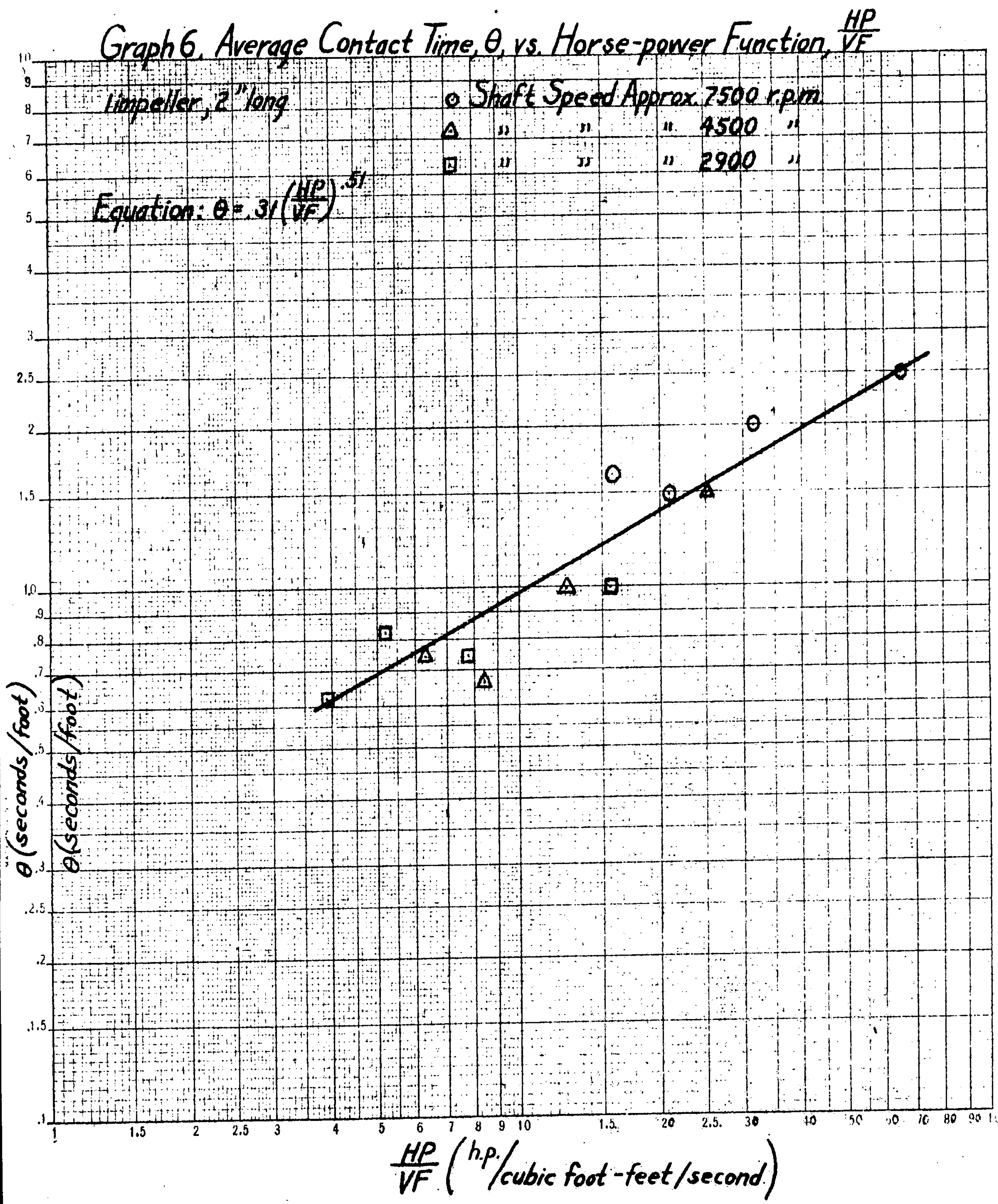
N is in r. p. m.

L is in inches.


Graph 4. Average Contact Time, θ, vs. Horse-power Function, HP/VF
2 impellers, 1¼" long
Shaft Speed Approx. 7500 r.p.m.
4500
2900
Equation: θ = .76 (HP/VF)^.38
θ (seconds/foot)
HP/VF (h.p./cubic foot - feet/second)

Graph 5. Average Contact Time, θ, vs. Horse-power Function, $\frac{HP}{VF}$




Graph 6. Average Contact Time, θ, vs. Horse-power Function, HP/VF
1 impeller, 2" long
Shaft Speed Approx. 7500 r.p.m.
" " " 4500 "
" " " 2900 "
Equation: θ = .31(HP/VF)^.51
θ (seconds/foot)
HP/VF (h.p./cubic foot-feet/second)

