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MIXING CHARACTERIZATION IN A SLAB TANK (U)

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ABSTRACT

Due to safety requirements, slab tanks are often used to process and purify radioactive materials. The configuration is that of a slit or a tank of rectangular cross section with very low aspect ratio. Due to its nonconventional geometry, very little is known about the slab tank mixing environment. To better understand it, experiments have been performed in a full scale standard configuration equipped with two stirrer shafts, each containing several axial impellers.

To characterize the velocity field, mean and RMS turbulent velocities have been measured at several impeller speeds with a two-component Laser Doppler Anemometer (LDA). The LDA data have been supplemented with flow visualization, circulation time, and mixing time studies. Since the slab tank is often used as a precipitator, solids suspension studies have also been performed.

The results of the various experiments will be presented and will be interpreted to elucidate slab tank dynamics. The implication to mixing efficiency will also be discussed.

*This article was prepared in connection with work done under Contract No. DE-AC09-76SR00001 (now Contract No. DE-AC09-88SR18035) with the U. S. Department of Energy.

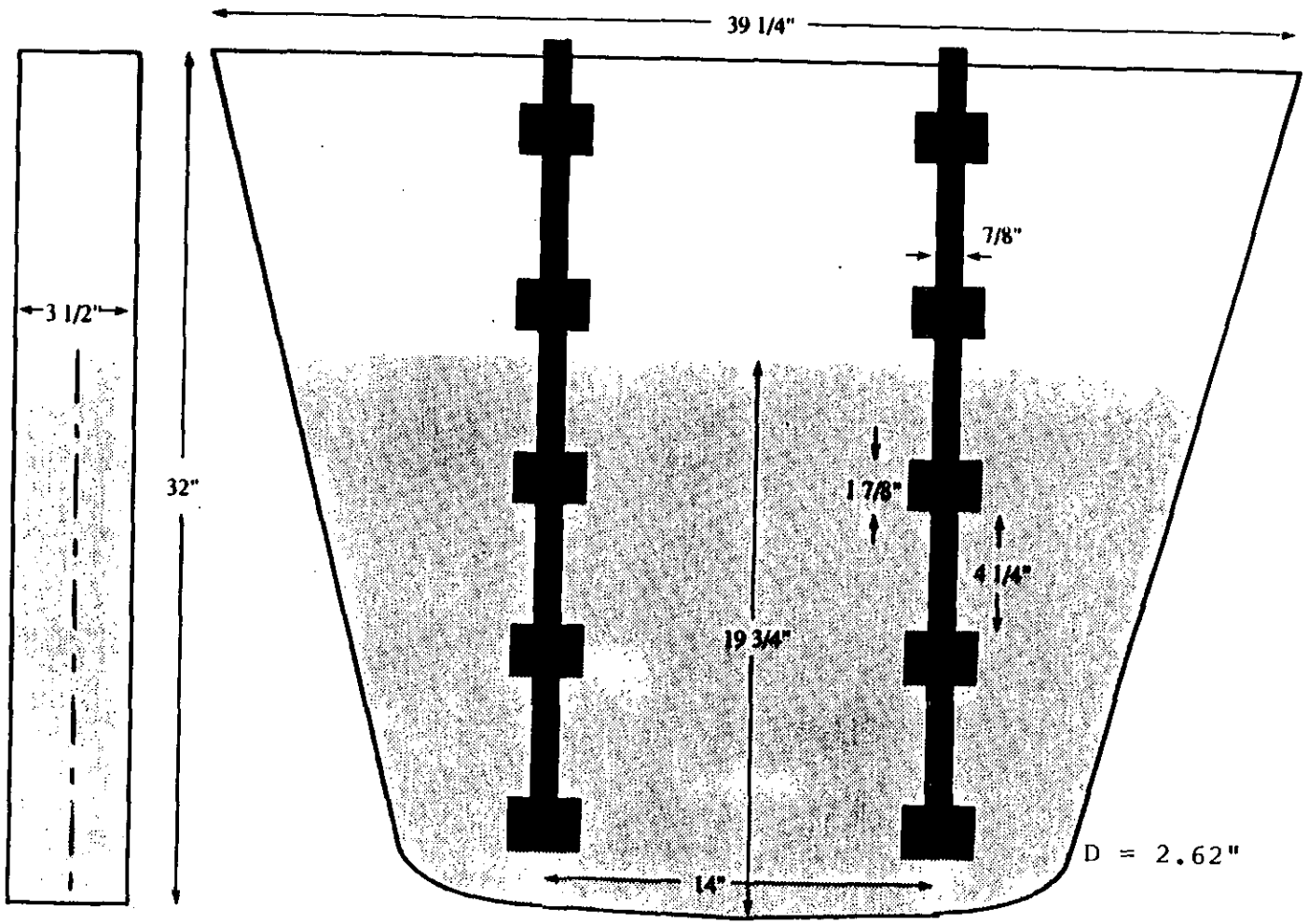
Objectives

Measure the 2 dimensional velocity field along the center plane for the standard slab tank geometry via LDA

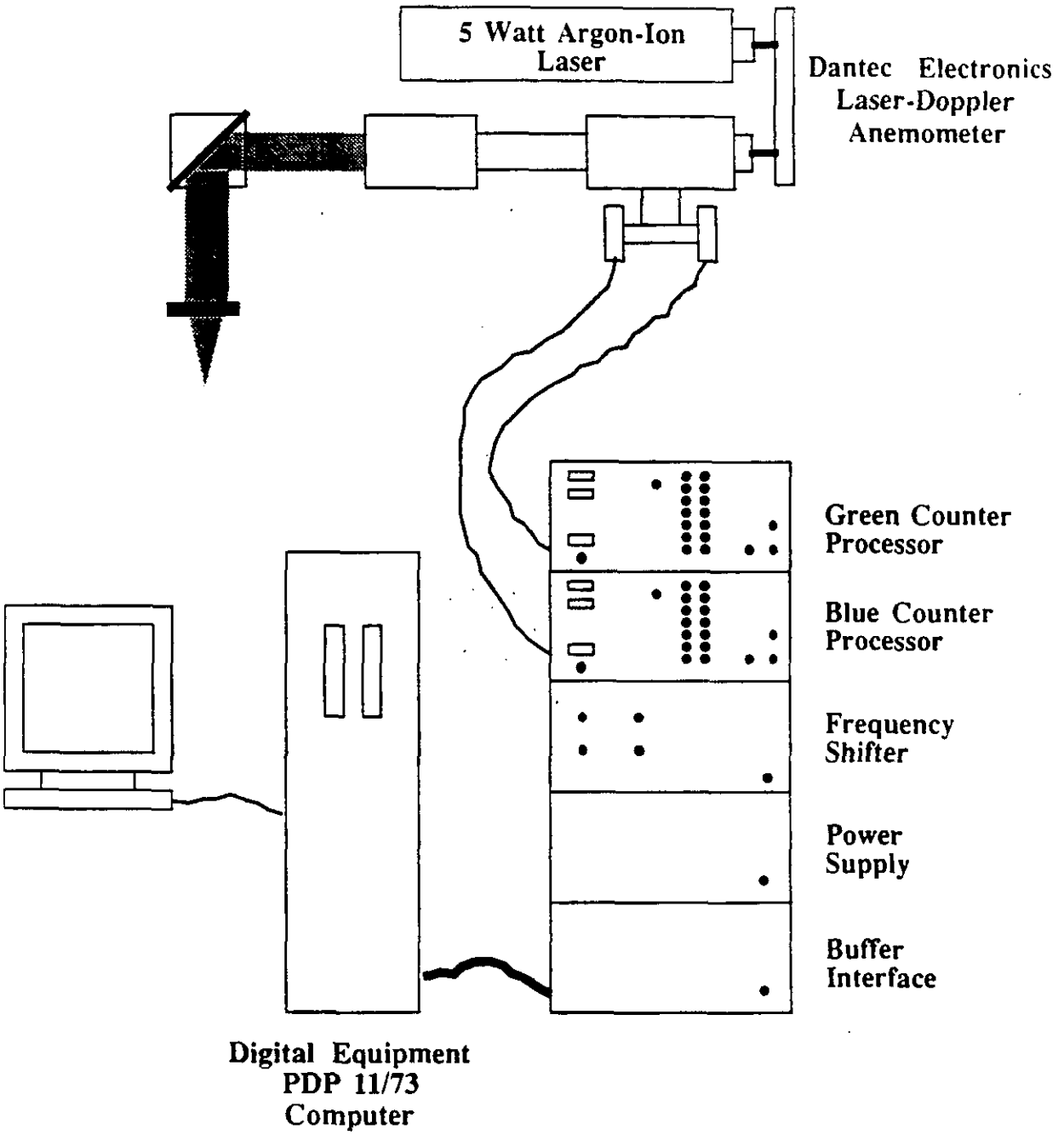
Determine if the velocity field scales on impeller tip speed

Assess suitability of current geometry for solid suspension

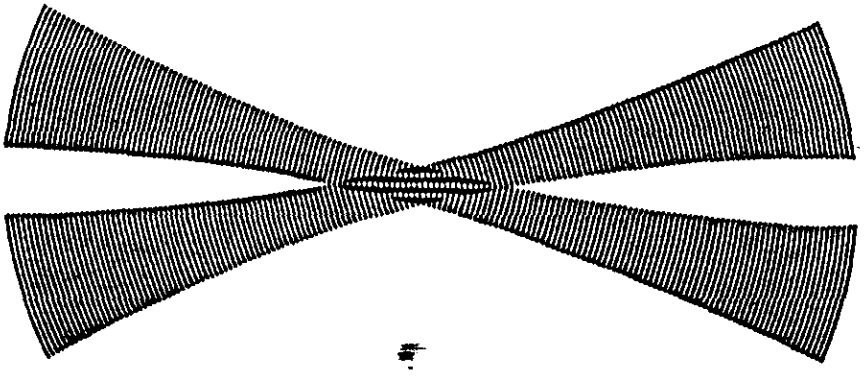
Gain insight into maximum hydrodynamical forces by measuring the velocity field close to and relative to the rotating blade



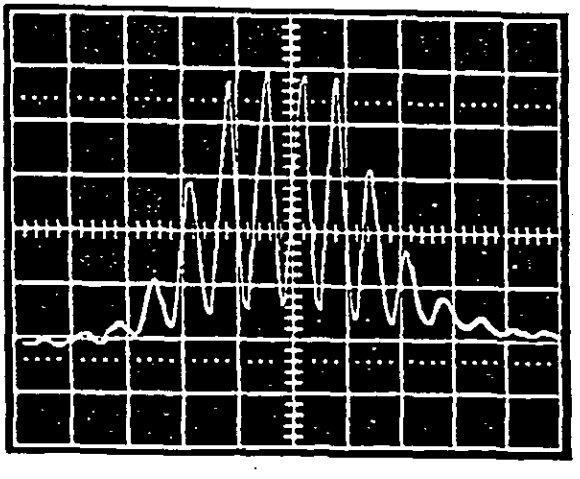
DuPont Slab Tank


5 Watt Argon-Ion Laser
Dantec Electronics Laser-Doppler Anemometer
Green Counter Processor
Blue Counter Processor
Frequency Shifter
Power Supply
Buffer Interface
Digital Equipment PDP 11/73 Computer

Laser-Doppler Anemometry Facility

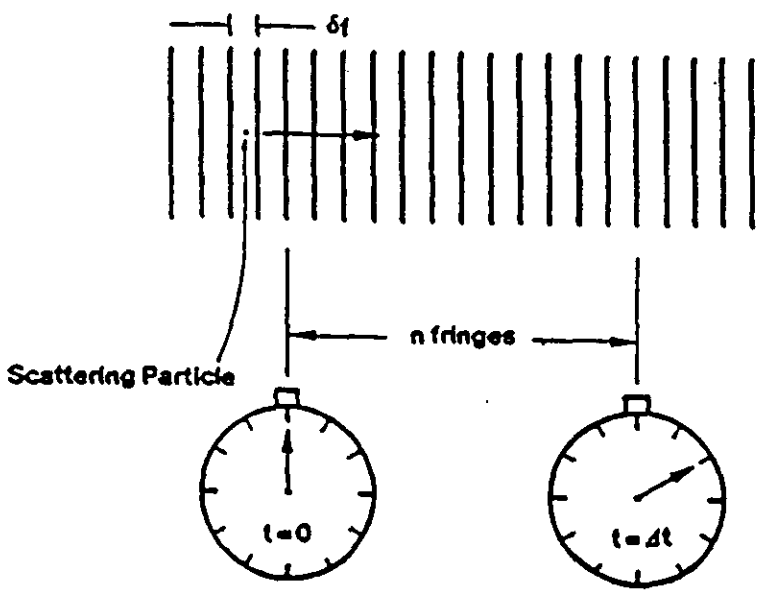


Representation of the beam intersection area.



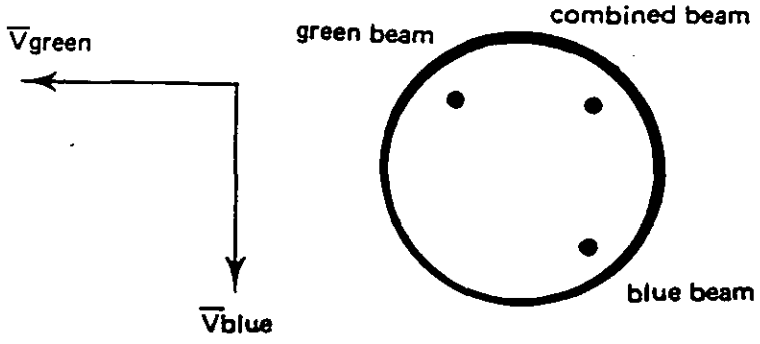
Oscilloscope trace of photo-multiplier tube ouput.

Laser-Doppler Anemometry Facility

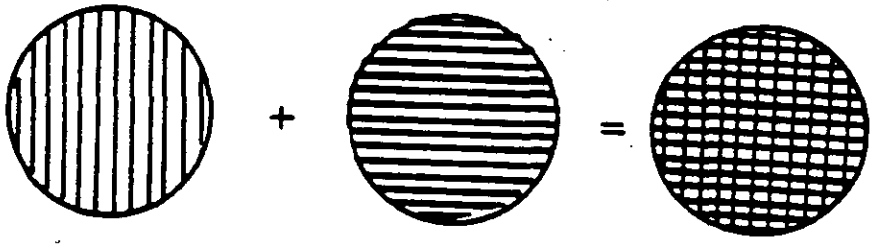


Particle velocity $v = \frac{n}{\Delta t} \cdot \delta f$

Laser-Doppler Anemometry Facility



Beam configuration leaving the front optics.



Orthogonal fringe systems formed in two color LDA.

Directly Measured Quantities
(163, 249, and 351 RPM)

$$v_i = \bar{v}_i + v_i'$$

Number of Realizations > 3000

Mean Velocity : $\bar{v}_x, \bar{v}_z$

$$\bar{v}_i = \frac{1}{N} \sum_j v_{ij}$$

RMS Turbulent Velocity : $\sqrt{\overline{v_x'^2}}, \sqrt{\overline{v_z'^2}}$

$$\overline{v_i'^2} = \frac{1}{N} \sum_j (v_{ij} - \bar{v}_i)^2$$

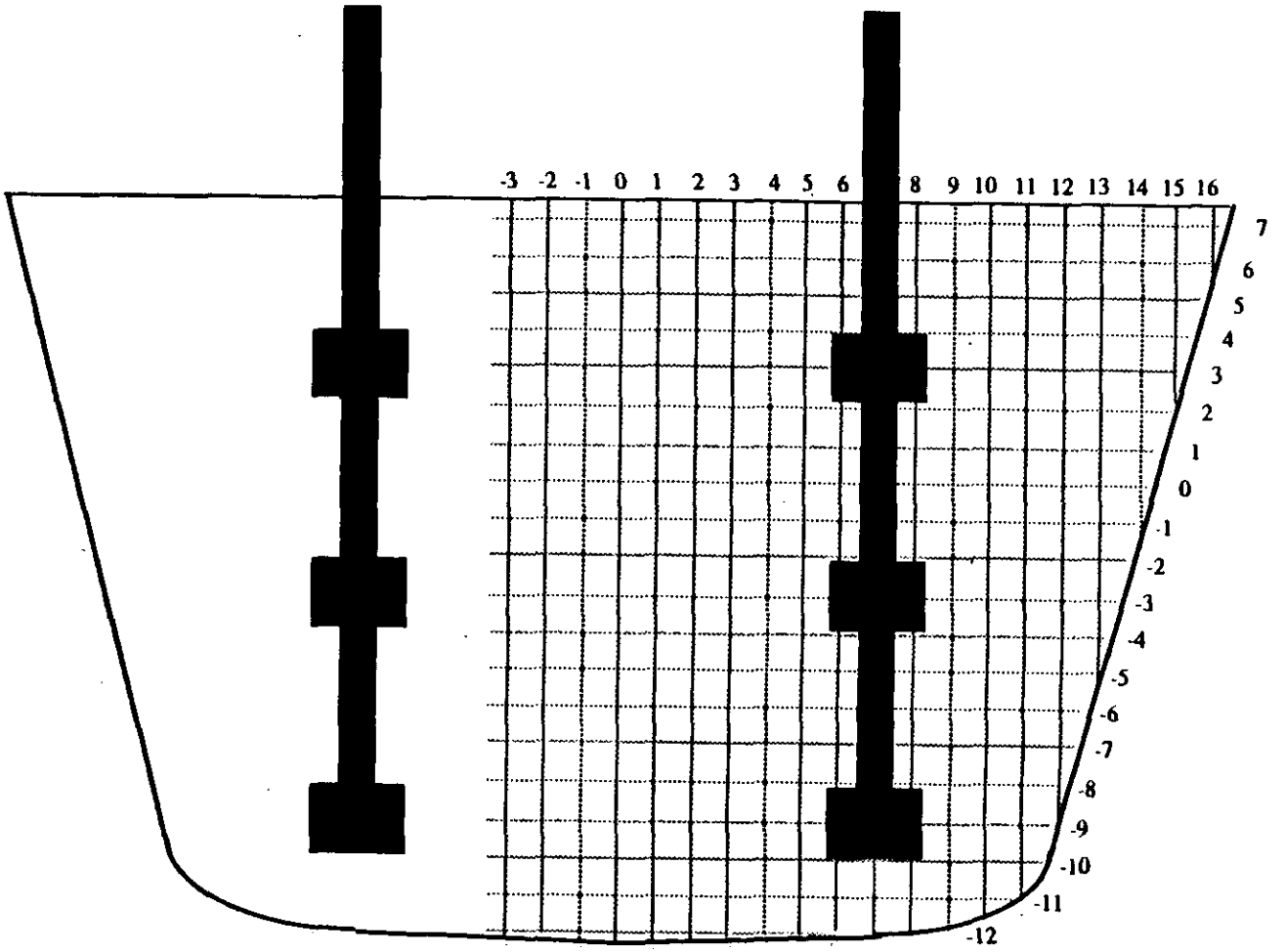
Derived Quantities

Magnitude and Direction of Mean Velocity Vector

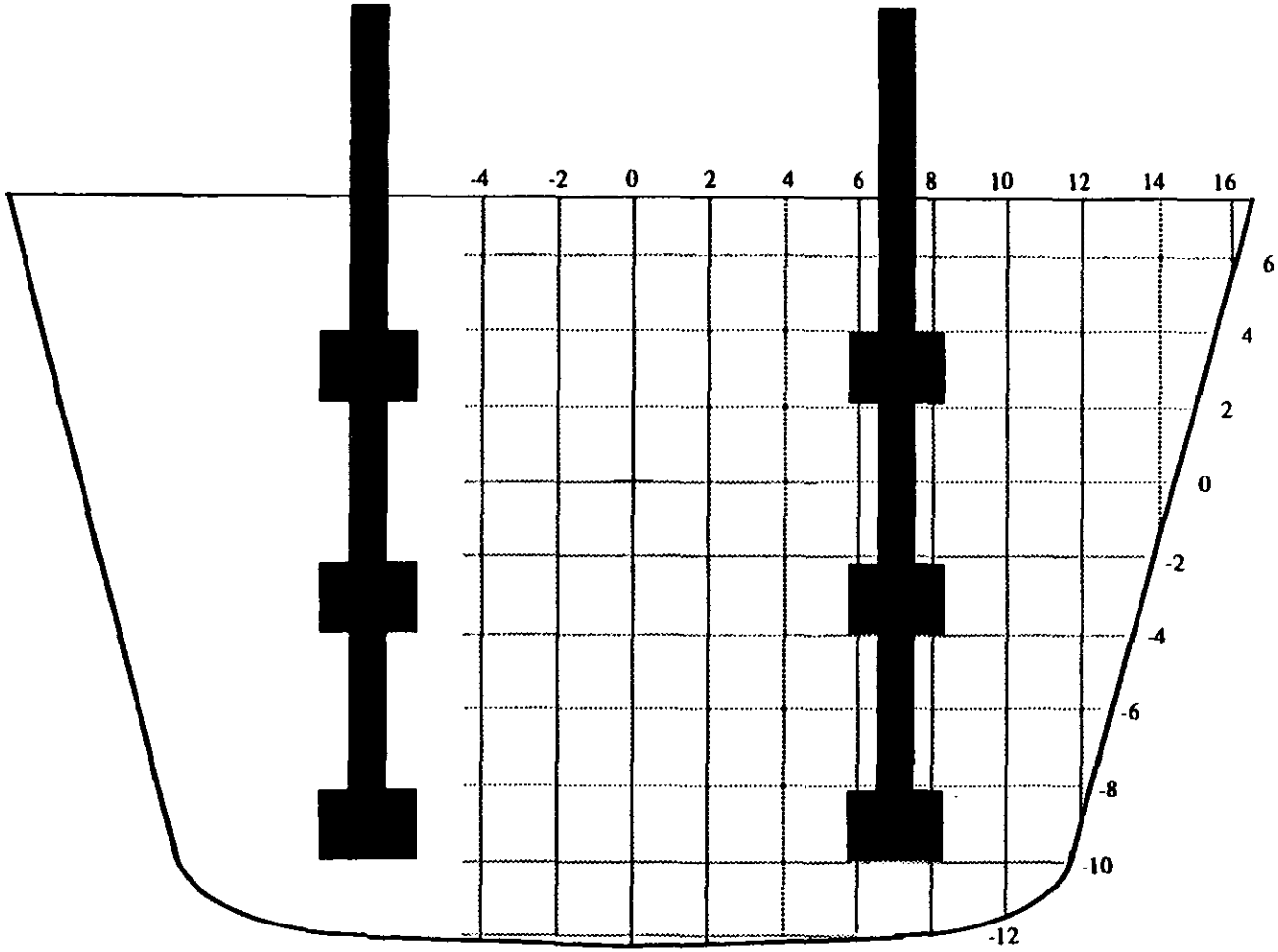
$$V = \left[\bar{v}_x^2 + \bar{v}_z^2\right]^{1/2}$$