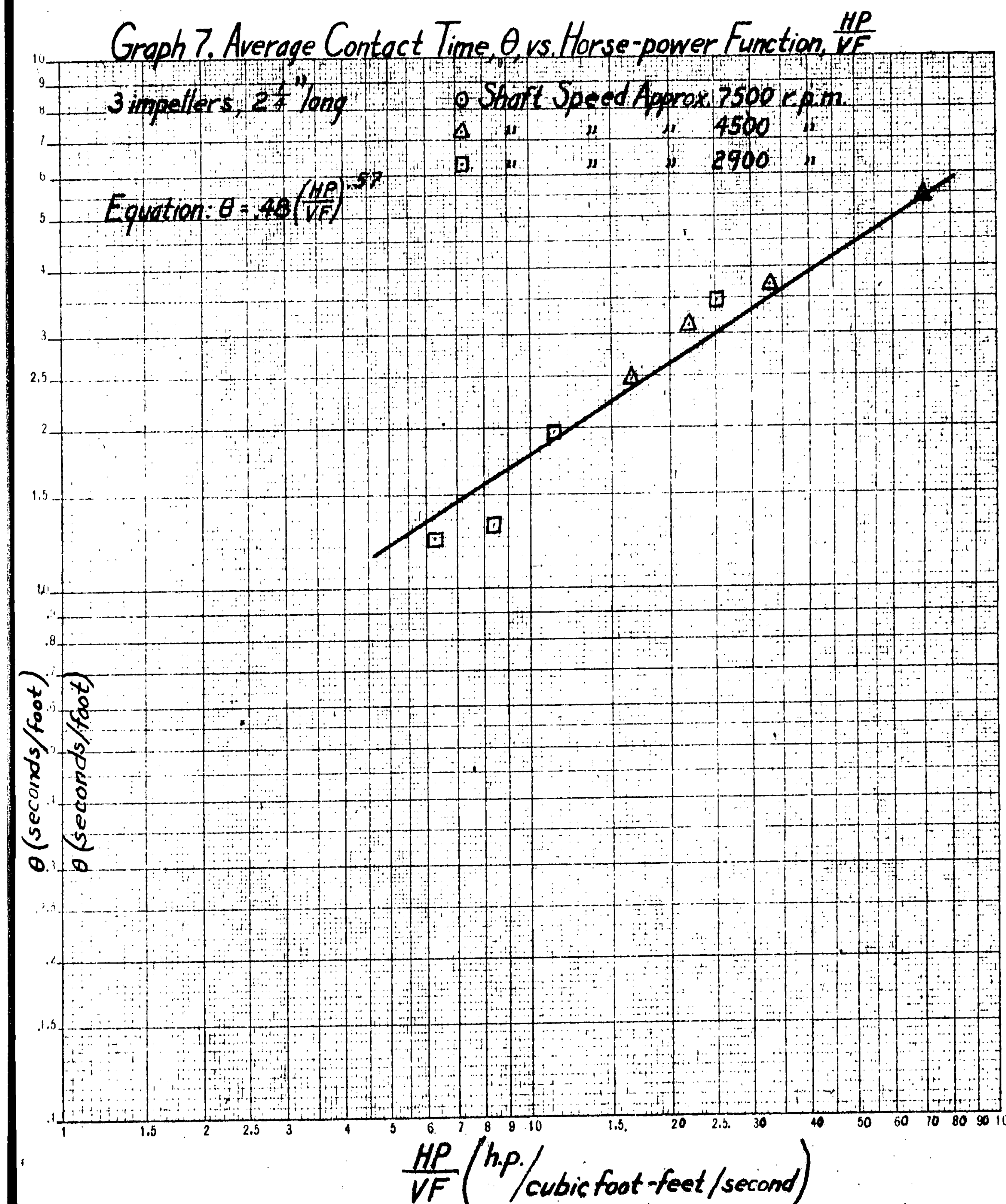

Graph 7. Average Contact Time, θ vs. Horse-power Function, HP/VF
3 impellers, 2¼" long
Shaft Speed Approx. 7500 r.p.m.
4500
2900
Equation: θ = .48(HP/VF)^.57
θ (seconds/foot)
HP/VF (h.p./cubic foot-feet/second)

TABLE IV

POWER REQUIRED FOR MIXING WITH THE ADDITION OF AIR

Water Depth: 1 foot
Motor Warmed to 40°C
Tank Cross Sectional Area: .495 square feet
Air Temperature: 75°F

RUN III, Drive Ratio: 4.22 (approx. 7500 r. p. m.)

Impellers No.	Length (in.)	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	1¼	6.00	1.1	225	4.0	7370	2.00	.0674	.150	1.36	4.5
"	"	3.40	1.0	226	4.0	7370	1.50	.0505	.150	1.65	6.0
"	"	1.55	.8	227	4.0	7370	1.00	.0337	.150	1.98	9.0
"	"	.40	.5	226	4.0	7370	.50	.0168	.150	2.48	18.0
"	"	0	0	226	4.2	7360	0	0	.215		
2	1¼	6.00	1.4	227	4.4	7360	2.00	.0674	.280	1.73	8.4
"	"	3.40	1.1	227	4.4	7340	1.50	.0505	.280	1.82	11.2
"	"	1.55	.9	226	4.4	7340	1.00	.0337	.280	2.22	16.8
"	"	.40	.6	224	4.4	7340	.50	.0168	.280	2.98	33.6
"	"	0	.1	225	4.7	7300	0	0	.355		
3	1¼	6.00	1.7	225	4.7	7300	2.00	.0674	.355	2.10	10.6
"	"	3.40	1.2	225	4.7	7300	1.50	.0505	.355	1.98	14.2
"	"	1.55	1.0	225	4.7	7270	1.00	.0337	.355	2.47	21.3
"	"	.40	.7	225	4.8	7270	.50	.0168	.380	3.46	45.6
"	"	0	.1	227	5.3	7230	0	0	.490		
4	1¼	6.00	1.6	226	5.0	7230	2.00	.0674	.425	1.98	12.8
"	"	3.40	1.3	227	5.1	7220	1.50	.0505	.450	2.14	18.0
"	"	1.55	1.2	228	5.1	7220	1.00	.0337	.450	2.96	27.0

TABLE IV (Continued)

RUN III (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
4	1¼	.40	.9	227	5.3	7220	.50	.0168	.490	4.46	58.8
"	"	0	.1	225	5.9	7160	0	0	.595		
1	1½	6.00	1.2	228	4.4	7350	2.00	.0674	.280	1.48	8.4
"	"	3.40	.8	229	4.4	7350	1.50	.0505	.280	1.32	11.2
"	"	1.55	.7	228	4.4	7350	1.00	.0337	.280	1.73	16.8
"	"	.40	.4	229	4.4	7350	.50	.0168	.280	1.98	33.6
"	"	0	.1	229	4.5	7340	0	0	.310		
2	1½	6.00	1.4	228	5.0	7260	2.00	.0674	.425	1.73	12.8
"	"	3.40	1.2	229	5.0	7260	1.50	.0505	.425	1.98	17.0
"	"	1.55	.9	229	5.0	7260	1.00	.0337	.425	2.22	25.5
"	"	.40	.8	229	5.2	7250	.50	.0168	.470	3.98	56.3
"	"	0	.2	229	5.5	7200	0	0	.525		
3	1½	6.00	1.7	228	5.8	7150	2.00	.0674	.580	2.10	17.4
"	"	3.40	1.4	228	6.0	7150	1.50	.0505	.610	1.73	24.4
"	"	1.55	1.2	228	6.0	7150	1.00	.0337	.610	2.96	36.6
"	"	.40	.8	227	6.1	7130	.50	.0168	.625	3.98	75.0
"	"	0	0	228	6.8	7000	0	0	.715		
4	1½	Motor Overloaded									
1	1¾	6.00	1.2	227	4.8	7300	2.00	.0674	.380	1.48	11.4
"	"	3.40	1.0	225	4.8	7280	1.50	.0505	.380	1.65	15.2
"	"	1.55	.7	225	4.8	7280	1.00	.0337	.380	1.73	22.8
"	"	.40	.5	225	4.9	7280	.50	.0168	.405	2.48	48.6
"	"	0	.2	225	5.0	7230	0	0	.425		
2	1¾	Motor Overloaded									
1	2	6.00	1.3	225	5.5	7160	2.00	.0674	.525	1.61	15.8

TABLE IV (Continued)

RUN III (Continued)

Impellers No.	Impellers Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	2	3.40	1.2	225	5.5	7160	1.50	.0505	.525	1.48	21.0
"	"	1.55	.8	224	5.5	7160	1.00	.0337	.525	1.98	71.5
"	"	.40	.5	224	5.6	7150	.50	.0168	.540	2.48	64.8
"	"	0	.2	223	5.9	7090	0	0	.595		
2	2	Motor Overloaded									

RUN IV, Drive Ratio: 2.56 (approx. 4500 r. p. m.)

Impellers No.	Impellers Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	$1\frac{1}{4}$	6.00	.9	229	3.5	4600	2.00	.0674	.110	1.11	3.3
"	"	3.40	.6	230	3.5	4600	1.50	.0505	.110	.99	4.4
"	"	1.55	.5	230	3.5	4600	1.00	.0337	.110	1.24	6.6
"	"	.40	.4	228	3.5	4600	.50	.0168	.110	1.98	13.2
"	"	0	0	228	3.5	4600	0	0	.110		
2	$1\frac{1}{4}$	6.00	.9	228	3.5	4600	2.00	.0674	.110	1.11	3.3
"	"	3.40	.7	230	3.5	4600	1.50	.0505	.110	1.15	4.4
"	"	1.55	.6	229	3.5	4600	1.00	.0337	.110	1.48	6.6
"	"	.40	.4	230	3.55	4600	.50	.0168	.145	1.98	17.4
"	"	0	0	230	3.55	4600	0	0	.145		
3	$1\frac{1}{4}$	6.00	1.0	229	3.6	4600	2.00	.0674	.170	1.24	5.1
"	"	3.40	.8	230	3.6	4600	1.50	.0505	.170	1.32	6.8
"	"	1.55	.6	230	3.6	4600	1.00	.0337	.170	1.48	10.2

TABLE IV (Continued)

RUN IV (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
3	1¼	.40	.4	230	3.6	4600	.50	.0168	.170	1.98	20.2
"	"	0	.1	230	3.7	4580	0	0	.210		
4	1¼	6.00	1.1	230	3.6	4590	2.00	.0674	.170	1.36	5.1
"	"	3.40	.9	230	3.6	4590	1.50	.0505	.170	1.49	6.8
"	"	1.55	.8	230	3.6	4590	1.00	.0337	.170	1.97	10.2
"	"	.40	.6	230	3.6	4590	.50	.0168	.170	2.98	20.2
"	"	0	.1	230	3.8	4560	0	0	.250		
1	1½	6.00	.7	230	3.5	4610	2.00	.0674	.110	.86	3.3
"	"	3.40	.5	230	3.5	4610	1.50	.0505	.110	.82	4.4
"	"	1.55	.3	230	3.5	4610	1.00	.0337	.110	.74	6.6
"	"	.40	.2	230	3.55	4610	.50	.0168	.145	.99	17.4
"	"	0	0	231	3.6	4600	0	0	.170		
2	1½	6.00	.7	230	3.6	4600	2.00	.0674	.170	.86	5.1
"	"	3.40	.6	230	3.6	4600	1.50	.0505	.170	.99	6.8
"	"	1.55	.5	230	3.6	4600	1.00	.0337	.170	.74	10.2
"	"	.40	.3	230	3.6	4600	.50	.0168	.170	1.49	20.2
"	"	0	.1	228	3.8	4570	0	0	.250		
3	1½	6.00	.9	230	3.7	4570	2.00	.0674	.210	1.11	6.3
"	"	3.40	.7	230	3.7	4570	1.50	.0505	.210	1.15	8.4
"	"	1.55	.6	230	3.7	4570	1.00	.0337	.210	1.48	12.6
"	"	.40	.4	230	3.8	4570	.50	.0168	.250	1.98	30.0
"	"	0	.1	231	4.0	4550	0	0	.320		
4	1½	6.00	1.1	231	3.8	4580	2.00	.0674	.250	1.36	7.5
"	"	3.40	1.0	230	3.8	4580	1.50	.0505	.250	1.65	10.0
"	"	1.55	.8	230	3.8	4580	1.00	.0337	.250	1.97	15.0

TABLE IV (Continued)

RUN IV (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
4	1½	.40	.5	231	3.8	4580	.50	.0168	.250	2.48	30.0
"	"	0	.2	230	4.1	4520	0	0	.355		
1	1¾	6.00	.7	230	3.6	4590	2.00	.0674	.170	.86	5.1
"	"	3.40	.6	233	3.6	4590	1.50	.0505	.170	.99	6.8
"	"	1.55	.4	232	3.6	4590	1.00	.0337	.170	.99	10.2
"	"	.40	.3	232	3.6	4590	.50	.0168	.170	1.49	20.2
"	"	0	.1	233	3.7	4590	0	0	.210		
2	1¾	6.00	1.0	232	3.8	4560	2.00	.0674	.250	1.24	7.5
"	"	3.40	.8	233	3.8	4560	1.50	.0505	.250	1.32	10.0
"	"	1.55	.6	232	3.8	4560	1.00	.0337	.250	1.48	15.0
"	"	.40	.5	233	3.8	4560	.50	.0168	.250	2.48	30.0
"	"	0	.2	233	4.0	4550	0	0	.320		
3	1¾	6.00	1.1	230	3.9	4550	2.00	.0674	.290	1.36	8.7
"	"	3.40	1.0	230	3.9	4550	1.50	.0505	.290	1.65	11.6
"	"	1.55	.9	230	3.9	4550	1.00	.0337	.290	2.22	17.4
"	"	.40	.5	230	4.0	4550	.50	.0168	.320	2.48	38.4
"	"	0	.2	232	4.3	4500	0	0	.415		
4	1¾	6.00	1.5	232	4.1	4540	2.00	.0674	.355	1.85	10.7
"	"	3.40	1.3	233	4.1	4540	1.50	.0505	.355	2.14	14.2
"	"	1.55	1.1	233	4.1	4540	1.00	.0337	.355	2.72	21.3
"	"	.40	.9	230	4.2	4540	.50	.0168	.390	4.46	46.8
"	"	0	.2	230	4.6	4480	0	0	.490		
1	2	6.00	.6	230	3.7	4580	2.00	.0674	.210	.74	6.3
"	"	3.40	.4	230	3.7	4580	1.50	.0505	.210	.66	8.4
"	"	1.55	.4	230	3.7	4580	1.00	.0337	.210	.99	12.6