Magnitude of RMS Turbulent Velocity

$$q = \left[\overline{v_x'^2} + \overline{v_z'^2}\right]^{1/2}$$



DuPont Slab Tank



DuPont Slab Tank

Mean Horizontal Velocity Component, m/s
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	-0.0668	-0.0849	-0.0668	0.0683	0.0790	0.0688	-0.0175	-0.0580	-0.0540	-0.0151
4	-0.1023	-0.0718	-0.0260	0.0115	0.0723	0.1422	-0.0755	-0.0764	-0.0871	-0.0388
2	-0.1296	-0.1285	-0.0801	0.0271	0.0940			-0.1113	-0.0835	-0.0081
0	-0.1261	-0.1084	-0.1303	-0.0582	0.0563	0.0541	-0.0746	-0.0347	-0.0310	-0.0776
-2	-0.0879	-0.1306	-0.1041	-0.0118	0.0439	-0.0764	0.0188	-0.0158	0.0490	
-4	0.0836	-0.0555	-0.0824	-0.1007	-0.0626	-0.0716	0.2633	0.1016	-0.2091	
-6	0.0893	-0.0520	-0.0635	-0.0668	-0.0440	0.0013	-0.0885	0.0928	0.0358	
-8	-0.0770	-0.0792	-0.0280	-0.0615	0.0225	0.1366	-0.0987	-0.0602		
-10	0.0409	-0.0230	-0.0013	-0.0787	-0.0110	-0.0835	0.0672	0.0162		
-12	0.1391	0.1092	0.0002	-0.0887	-0.0831					

Mean Vertical Velocity Component, m/s
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	0.0549	0.0678	0.0231	0.0840	0.0251	-0.0262	-0.0568	0.0062	0.0518	0.0481
4	0.0773	0.1147	0.1069	0.0397	-0.0206	-0.0977	-0.0855	0.0103	0.0717	0.0552
2	0.0954	0.1457	0.1354	0.1204	-0.0111			-0.0273	0.1145	0.1574
0	0.0821	0.2582	0.1960	0.1077	-0.0367	-0.3825	-0.4342	-0.0270	0.2179	0.1347
-2	0.0886	0.2593	0.2605	0.2419	-0.0063	-0.3950	-0.2325	-0.0350	0.3105	
-4	-0.0270	0.2456	0.2436	0.1790	-0.0728	0.0636	-0.2538	-0.0252	-0.0198	
-6	-0.0634	0.1538	0.1960	0.1542	-0.0518	0.0231	0.0620	-0.0735	0.1754	
-8	0.0260	0.1252	0.1824	0.0897	-0.0222	-0.1481	-0.1514	0.0230		
-10	-0.0203	0.0752	0.1579	0.0674	0.0107	0.0503	-0.1503	0.0698		
-12	0.0364	0.0136	0.0255	0.0722	0.0534					

SQRT(U~2 + V~2), m/s
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	0.0865	0.1086	0.0707	0.1082	0.0829	0.0736	0.0872	0.0589	0.0898	0.0572
4	0.1282	0.1353	0.1100	0.0413	0.0751	0.1726	0.4407	0.0811	0.1439	0.1621
2	0.1609	0.1943	0.1573	0.1234	0.0946			0.1145	0.2334	0.1349
0	0.1505	0.2800	0.2354	0.1224	0.0672	0.3863	0.2442	0.0493	0.3120	0.0776
-2	0.1248	0.2903	0.2805	0.2422	0.0444	0.4023	0.2545	0.0297	0.0528	
-4	0.0878	0.2518	0.2571	0.2054	0.0960	0.0957	0.2705	0.1254	0.2729	
-6	0.1095	0.1624	0.2060	0.1680	0.0679	0.0231	0.1754	0.0956	0.0599	
-8	0.0813	0.1481	0.1845	0.1087	0.0316	0.2000	0.1798	0.0922		
-10	0.0456	0.0787	0.1579	0.1036	0.0154	0.0974	0.0675	0.0542		
-12	0.1438	0.1100	0.0255	0.1144	0.0987					

RMS Horizontal Velocity Component / Tip Speed
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	0.2464	0.2641	0.3076		0.3169	0.2278	0.2189	0.2092	0.2068	0.1945
4	0.2445	0.2704	0.3275		2.7709	0.2770	0.4178	0.2453	0.2084	0.2287
2		0.2777	0.3428	0.3564	0.3012			0.2423	0.2326	0.2368
0		0.3035	0.3690	0.3782	0.3103	0.5080	0.3995	0.2922	0.2704	0.3645
-2		0.3446	2.9137	0.3517	0.3524	0.3572	0.4495	0.2876	0.2998	
-4	0.3362	0.3800	0.3630		0.3470	0.2598	0.4189	0.2737	0.3738	
-6		0.3403	0.3320	0.3288	0.3965	0.3552	0.3052	0.3391	0.3583	
-8	0.3014	0.2897	0.3114	0.3313	0.3510	0.3435	0.4009	0.3129		
-10		0.3358		0.3108	0.3078	0.2616	0.4480	0.3234		
-12	0.3421	0.3470		0.2873						

RMS Vertical Velocity Component / Tip Speed
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	0.2466	0.2706	0.3047		0.3041	0.2337	0.2002	0.2069	0.2185	0.2200
4	0.2545	0.2542	0.3070		0.3257	0.2641	0.4073	0.2470	0.2364	0.2498
2		0.2690	0.3218	0.3363	0.3152			0.2632	0.2495	0.2602
0		0.2125	0.3347	0.3645	0.3132	0.3667	0.2006	0.3022	0.2334	0.3447
-2		0.2661	0.3117	0.2550	0.3463	0.1000	0.3985	0.2967	0.1402	
-4	0.3355	0.2962	0.3021		0.3480	0.2604	0.4201	0.3109	0.3968	
-6		0.3062	0.2806	0.2955	0.3862	0.3530	0.3372	0.3493	0.3051	
-8	0.3078	2.9360	0.2652	0.3175	0.3417	0.3221	0.3841	0.3174		
-10		0.3180		0.3025	0.3073	0.2930	0.4547	0.3230		
-12	0.3219	0.3487		0.2709						

SQRT(u~2 + v~2 / Tip Speed
351 RPM

Y/X	-4	-2	0	2	4	6	8	10	12	14
6	0.3487	0.3781	0.4330		0.4393	0.3263	0.2968	0.2942	0.3008	0.2936
4	0.3530	0.3711	0.4489		2.7900	0.3827	0.5835	0.3481	0.3152	0.3385
2		0.3867	0.4700	0.4900	0.4359			0.3578	0.3411	0.3518
0		0.3705	0.4981	0.5252	0.4409	0.6265	0.4470	0.4203	0.3572	0.5017
-2		0.4354	2.9303	0.4345	0.4941	0.3709	0.6007	0.4132	0.3309	
-4	0.4750	0.4818	0.4723		0.4914	0.3679	0.5933	0.4142	0.5451	
-6		0.4578	0.4347	0.4421	0.5535	0.5007	0.4548	0.4868	0.4706	
-8	0.4308	2.9503	0.4090	0.4589	0.4898	0.4709	0.5552	0.4457		
-10		0.4624		0.4337	0.4349	0.3927	0.6383	0.4570		
-12	0.4698	0.4920		0.3949						

Mean Horizontal Velocity Component, m/s
249 RPM

Y/X	-3	-2	-1	0	1	2	3	4	5	6
7	-0.0496	-0.0273	0.0058	0.0260	0.0368	0.0648	0.0817	0.0326	0.0831	0.0694
6	-0.0362	-0.0465	0.0062		0.0436	-0.0312	0.1008	0.0870	0.0975	0.0643
5	-0.0479	-0.0136	-0.0224	-0.0355	0.0677	0.0850	0.0882	0.0724	0.0847	0.0792
4	-0.0598	-0.0304	0.0090	-0.0004	0.0336	0.0965	0.1014	0.0316	0.1271	0.1470
3	-0.0782	-0.0364	-0.0911	-0.0017	0.0503	0.0535	0.1032	0.0552	0.0699	
2	-0.0908	-0.0797	-0.0624	-0.0463	0.0624	-0.0110	0.0771	0.0466	0.0568	
1	-0.1098	-0.1015	-0.1090	-0.0665	0.0230	0.0444	0.0598	0.0565	0.0477	-0.0189
0	-0.0838	-0.0405	-0.0744	-0.1209	-0.0004	-0.1308	0.0525	0.0177	0.0387	-0.0059
-1	-0.1330	-0.0514	-0.0201	-0.0814	-0.1021	-0.0160	-0.0421	0.0099	0.0450	-0.0043
-2	-0.0736	-0.0225	-0.1224	-0.0831	-0.0115	-0.0254	-0.0298	-0.0028	0.0326	0.0451
-3	-0.0302	0.0020	-0.0465	-0.0590	-0.0275	-0.0943	-0.0507	-0.0185	0.0134	
-4	0.0353	0.0319	-0.0228	-0.0110	-0.0398	-0.0422	-0.0895	-0.0518	0.0715	-0.1372
-5	0.0499	-0.0045	0.0053	-0.0841	-0.1328	-0.0718	-0.0365	-0.0007	-0.0646	-0.0027
-6	0.0086	0.0216	0.0157	-0.0626	-0.0856	-0.0124	-0.0432	0.0383	0.0079	0.0811
-7	-0.0284	-0.0126	0.0076	-0.0238	-0.1020	-0.0056	0.0132	0.0324	0.0948	0.0999
-8	-0.0425	-0.0637	0.0147	-0.0052	0.0189	0.0189	-0.0469	0.0352	0.0837	0.1324
-9	-0.0068	0.0220	0.0280	0.0238	0.0224	0.0102	0.0113	0.0648	0.0677	
-10	0.0688	0.0653	0.0401	0.0359	0.0250	-0.0264	-0.0562	-0.0116	0.0344	-0.1099
-11	0.0665	0.0196	0.0648	0.0819	0.0298	-0.0195	-0.0749	-0.1401	-0.1184	-0.0047
-11.5	0.0829	0.1081	0.0896	0.0475	-0.0230	-0.0412	-0.0719	-0.0504	-0.0252	-0.0892
-12	0.0833	0.1341	0.1011	0.0632	-0.0217	-0.0705	-0.0796	-0.0622	-0.0257	0.0266

Y/X	7	8	9	10	10.5	11	11.25	11.75	12	12.25
7		-0.0075	-0.0375	-0.0408		-0.0349			-0.0183	
6		0.0052	-0.0246	-0.0337		-0.0401			-0.0370	
5		-0.0111	-0.0370	-0.0282		-0.0489			-0.0383	
4		-0.0799	-0.0625	-0.0691		-0.0663			-0.0562	
3			-0.0310	-0.0773		-0.0628			-0.0630	
2			-0.0500	-0.0356		-0.0708			-0.0685	
1		0.0359	0.0609	-0.0912		-0.0769			-0.0545	
0		-0.0255	-0.0025	-0.0067		-0.0664			-0.0469	
-1		-0.0196	-0.0449	-0.0561		-0.0428			-0.0066	
-2		0.1991	-0.0326	0.0043		-0.0288			0.0202	
-3			-0.0033	0.0304		0.0402			0.0231	
-4		0.1938	0.0509	0.0517		0.0792			0.0820	
-5		0.0422	0.1603	0.1284		0.0933			0.0984	
-6		-0.0135	-0.0010	0.0755		0.0933			0.0699	
-7		-0.0453	-0.0151	0.0187		0.0081			0.0138	
-7.5										-0.0324
-8		-0.0827	-0.0765	-0.0302		-0.0220				
-8.5								0.0275		
-9			-0.0687	-0.0581		-0.0104				
-9.5							0.0672			
-10		0.1527	0.0351	-0.0006		0.0652				
-10.5					0.1580					
-11	-0.0042	-0.0211	0.1357	0.1912						
-11.25			0.0578							
-11.5	-0.0501	-0.0358								

Y/X	12.5	12.75	13	13.25	13.5	13.75	14	14.25	14.5	14.75
7			0.0024				0.0236			
6			-0.0229				-0.0093			
5			-0.0215				-0.0219			
4			-0.0345				-0.0257			
3			-0.0411				-0.0504			
2.5										0.0065
2			-0.0356				-0.0340			
1.5									0.0080	
1			-0.0867				-0.0192			
0.5								0.0088		
0			-0.0975							
-0.5							0.0023			
-1			0.0361							
-1.5						0.0329				
-2			0.0335							
-2.5					0.0060					
-3			0.0589							
-3.5				-0.0438						
-4.5			-0.0035							
-5.5		0.0556								
-6.5	0.0179									

Y/X	15
7	-0.0033
6	0.0043
5	0.0058
4	-0.0016

Data Tables
(163, 249, 351 Rpm)