TABLE IV (Continued)

RUN IV (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	2	.40	.3	231	3.7	4580	.50	.0168	.210	1.49	25.2
"	"	0	.1	230	3.8	4560	0	0	.250		
2	2	6.00	1.1	230	4.0	4550	2.00	.0674	.320	1.36	9.6
"	"	3.40	1.0	230	4.0	4550	1.50	.0505	.320	1.65	12.8
"	"	1.55	.8	230	4.0	4550	1.00	.0337	.320	1.97	19.2
"	"	.40	.6	230	4.0	4550	.50	.0168	.320	2.98	38.4
"	"	0	.1	230	4.3	4550	0	0	.415		
3	2	6.00	1.6	228	4.3	4500	2.00	.0674	.415	1.98	12.5
"	"	3.40	1.4	228	4.3	4500	1.50	.0505	.415	2.31	16.6
"	"	1.55	1.2	228	4.3	4500	1.00	.0337	.415	2.97	24.8
"	"	.40	1.0	228	4.4	4500	.50	.0168	.440	4.96	52.8
"	"	0	.2	227	4.9	4450	0	0	.550		
4	2	6.00	1.8	226	4.6	4450	2.00	.0674	.490	2.23	14.7
"	"	3.40	1.6	226	4.6	4450	1.50	.0505	.490	2.64	19.6
"	"	1.55	1.4	225	4.7	4450	1.00	.0337	.510	3.46	30.6
"	"	.40	1.0	227	4.8	4450	.50	.0168	.530	4.96	63.6
"	"	0	.2	224	5.5	4390	0	0	.645		
1	2¼	6.00	.9	226	3.8	4560	2.00	.0674	.250	1.11	7.5
"	"	3.40	.8	225	3.8	4560	1.50	.0505	.250	1.32	10.0
"	"	1.55	.8	225	3.8	4560	1.00	.0337	.250	1.97	15.0
"	"	.40	.5	226	3.8	4560	.50	.0168	.250	2.48	30.0
"	"	0	.2	227	3.9	4560	0	0	.290		
2	2¼	6.00	1.6	224	4.2	4510	2.00	.0674	.390	1.98	11.7
"	"	3.40	1.5	224	4.2	4510	1.50	.0505	.390	2.48	15.6
"	"	1.55	1.3	224	4.3	4510	1.00	.0337	.415	3.22	24.8
"	"	.40	.9	225	4.3	4510	.50	.0168	.415	4.46	49.8
"	"	0	.3	227	4.7	4470	0	0	.510		

TABLE IV (Continued)

RUN IV (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
3	2¼	6.00	2.0	228	4.9	4470	2.00	.0674	.550	2.48	16.5
"	"	3.40	1.9	229	4.9	4470	1.50	.0505	.550	3.14	22.0
"	"	1.55	1.5	227	4.9	4470	1.00	.0337	.550	3.70	33.0
"	"	.40	1.1	227	5.1	4460	.50	.0168	.585	5.46	70.2
"	"	0	.3	227	5.7	4370	0	0	.675		
4	2¼	6.00	2.2	225	5.6	4380	2.00	.0674	.660	2.72	19.8
"	"	3.40	2.1	226	5.6	4380	1.50	.0505	.660	3.46	26.4
"	"	1.55	2.0	228	5.7	4380	1.00	.0337	.675	4.95	40.5
"	"	.40	1.3	227	5.9	4350	.50	.0168	.700	6.45	84.0
"	"	0	.8	230	6.4	4310	0	0	.770		
1	2½	6.00	1.3	227	3.9	4550	2.00	.0674	.290	1.61	8.7
"	"	3.40	1.1	227	3.9	4550	1.50	.0505	.290	1.81	11.6
"	"	1.55	1.0	228	3.9	4550	1.00	.0337	.290	2.47	17.4
"	"	.40	.5	228	3.9	4550	.50	.0168	.290	2.48	34.8
"	"	0	.1	229	4.1	4550	0	0	.355		
2	2½	6.00	1.9	228	4.6	4490	2.00	.0674	.490	2.35	14.7
"	"	3.40	1.6	227	4.6	4490	1.50	.0505	.490	2.64	19.6
"	"	1.55	1.3	226	4.7	4490	1.00	.0337	.510	3.22	30.6
"	"	.40	1.0	225	4.8	4460	.50	.0168	.530	4.96	63.5
"	"	0	.2	226	5.2	4410	0	0	.600		
3	2½	6.00	2.1	224	5.7	4370	2.00	.0674	.675	2.60	20.2
"	"	3.40	2.0	227	5.7	4370	1.50	.0505	.675	3.30	27.0
"	"	1.55	1.7	225	5.8	4370	1.00	.0337	.685	4.20	41.1
"	"	.40	1.2	225	5.9	4340	.50	.0168	.700	5.95	84.0
"	"	0	.6	225	6.7	4250	0	0	.800		

TABLE IV (Continued)