ABSOLUTE QUANTITIES*

Mean Horizontal Velocity
Mean Vertical Velocity
Magnitude of Mean Velocity

Horizontal RMS Turbulent Velocity
Vertical RMS Turbulent Velocity
Magnitude of RMS Turbulent Velocity

*163 and 351 RPM - Course Grid Tables only
249 RPM - Both Course and Fine Grid Tables

NORMALIZED QUANTITIES

All tables for absolute quantities repeated with data normalized by tip speed

Tip Speed $V_T = \Pi DN$

General Trends

Mean Velocities

Horizontal	< 10% of Tip Speed
Vertical	< 30% of Tip Speed
Magnitude	< 30% of Tip Speed

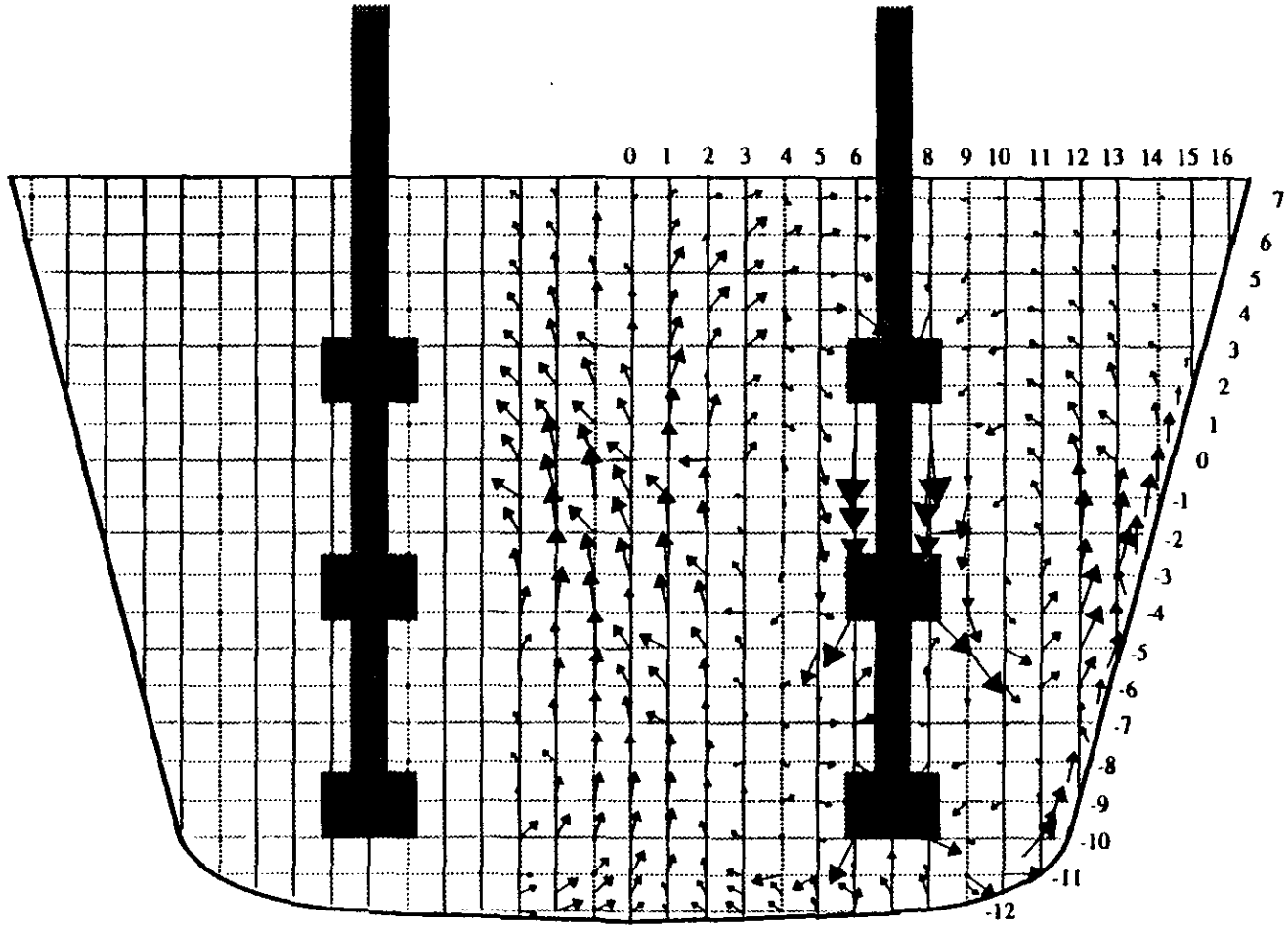
RMS Turbulent Velocities

Horizontal	20% to 60% of Tip Speed
Vertical	20% to 60% of Tip Speed
Magnitude	up to 70% of Tip Speed

RMS Turbulent Velocities are relatively uniform throughout the tank and are generally larger in magnitude than the mean velocity.