RUN IV (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75^oF, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
4	2¼	Motor	Overloaded								
1	2¼	6.00	1.4	225	4.0	4530	2.00	.0674	.320	1.73	9.6
"	"	3.40	1.3	227	4.1	4530	1.50	.0505	.355	2.14	14.2
"	"	1,55	1.0	227	4.1	4530	1.00	.0337	.355	2.47	21.3
"	"	.40	.6	227	4.1	4530	.50	.0168	.355	2.98	42.6
"	"	0	.1	229	4.2	4500	0	.0	.390		
2	2¾	6.00	2.1	230	5.1	4430	2.00	.0674	.585	2.60	17.6
"	"	3.40	2.0	227	5.1	4430	1.50	.0505	.585	3.30	23.4
"	"	1.55	1.6	228	5.2	4430	1.00	.0337	.600	3.96	36.0
"	"	.40	1.1	230	5.3	4430	.50	.0168	.615	5.46	73.9
"	"	0	.2	229	5.7	4360	0	0	.675		
3	2¾	Motor	Overloaded								

RUN V, Drive Ratio: 1.71 (approx. 2900 r. p. m.)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75^oF, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	1¼	6.00	.7	230	$3.3\overline{5}$	3013	2.00	.0674	.075	.86	2.3
"	"	3.40	.6	230	$3.3\overline{5}$	3013	1.50	.0505	.075	.99	3.0
"	"	1.55	.4	230	$3.3\overline{5}$	3013	1.00	.0337	.075	.99	4.5
"	"	.40	.2	230	$3.3\overline{5}$	3013	.50	.0168	.075	.99	9.0
"	"	0	0	230	$3.3\overline{5}$	3013	0	0	.075		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
2	1¼	6.00	1.0	230	3.4	3013	2.00	.0674	.100	1.24	3.0
"	"	3.40	.8	234	3.4	3013	1.50	.0505	.100	1.32	4.0
"	"	1.55	.7	234	3.4	3013	1.00	.0337	.100	1.73	6.0
"	"	.40	.4	233	3.4	3006	.50	.0168	.100	1.98	12.0
"	"	0	0	233	3.4	3001	0	0	.100		
3	1¼	6.00	1.1	233	3.4	3001	2.00	.0674	.100	1.36	3.0
"	"	3.40	.9	234	3.4	3001	1.50	.0505	.100	1.49	4.0
"	"	1.55	.8	232	3.4	3001	1.00	.0337	.100	1.97	6.0
"	"	.40	.5	232	3.4	3001	.50	.0168	.100	2.48	12.0
"	"	0	0	232	3.4	2997	0	0	.100		
4	1¼	6.00	1.2	232	3.5	3001	2.00	.0674	.150	1.49	4.5
"	"	3.40	1.0	233	3.5	3001	1.50	.0505	.150	1.65	6.0
"	"	1.55	.7	232	3.5	3001	1.00	.0337	.150	1.73	9.0
"	"	.40	.5	233	3.5	3001	.50	.0168	.150	2.48	18.0
"	"	0	.1	233	3.5	2993	0	0	.150		
1	1⅛	6.00	.6	233	3.4	3008	2.00	.0674	.100	.74	3.0
"	"	3.40	.5	232	3.4	3003	1.50	.0505	.100	.82	4.0
"	"	1.55	.3	232	3.4	3003	1.00	.0337	.100	.74	6.0
"	"	.40	.2	230	3.4	3003	.50	.0168	.100	.99	12.0
"	"	0	0	230	3.4	3000	0	0	.100		
2	1⅛	6.00	.8	233	3.4	2997	2.00	.0674	.100	.99	3.0
"	"	3.40	.7	233	3.4	2997	1.50	.0505	.100	1.15	4.0
"	"	1.55	.5	233	3.4	2997	1.00	.0337	.100	1.24	6.0
"	"	.40	.3	233	3.4	2997	.50	.0168	.100	1.49	12.0
"	"	0	0	233	3.4	2997	0	0	.100		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
3	1½	6.00	.9	230	3.4	2997	2.00	.0674	.100	1.11	3.0
"	"	3.40	.8	230	3.4	2997	1.50	.0505	.100	1.32	4.0
"	"	1.55	.6	230	3.4	2997	1.00	.0337	.100	1.48	6.0
"	"	.40	.5	231	3.4	2997	.50	.0168	.100	2.48	12.0
"	"	0	0	230	3.5	2990	0	0	.150		
4	1½	6.00	1.1	230	3.45	2990	2.00	.0674	.130	1.36	3.9
"	"	3.40	1.0	230	3.45	2990	1.50	.0505	.130	1.65	5.2
"	"	1.55	.7	230	3.45	2990	1.00	.0337	.130	1.73	7.8
"	"	.40	.5	230	3.45	2987	.50	.0168	.130	2.48	15.6
"	"	0	.1	230	3.5	2978	0	0	.150		
1	1¾	6.00	.5	230	3.45	2990	2.00	.0674	.130	.62	3.9
"	"	3.40	.4	227	3.45	2990	1.50	.0505	.130	.66	5.2
"	"	1.55	.3	227	3.45	2990	1.00	.0337	.130	.74	7.8
"	"	.40	.2	230	3.45	2990	.50	.0168	.130	.99	15.6
"	"	0	0	230	3.45	2990	0	0	.130		
2	1¾	6.00	.7	230	3.45	2990	2.00	.0674	.130	.86	3.9
"	"	3.40	.6	230	3.45	2990	1.50	.0505	.130	.99	5.2
"	"	1.55	.5	230	3.45	2990	1.00	.0337	.130	1.24	7.8
"	"	.40	.4	227	3.45	2990	.50	.0168	.130	1.98	15.6
"	"	0	.1	230	3.5	2980	0	0	.150		
3	1¾	6.00	1.0	230	3.45	2990	2.00	.0674	.130	1.24	3.9
"	"	3.40	.9	230	3.45	2990	1.50	.0505	.130	1.49	5.2
"	"	1.55	.7	230	3.45	2990	1.00	.0337	.130	1.73	7.8
"	"	.40	.5	230	3.45	2990	.50	.0168	.130	2.48	15.6
"	"	0	.1	227	3.5	2972	0	0	.150		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
4	1¾	6.00	1.2	228	3.5	2980	2.00	.0674	.150	1.49	4.5
"	"	3.40	1.1	230	3.5	2980	1.50	.0505	.150	1.81	6.0
"	"	1.55	1.0	230	3.5	2980	1.00	.0337	.150	2.47	9.0
"	"	.40	.7	229	3.5	2980	.50	.0168	.150	3.48	18.0
"	"	0	.2	229	3.55	2960	0	0	.180		
1	2	6.00	.5	230	3.45	2992	2.00	.0674	.130	.62	3.9
"	"	3.40	.5	230	3.45	2995	1.50	.0505	.130	.82	5.2
"	"	1.55	.3	230	3.45	2995	1.00	.0337	.130	.74	7.8
"	"	.40	.2	230	3.45	2987	.50	.0168	.130	.99	15.6
"	"	0	0	230	3.45	2987	0	0	.130		
2	2	6.00	.7	230	3.45	2987	2.00	.0674	.130	.86	3.9
"	"	3.40	.6	230	3.45	2987	1.50	.0505	.130	.99	5.2
"	"	1.55	.5	230	3.45	2981	1.00	.0337	.130	1.24	7.8
"	"	.40	.1	230	3.45	2981	.50	.0168	.130	.50	15.6
"	"	0	.1	230	3.5	2971	0	0	.150		
3	2	6.00	1.0	230	3.5	2971	2.00	.0674	.150	1.24	4.5
"	"	3.40	.8	230	3.5	2971	1.50	.0505	.150	1.32	6.0
"	"	1.55	.6	230	3.5	2971	1.00	.0337	.150	1.48	9.0
"	"	.40	.5	229	3.5	2971	.50	.0168	.150	2.48	18.0
"	"	0	.1	229	3.6	2957	0	0	.210		
4	2	6.00	1.2	230	3.6	2970	2.00	.0674	.210	1.49	6.3
"	"	3.40	1.0	230	3.6	2970	1.50	.0505	.210	1.65	8.4
"	"	1.55	.9	230	3.6	2970	1.00	.0337	.210	2.22	11.2
"	"	.40	.8	230	3.6	2960	.50	.0168	.210	3.96	25.2
"	"	0	.2	230	3.8	2940	0	0	.290		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
1	2¼	6.00	.4	228	3.45	2985	2.00	.0674	.130	.49	3.9
"	"	3.40	.4	228	3.45	2985	1.50	.0505	.130	.66	5.2
"	"	1.55	.3	229	3.45	2985	1.00	.0337	.130	.74	7.8
"	"	.40	.2	226	3.45	2985	.50	.0168	.130	.99	15.6
"	"	0	0	226	3.45	2971	0	0	.130		
2	2¼	6.00	.8	226	3.5	2965	2.00	.0674	.150	.99	4.5
"	"	3.40	.6	226	3.5	2965	1.50	.0505	.150	.99	6.0
"	"	1.55	.5	226	3.5	2965	1.00	.0337	.150	1.24	9.0
"	"	.40	.4	226	3.5	2965	.50	.0168	.150	1.98	18.0
"	"	0	0	226	3.6	2948	0	0	.210		
3	2¼	6.00	1.0	226	3.6	2960	2.00	.0674	.210	1.24	6.3
"	"	3.40	.8	226	3.6	2960	1.50	.0505	.210	1.32	8.4
"	"	1.55	.8	226	3.6	2960	1.00	.0337	.210	1.97	11.2
"	"	.40	.7	229	3.6	2960	.50	.0168	.210	3.48	25.2
"	"	0	.1	229	3.9	2928	0	0	.325		
4	2¼	6.00	1.3	230	3.7	2945	2.00	.0674	.250	1.61	7.5
"	"	3.40	1.2	230	3.7	2945	1.50	.0505	.250	1.98	10.0
"	"	1.55	1.1	230	3.7	2945	1.00	.0337	.250	2.72	15.0
"	"	.40	.9	230	3.8	2945	.50	.0168	.290	4.46	34.8
"	"	0	.2	230	4.2	2912	0	0	.415		
1	2⅛	6.00	.6	230	3.5	3013	2.00	.0674	.150	.74	4.5
"	"	3.40	.5	230	3.5	3013	1.50	.0505	.150	.82	6.0
"	"	1.55	.4	230	3.5	3013	1.00	.0337	.150	.99	9.0
"	"	.40	.3	230	3.5	3013	.50	.0168	.150	1.49	18.0
"	"	0	0	230	3.5	3005	0	0	.150		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	HP/VF
2	2½	6.00	1.0	230	3.6	3005	2.00	.0674	.210	1.24	6.3
"	"	3.40	.8	230	3.6	2996	1.50	.0505	.210	1.32	8.4
"	"	1.55	.6	230	3.6	2996	1.00	.0337	.210	1.48	11.2
"	"	.40	.4	230	3.6	2988	.50	.0168	.210	1.98	25.2
"	"	0	0	230	3.8	2964	0	0	.290		
3	2½	6.00	1.3	230	3.8	2970	2.00	.0674	.290	1.61	8.7
"	"	3.40	1.2	230	3.8	2970	1.50	.0505	.290	1.98	11.6
"	"	1.55	1.1	230	3.8	2970	1.00	.0337	.290	2.72	17.4
"	"	.40	.7	230	3.9	2960	.50	.0168	.325	3.48	39.0
"	"	0	.1	230	4.2	2937	0	0	.415		
4	2½	6.00	1.5	232	4.0	2957	2.00	.0674	.360	1.85	10.8
"	"	3.40	1.3	233	4.0	2957	1.50	.0505	.360	2.14	14.4
"	"	1.55	1.2	233	4.0	2957	1.00	.0337	.360	2.97	21.6
"	"	.40	1.0	234	4.1	2948	.50	.0168	.390	4.96	46.8
"	"	0	.3	230	4.5	2914	0	0	.485		
1	2¾	6.00	.9	234	3.5	2995	2.00	.0674	.150	1.11	4.5
"	"	3.40	.8	234	3.5	2995	1.50	.0505	.150	1.32	6.0
"	"	1.55	.7	234	3.5	2995	1.00	.0337	.150	1.73	9.0
"	"	.40	.5	234	3.5	2995	.50	.0168	.150	2.48	18.0
"	"	0	.1	234	3.6	2982	0	0	.210		
2	2¾	6.00	1.2	233	3.7	2972	2.00	.0674	.250	1.49	7.5
"	"	3.40	1.1	233	3.7	2972	1.50	.0505	.250	1.81	10.0
"	"	1.55	1.0	234	3.7	2972	1.00	.0337	.250	2.47	15.0
"	"	.40	.7	234	3.7	2972	.50	.0168	.250	3.48	30.0
"	"	0	.1	233	4.0	2950	0	0	.360		