Normalized Mean Velocity Vectors

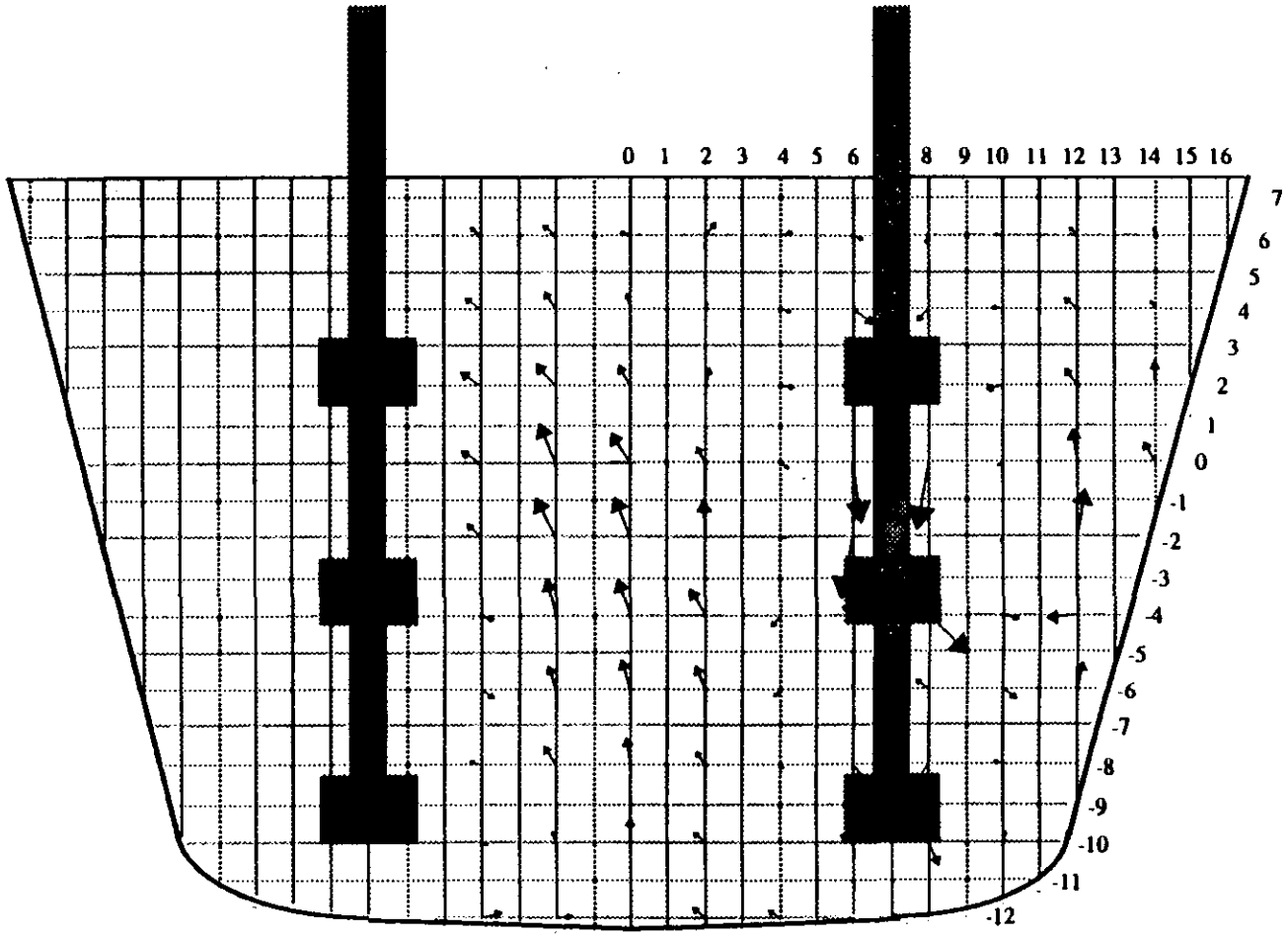
249 RPM V_T = 0.868 m/s



DuPont Slab Tank

Normalized Mean Velocity Vectors

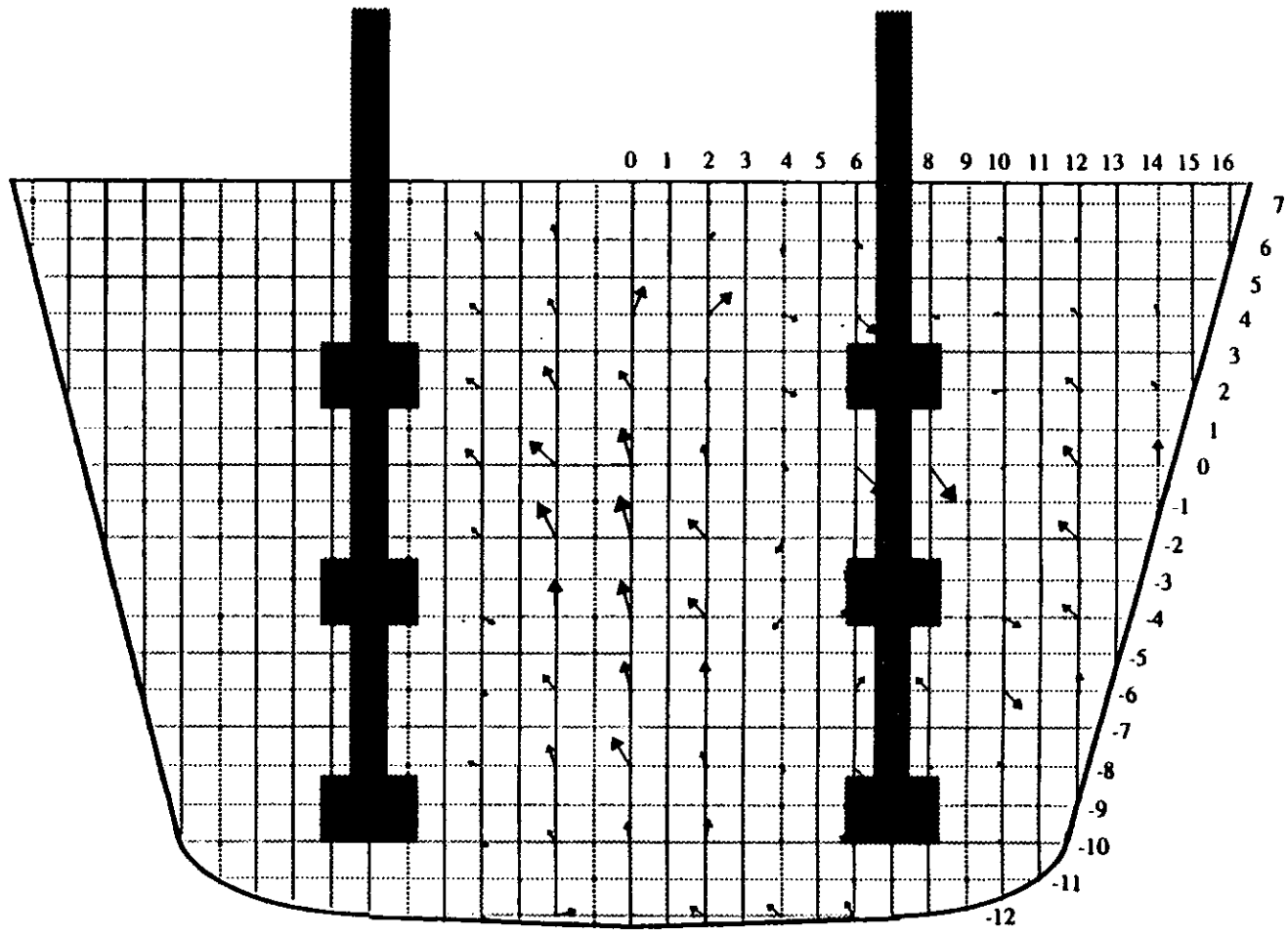
351 RPM V_T = 1.22 m/s



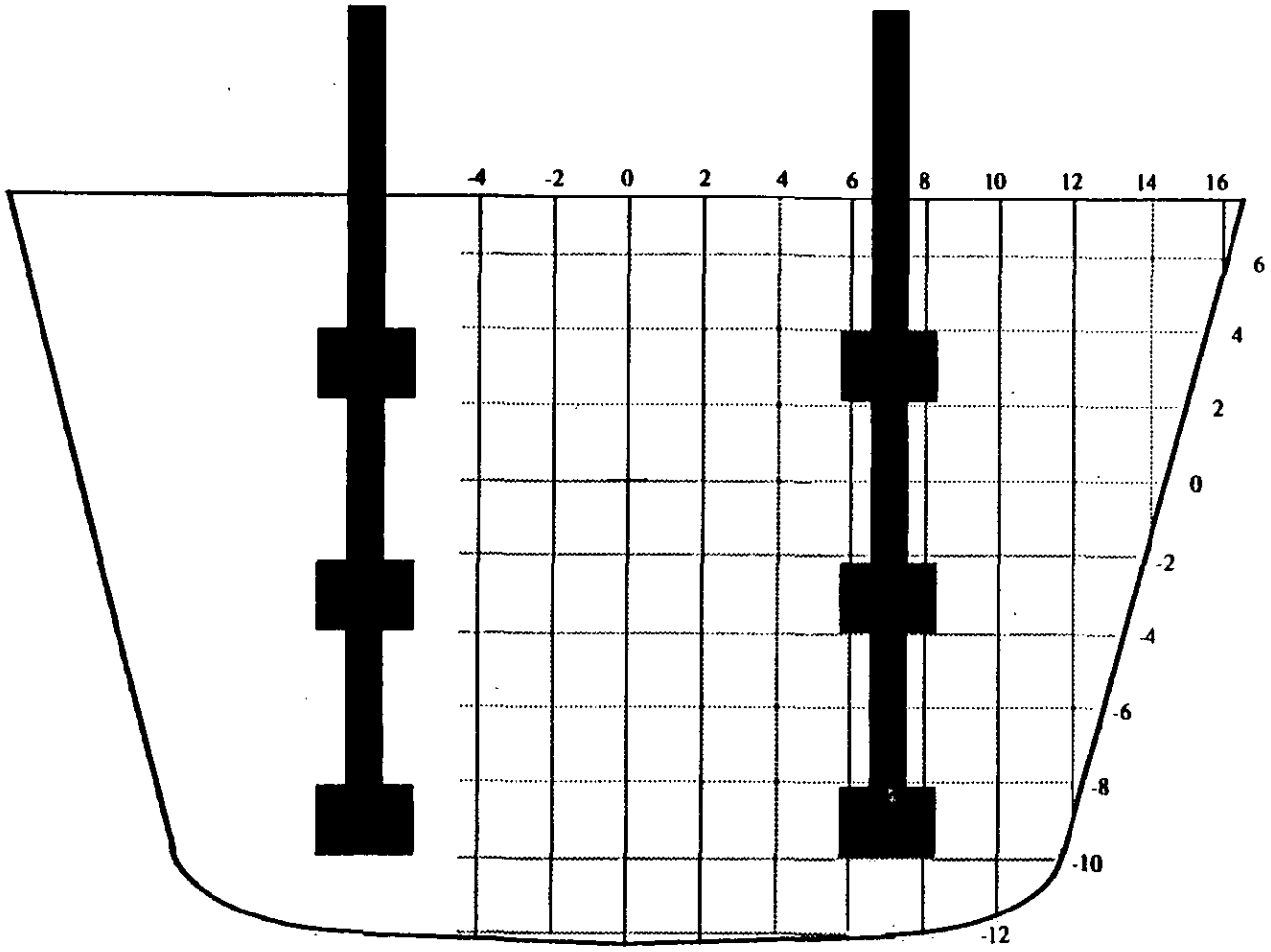
DuPont Slab Tank

Normalized Mean Velocity Vectors

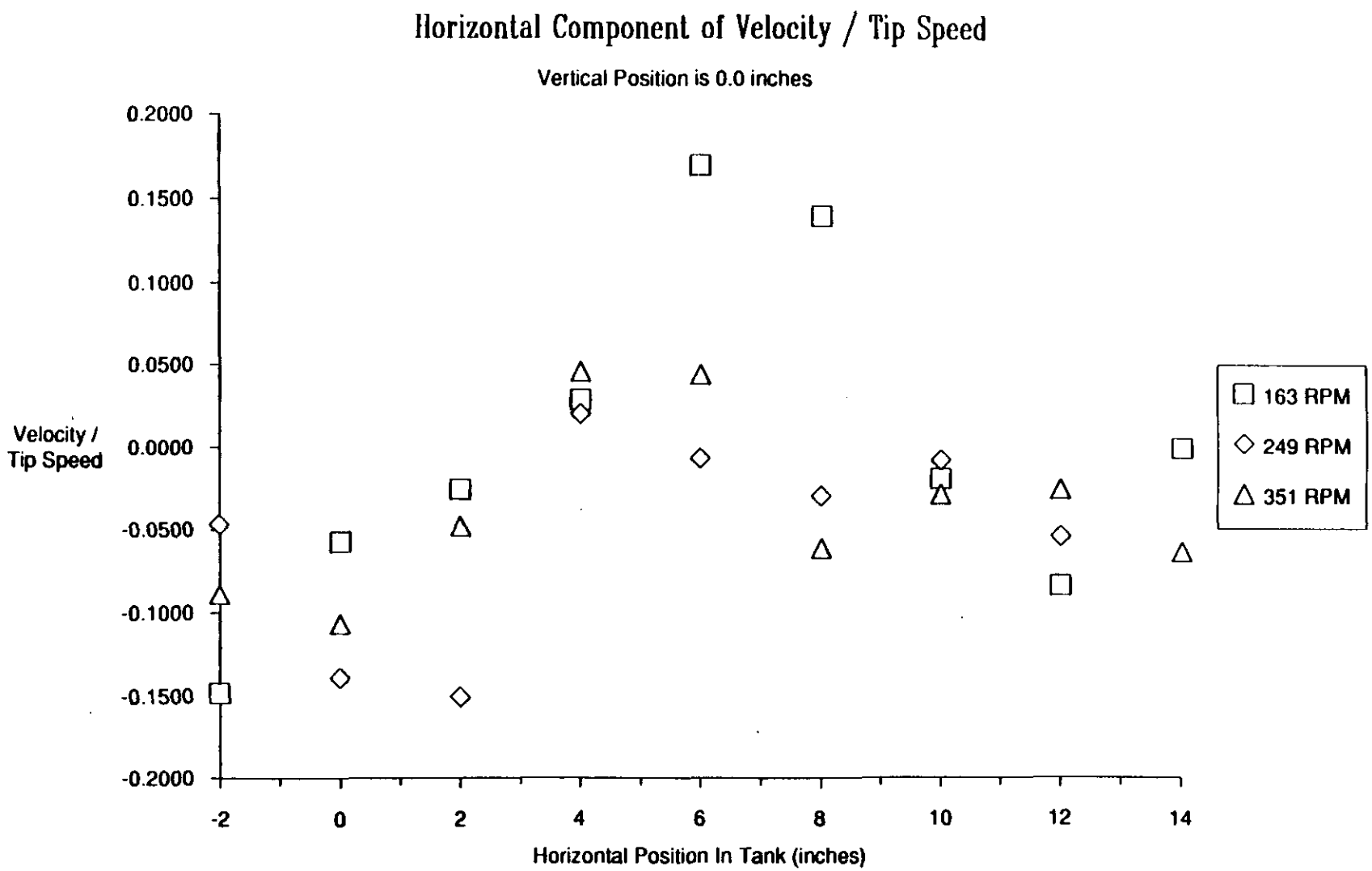
163 RPM V_T = 0.568 m/s

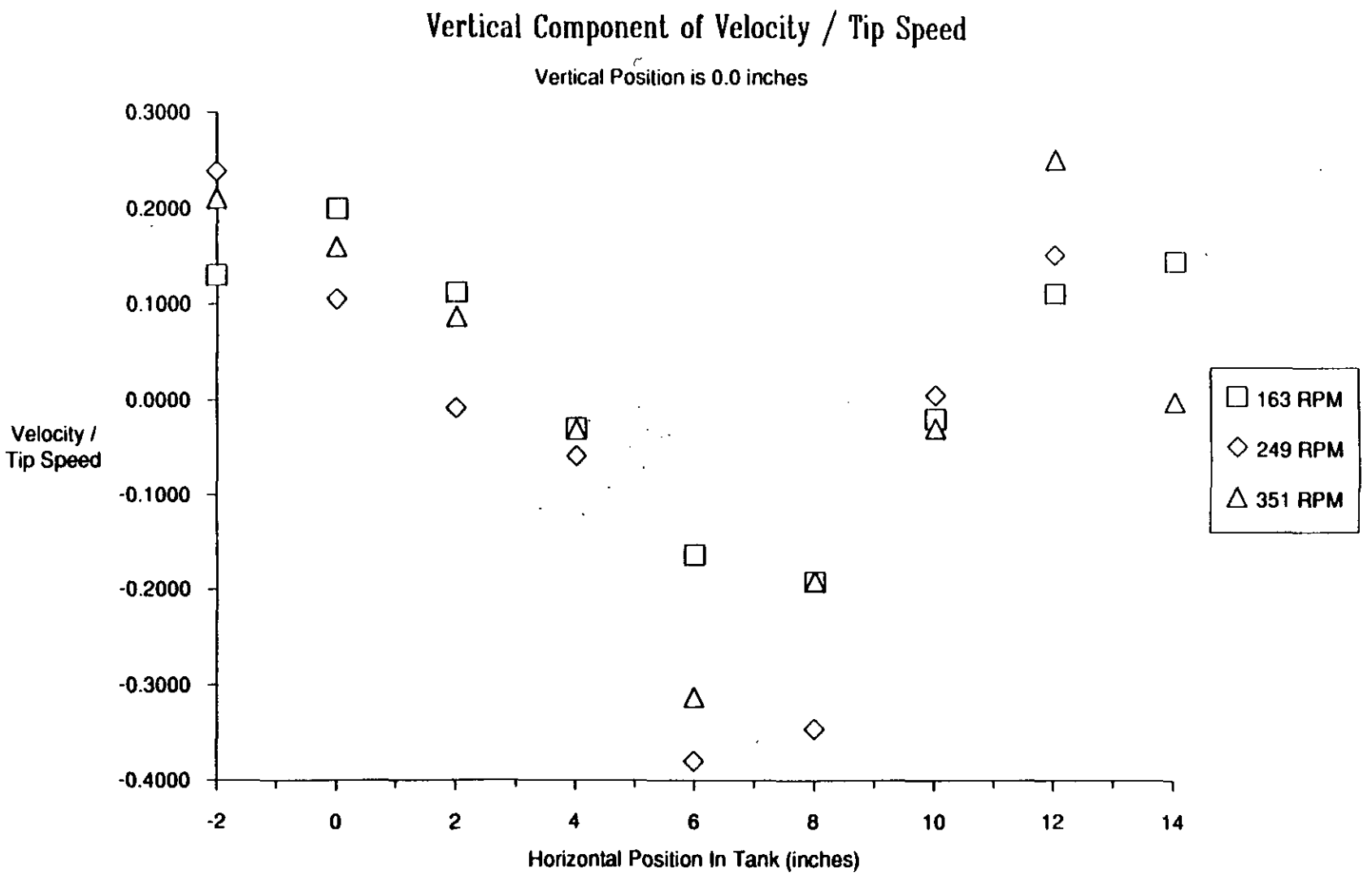


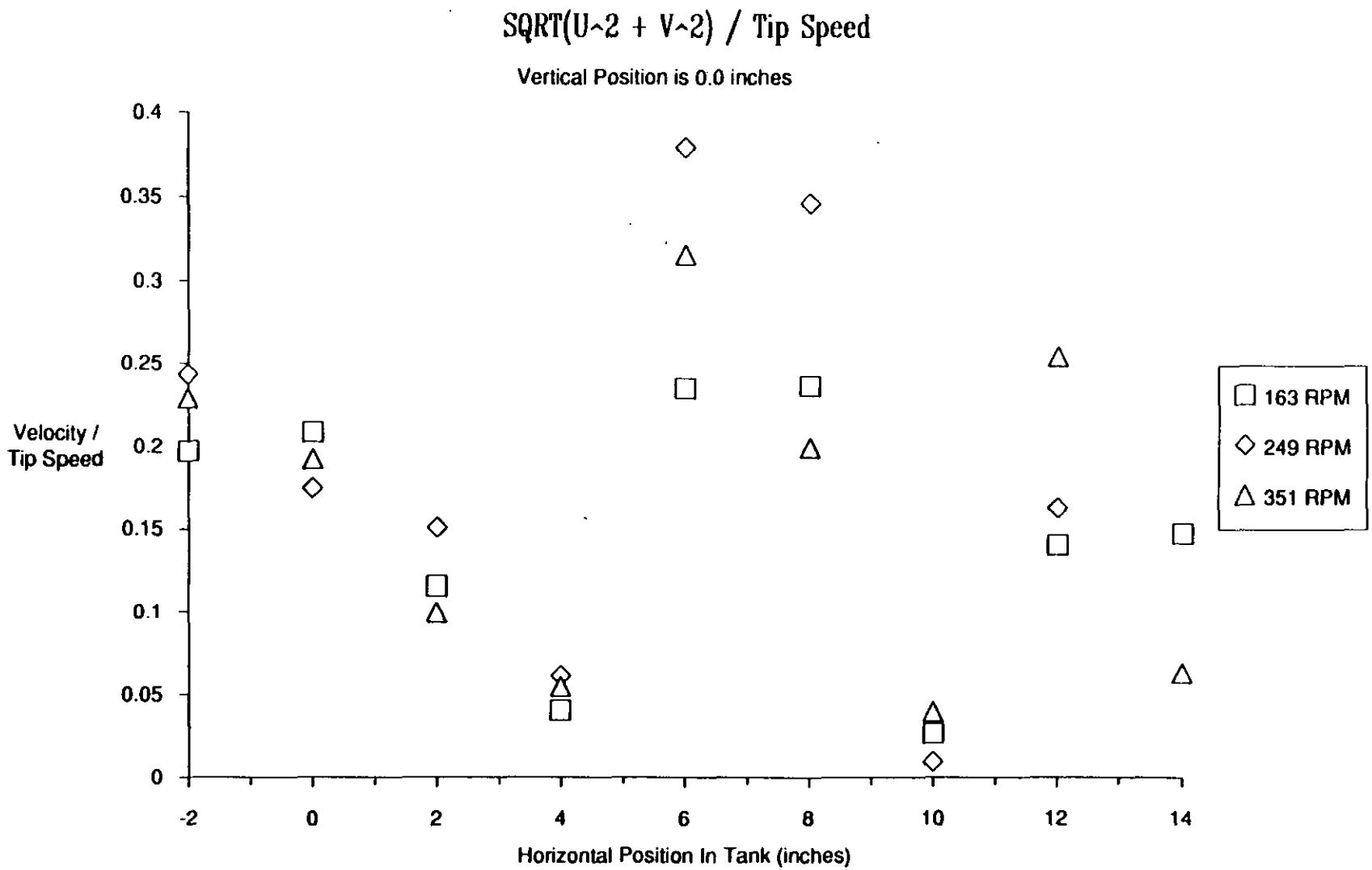
DuPont Slab Tank

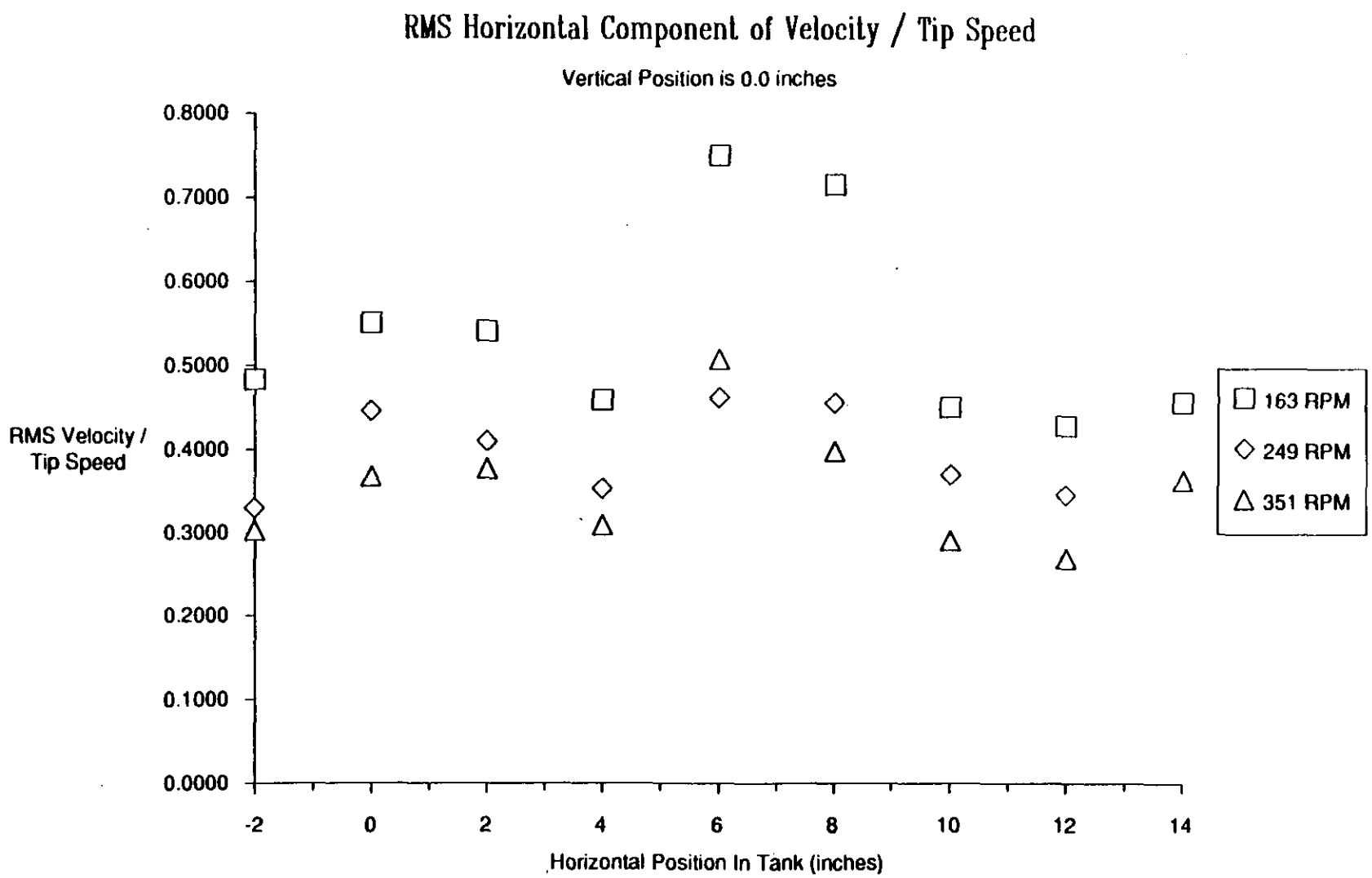


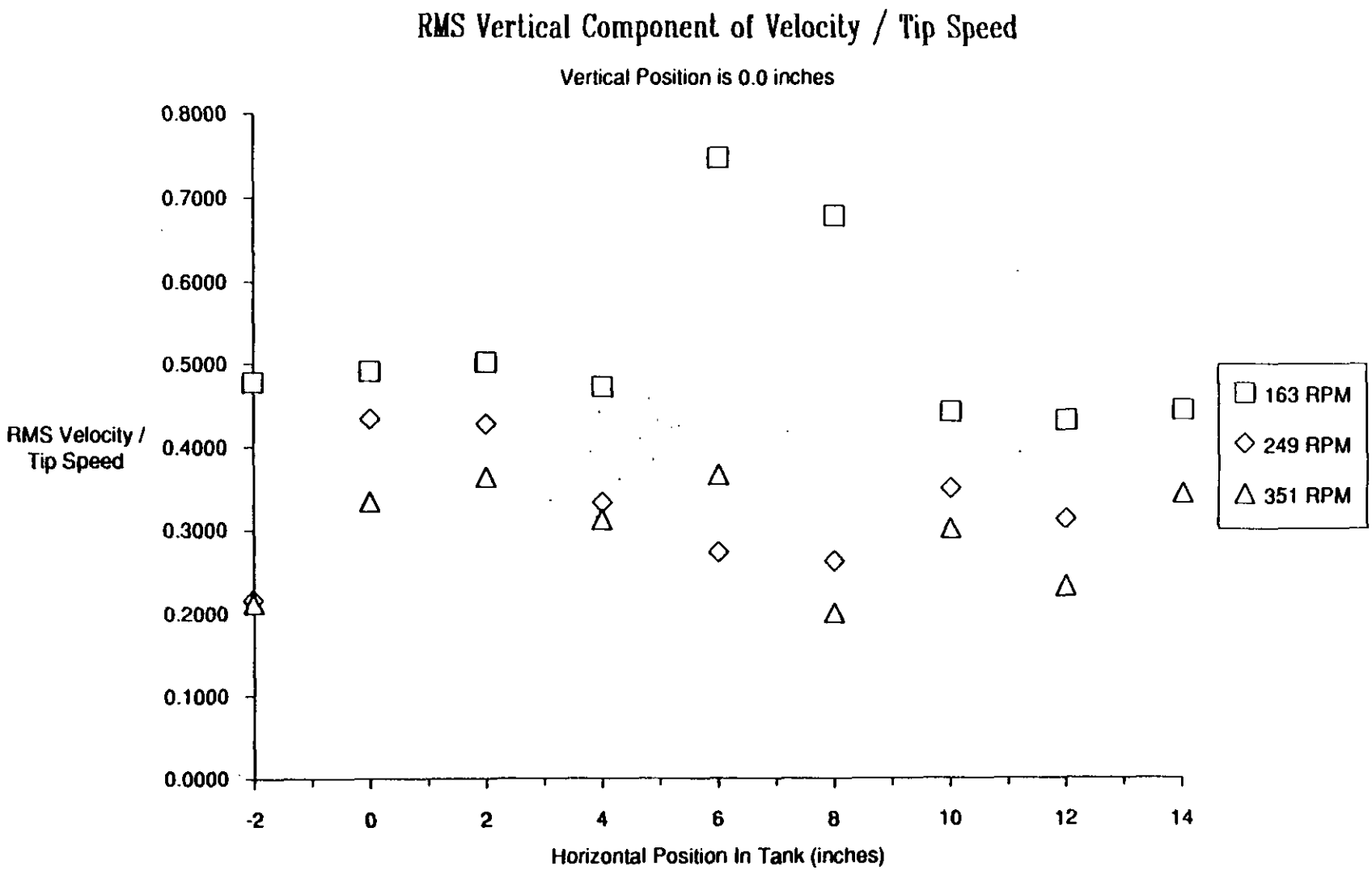
DuPont Slab Tank

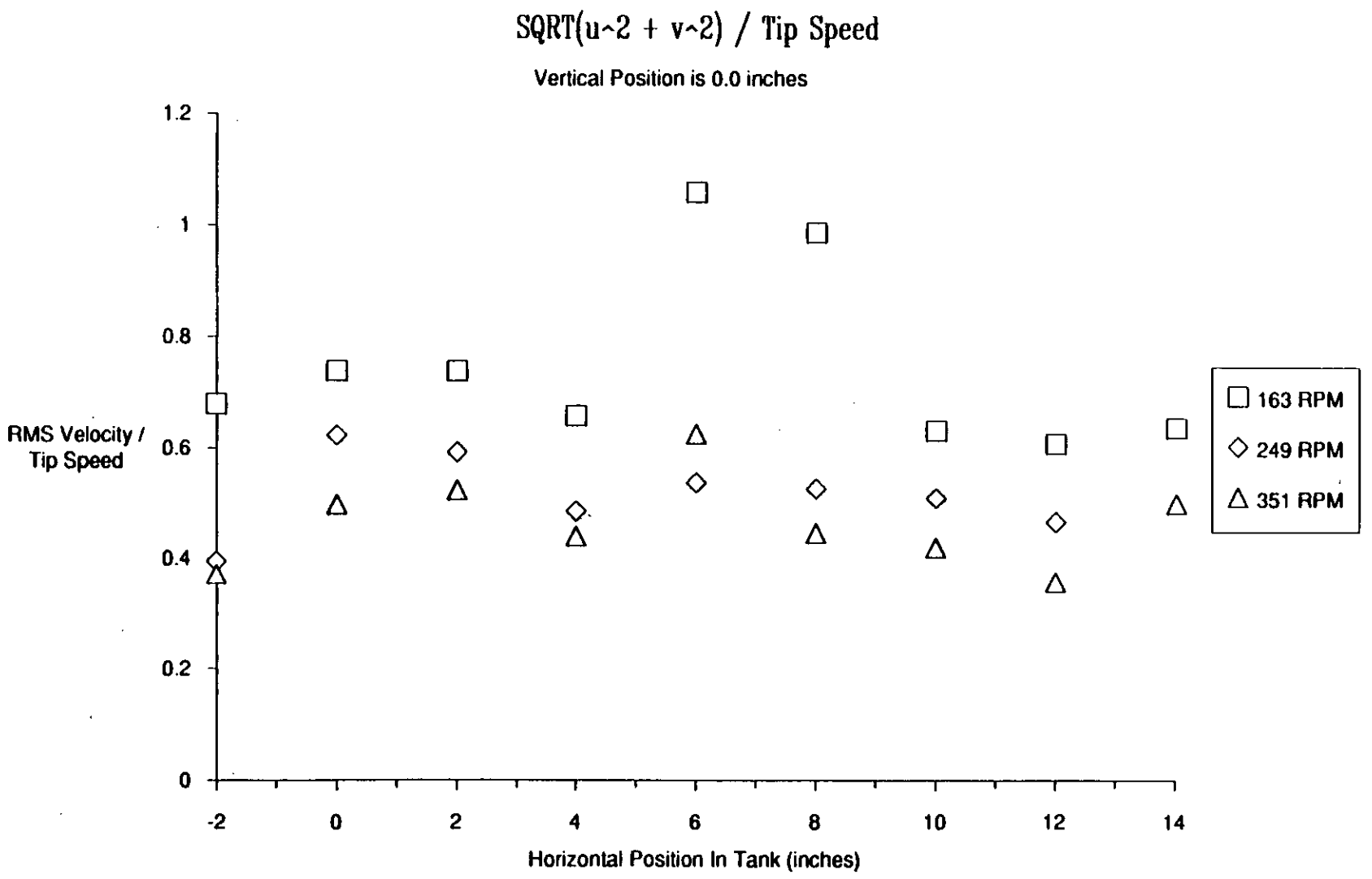

Horizontal Component of Velocity / Tip Speed
Vertical Position is 0.0 inches
Velocity / Tip Speed
0.2000
0.1500
0.1000
0.0500
0.0000
-0.0500