TABLE IV (Continued)

RUN V (Continued)

Impellers No.	Length (")	Orif. ("Hg)	Hold up (")	Line Volt.	Curr. (amp)	Shaft r.p.m.	Air Rate (ft^3/min) 75°F, 1 atm	F (ft/sec)	Power Output (h.p.)	Average Cont. Time (sec/ft)	$\frac{HP}{VF}$
3	2¾	6.00	1.7	235	4.0	2956	2.00	.0674	.360	2.10	6.3
"	"	3.40	1.5	235	4.0	2956	1.50	.0505	.360	2.48	14.4
"	"	1.55	1.3	235	4.0	2956	1.00	.0337	.360	3.22	21.6
"	"	.40	.9	234	4.0	2940	.50	.0168	.360	4.46	43.2
"	"	0	.2	234	4.5	2910	0	0	.485		
4	2¾	6.00	2.0	232	4.3	2920	2.00	.0674	.440	2.48	13.2
"	"	3.40	1.7	232	4.3	2920	1.50	.0505	.440	2.80	17.6
"	"	1.55	1.4	233	4.3	2920	1.00	.0337	.440	3.46	26.4
"	"	.40	1.1	233	4.3	2910	.50	.0168	.440	5.46	52.8
"	"	0	.4	233	4.7	2881	0	0	.525		
1	3	6.00	.7	233	3.6	2981	2.00	.0674	.210	.86	6.3
"	"	3.40	.6	234	3.6	2981	1.50	.0505	.210	.99	8.4
"	"	1.55	.5	235	3.6	2981	1.00	.0337	.210	1.24	12.6
"	"	.40	.4	235	3.6	2981	.50	.0168	.210	1.98	25.2
"	"	0	0	233	3.6	2970	0	0	.210		
2	3	6.00	1.5	234	3.9	2955	2.00	.0674	.325	1.85	9.8
"	"	3.40	1.1	234	3.9	2955	1.50	.0505	.325	1.81	13.0
"	"	1.55	1.0	236	4.0	2955	1.00	.0337	.360	2.47	21.6
"	"	.40	.6	236	4.0	2955	.50	.0168	.360	2.98	43.2
"	"	0	.1	235	4.2	2935	0	0	.415		

TABLE IV (Continued)

Sample Calculations:

The mechanical transmission friction of the gas-liquid contactor had changed between the time that the ammeter was calibrated and the time that these above tests were made. No load tests were made to check this, and the ammeter reading corrections are listed below:

Drive Ratio	Approximate r. p. m.	Original Ammeter Rdg. (amperes)	Observed Ammeter Rdg. (amperes)	Correction (amperes)
Disconnected	1800	3.3	3.1	-.2
1.71	2900	3.4	3.25	-.15
2.56	4500	3.5	3.3	-.2
4.22	7500	3.95	3.6	-.35

These corrections are used on the ammeter readings of this data.

Take the next to the last row of figures in Run V as an example:

Cross sectional area of tank is measured to be .495 sq. feet

From the orifice calibration curve .40 "Hg gives .50 cu. ft. air per minute at 75°F and 1 atmosphere.

$$F = \frac{.50}{60 \times .495} = .0168 \text{ feet/second}$$

Power Output is read from the ammeter calibration curve with the correction mentioned above. In this case read 4.15 amps. for 4.0 amps.

TABLE IV (Continued)

Sample Calculations (Continued):

$$\theta = \frac{h}{F} = \frac{.6}{.495 \times .0168} = .298 \text{ seconds/foot}$$

$$\frac{HP}{VF} = \frac{.360}{.495 \times .0168} = 43.2 \text{ h.p./(cu.ft.)(ft./sec.)}$$

V. DISCUSSION OF RESULTS

The power requirement tests without the addition of air were used to test for turbulence of agitation. In order that this be done the functions, $\frac{HP}{N^3L^4S}$ and NL^2, were computed for each reading. NL^2 was used in place of the modified Reynolds number, $\frac{NL^2\rho}{\mu}$, because ρ and μ were constant in this work. $\frac{HP}{N^3L^4S}$ was plotted against NL^2 on log-log coordinates. This plot is shown in Graph 3. It will be noticed that the points form a line that has a slope of approximately negative unity, which is strong evidence that even at the high impeller speeds used, only pure viscous agitation was obtained. This is entirely possible, since the impellers were only .047 inches in diameter and were circular in cross section, thus approaching a streamlined shape. Another point to notice is that the power consumption per unit volume under these conditions was also much greater than that obtained with impellers moving at much lower speeds and with turbulence (1,5,6,7). Under ordinary conditions of low impeller speeds the consumed power has been found to be less than .1 h. p. per cubic foot, while in these tests it was of the order of one h. p. per cubic foot.

The data from the power requirement tests with the addition of air were used to compute the average contact time, θ, and the horse-power function, $\frac{HP}{VF}$. The average contact time was then plotted against the horse-power function on log-log coordinates for a constant number of impellers and impeller length. Four illustrations of these plots are shown in Graphs 4 to 7. The equation constants, C and n, were measured in each case and are listed in Table V. These plots gave a means of comparison of the performance of the high speed equipment used in this work with that of equipment operated at ordinary speeds less than 1000 r. p. m. The slope, n, of these plots stayed essentially .5, but the value of the intercept, C, varied both with impeller length and number of impellers. This intercept, C, should be a measure of how economically the equipment operates with respect to power required for given contact time. The value of C varied from .28 to .80 and compared poorly with values of C obtained Rushton, Mack, and Foust (5) using turbulent agitation at ordinary speeds. Their value of C was approximately 1.5, which meant that it took ten times as much power with the high speed equipment for a given average contact time.