-0.1000
-0.1500
-0.2000
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM


Vertical Component of Velocity / Tip Speed
Vertical Position is 0.0 inches
0.3000
0.2000
0.1000
0.0000
-0.1000
-0.2000
-0.3000
-0.4000
Velocity / Tip Speed
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM


SQRT(U^2 + V^2) / Tip Speed
Vertical Position is 0.0 inches
Velocity / Tip Speed
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM


RMS Horizontal Component of Velocity / Tip Speed
Vertical Position is 0.0 inches
RMS Velocity / Tip Speed
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM


RMS Vertical Component of Velocity / Tip Speed
Vertical Position is 0.0 inches
RMS Velocity / Tip Speed
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM


SQRT(u^2 + v^2) / Tip Speed
Vertical Position is 0.0 inches
RMS Velocity / Tip Speed
1.2
1
0.8
0.6
0.4
0.2
0
-2
0
2
4
6
8
10
12
14
Horizontal Position In Tank (inches)
163 RPM
249 RPM
351 RPM

Frame of Reference

RELATIVE TO LABORATORY COORDINATES

Impeller region highly turbulent and void of coherent structures

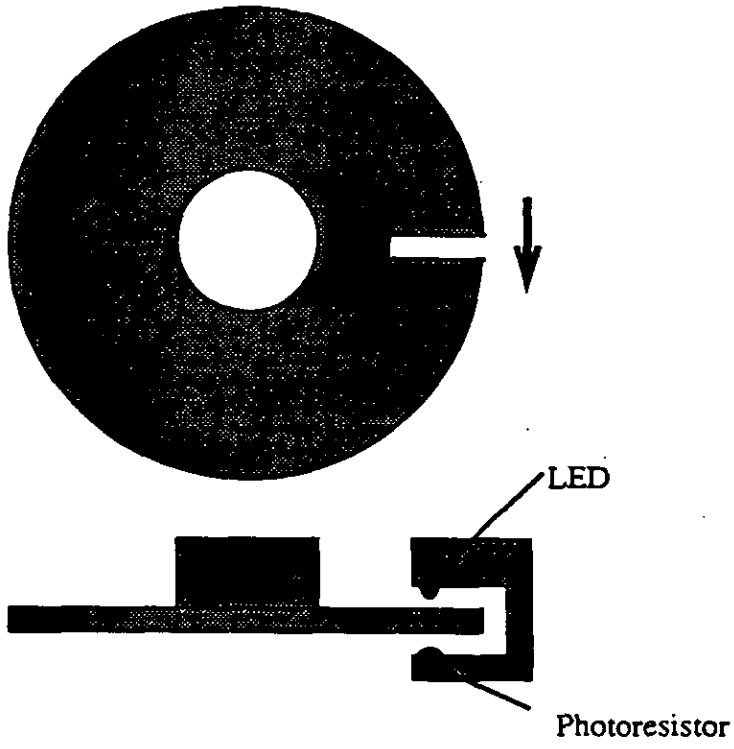
Location of individual impeller blades relative to sampling volume is ignored

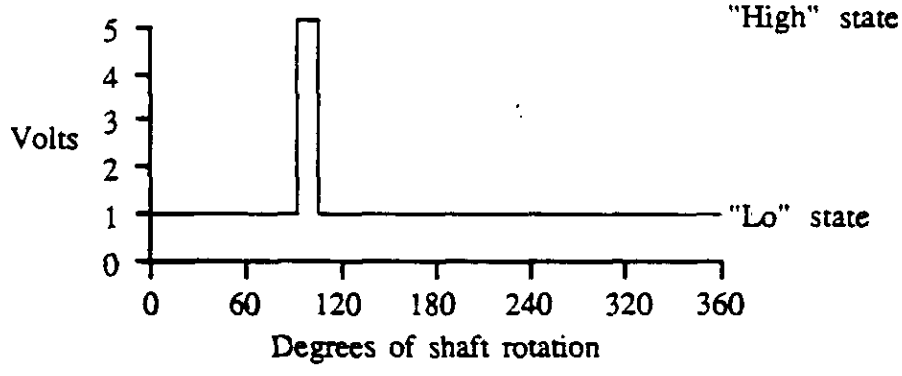
Velocity data adequate for design of blending and solid suspension processes

RELATIVE TO THE ROTATING IMPELLER

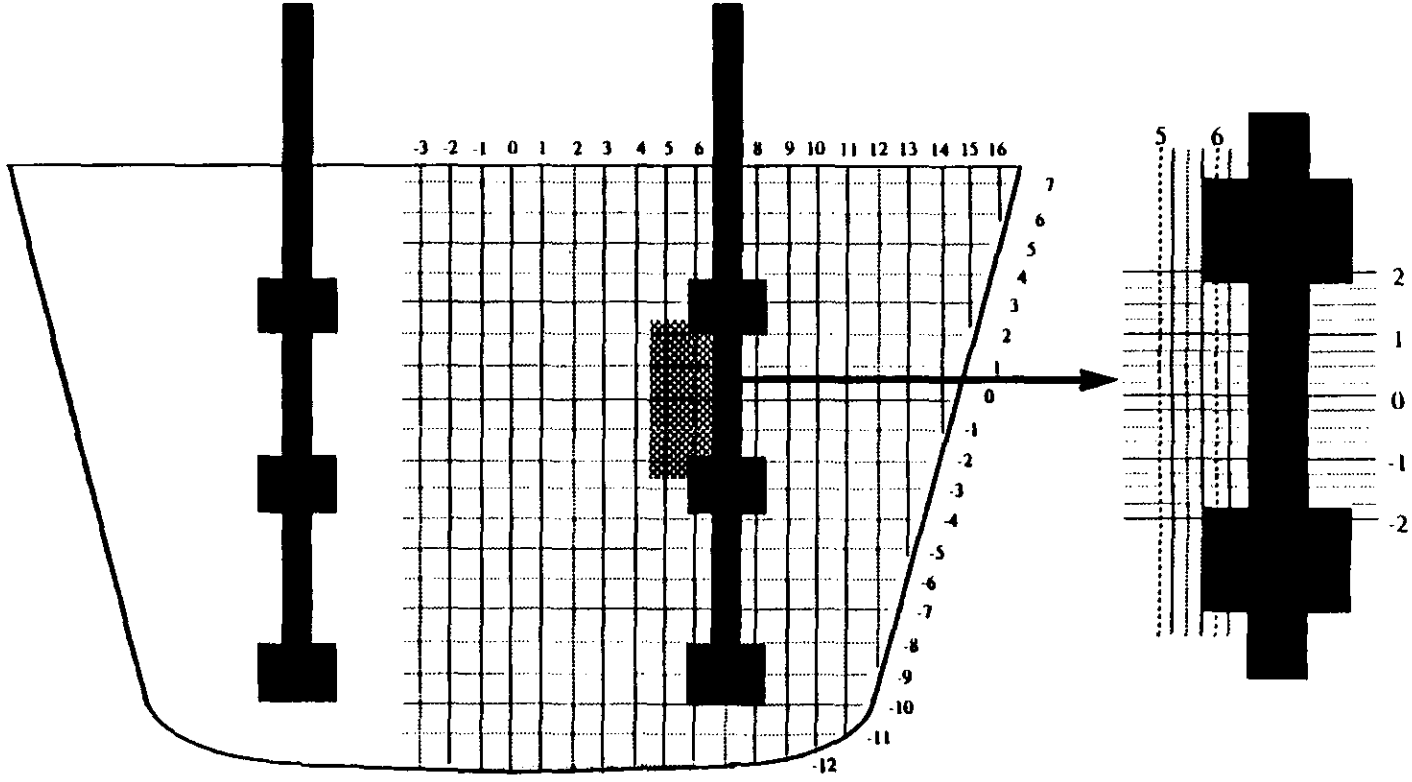
Periodic Velocity relative to fixed coordinates
Trailing Vortices or Coherent Wakes
Steep mean velocity gradients
Localized regions of high turbulent energy