An attempt was made to correlate the variation of C with the other variables. However, the values of C were rather inaccurate in this work, since extrapolation was required to obtain them. Consequently it was decided that the values of θ where $\frac{HP}{VF}$ is equal to ten instead of unity

TABLE V

EQUATION CONSTANTS FOR THE RELATION BETWEEN AVERAGE CONTACT TIME, Θ, AND HORSE-POWER FUNCTION, $\frac{HP}{VF}$

Impeller Length (inches)	1 impeller			2 impellers			3 impellers			4 impellers		
	I*	C	n	I	C	n	I	C	n	I	C	n
$1\frac{1}{4}$	1.85	.62	.48	1.82	.76	.38	1.86	.75	.39	1.82	.60	.48
$1\frac{1}{2}$	1.25	.47	.45	1.42	.36	.60	1.63	.60	.43	1.80	.70	.41
$1\frac{3}{4}$	1.05	.28	.59	1.40	.42	.52	1.75	.57	.49	2.08	.50	.62
2	.97	.31	.51	1.42	.40	.55	1.59	.33	.69	1.37	.56	.53
$2\frac{1}{4}$	1.03	.30	.55	1.60	.37	.63	1.78	.48	.57	1.93	.52	.57
$2\frac{1}{2}$	1.27	.36	.55	1.66	.62	.43	1.72	.46	.58	1.72	.56	.50
$2\frac{3}{4}$	1.70	.50	.54	1.76	.43	.61	2.25	.80	.45	2.12	.58	.56
3	1.25	.33	.56	1.73	.71	.39						

*I is the value of Θ when $\frac{HP}{VF}$ equals ten.

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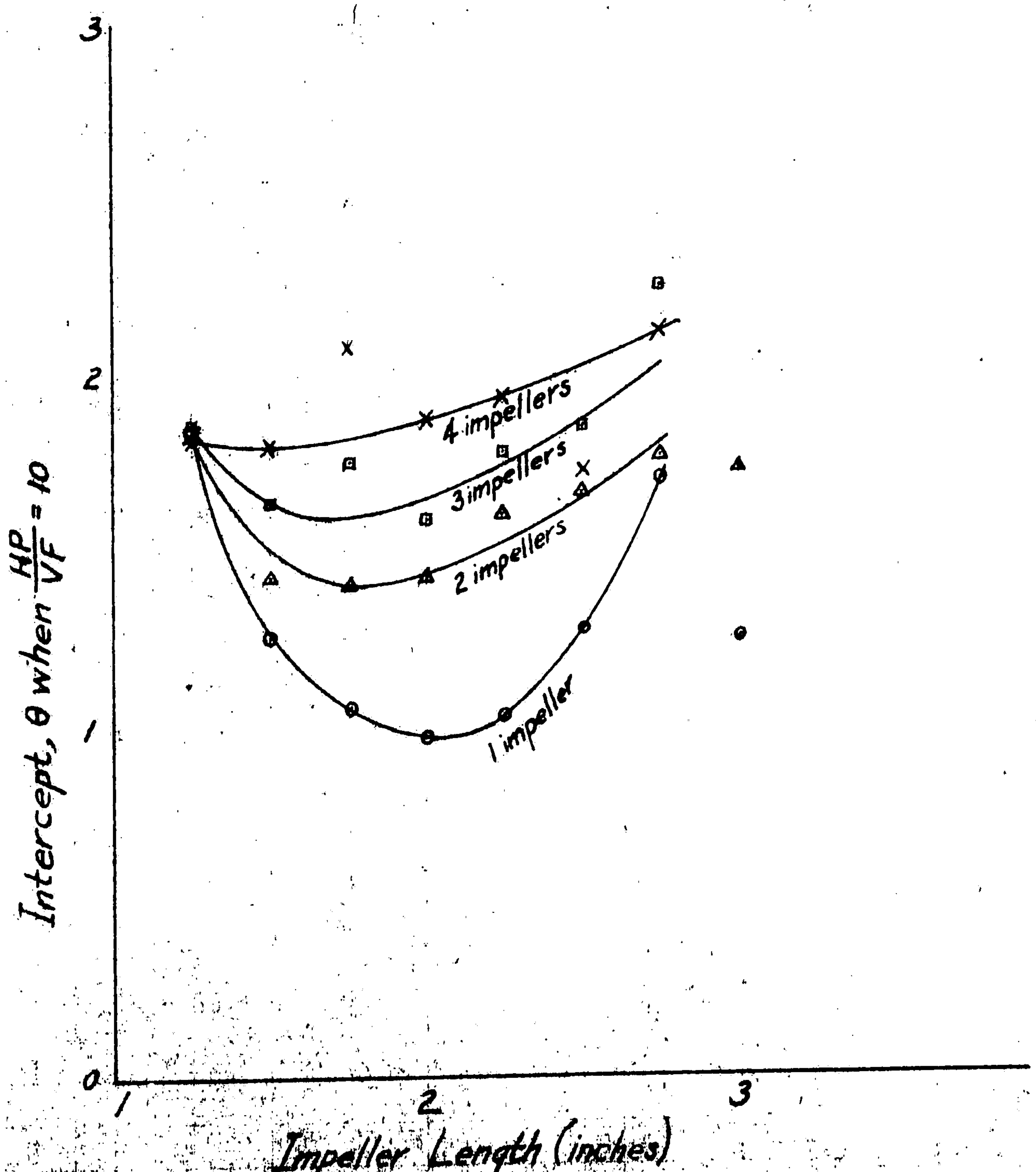
Graph 8. Intercept, Average Contact Time, θ, when Horse-power Function = 10, vs. Impeller Length



should be used, since no extrapolation would be necessary with this intercept. When this was done, an interesting result was obtained. These intercepts were found to pass through a minimum as the impeller lengths increased. In other words, the power consumed for a given contact time passed through a minimum. No explanation has been found for this. In Graph 8 this intercept has been plotted against impeller length keeping the number of impellers constant. With one impeller an almost perfect parabola is formed, but with each succeeding number the effect becomes less and less until, finally, with four impellers it is hardly noticeable.

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VI CONCLUSIONS

The principal fact to be derived from this work is that gas-liquid contacting with high speed thin impellers, as carried out under the conditions of the above experiments, does not compare favorably with that carried out under the more conventional conditions of larger impellers and speeds less than 1000 r. p. m. This work has shown that mere impeller speed is not enough to break up the gas bubbles and increase contact time, but that turbulence is required, and since the impellers used herein caused only viscous agitation, they did not show good performance. Such findings suggest that the search for more efficient gas-liquid contacting be made at lower impeller speeds.

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