Velocity data needed to characterize the hydrodynamic forces which break particles

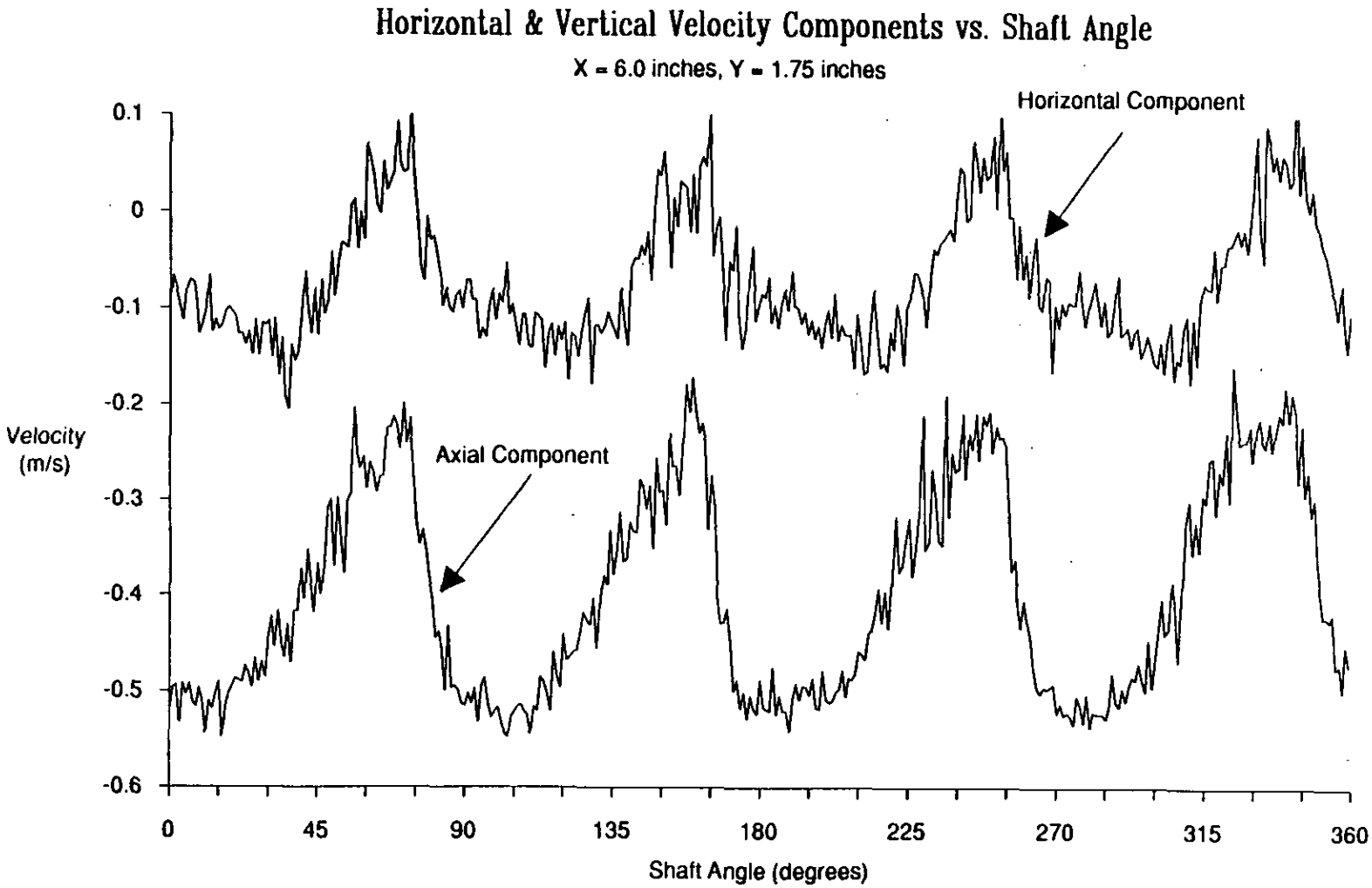


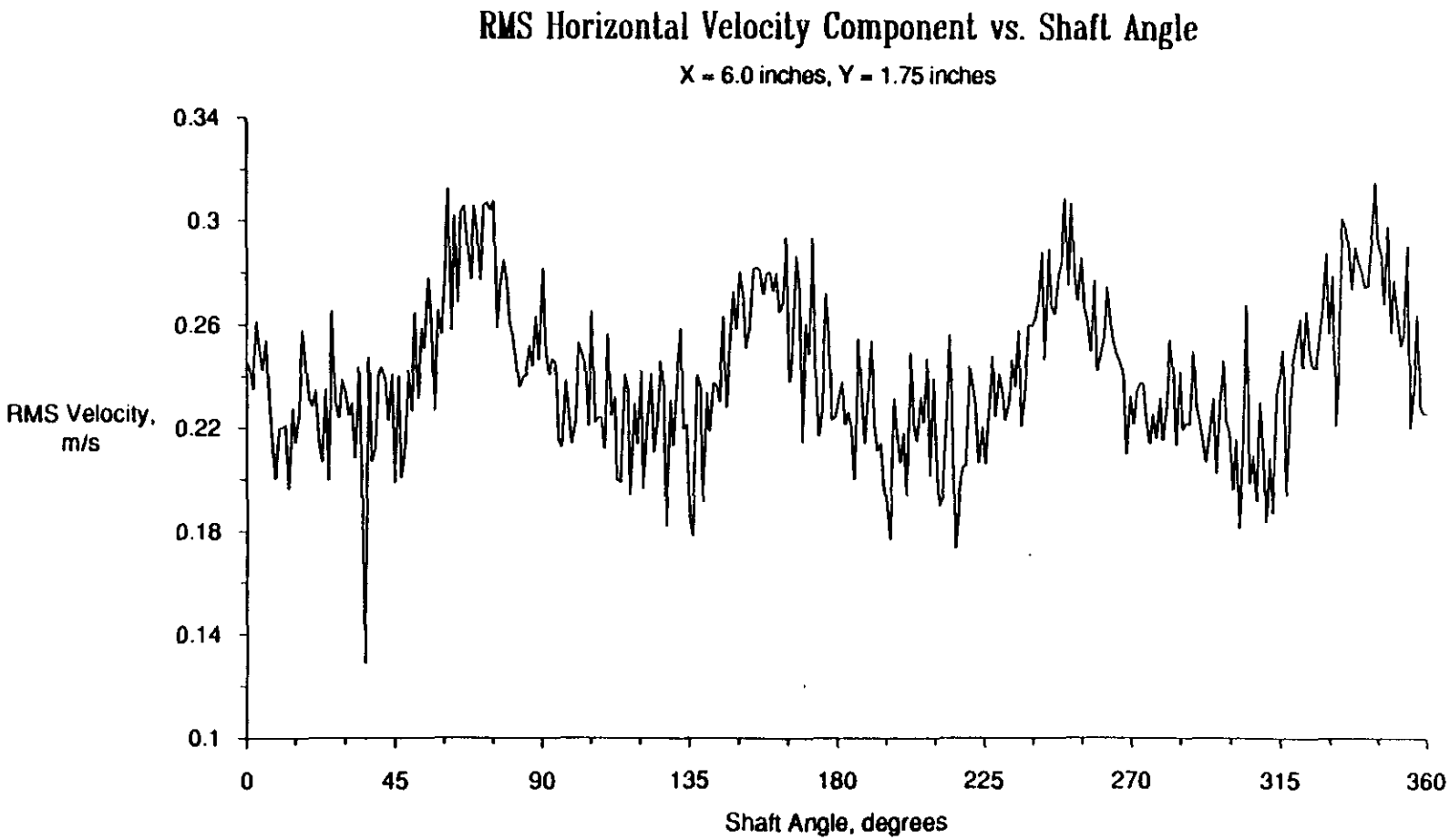


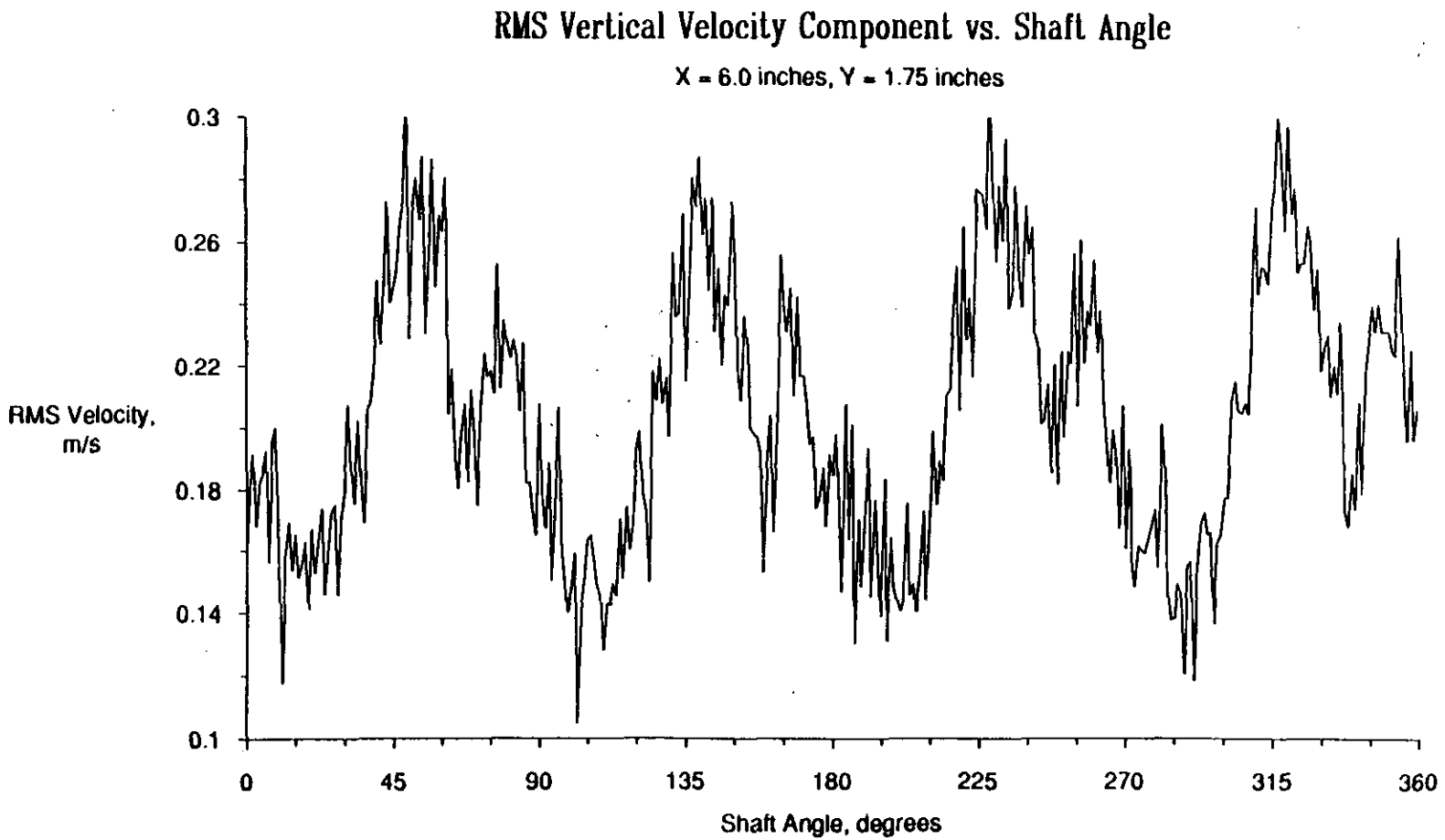
Once per revolution the signal from the photoresistor goes "high." This signal triggers the Dual Timing Board (DTB) in the LDA electronics to reset. The DTB measures the time between resets as well as the time at which each velocity realization is obtained. From these, it back-calculates the angular position of the stirrer for each data point and the RPM of the shaft.

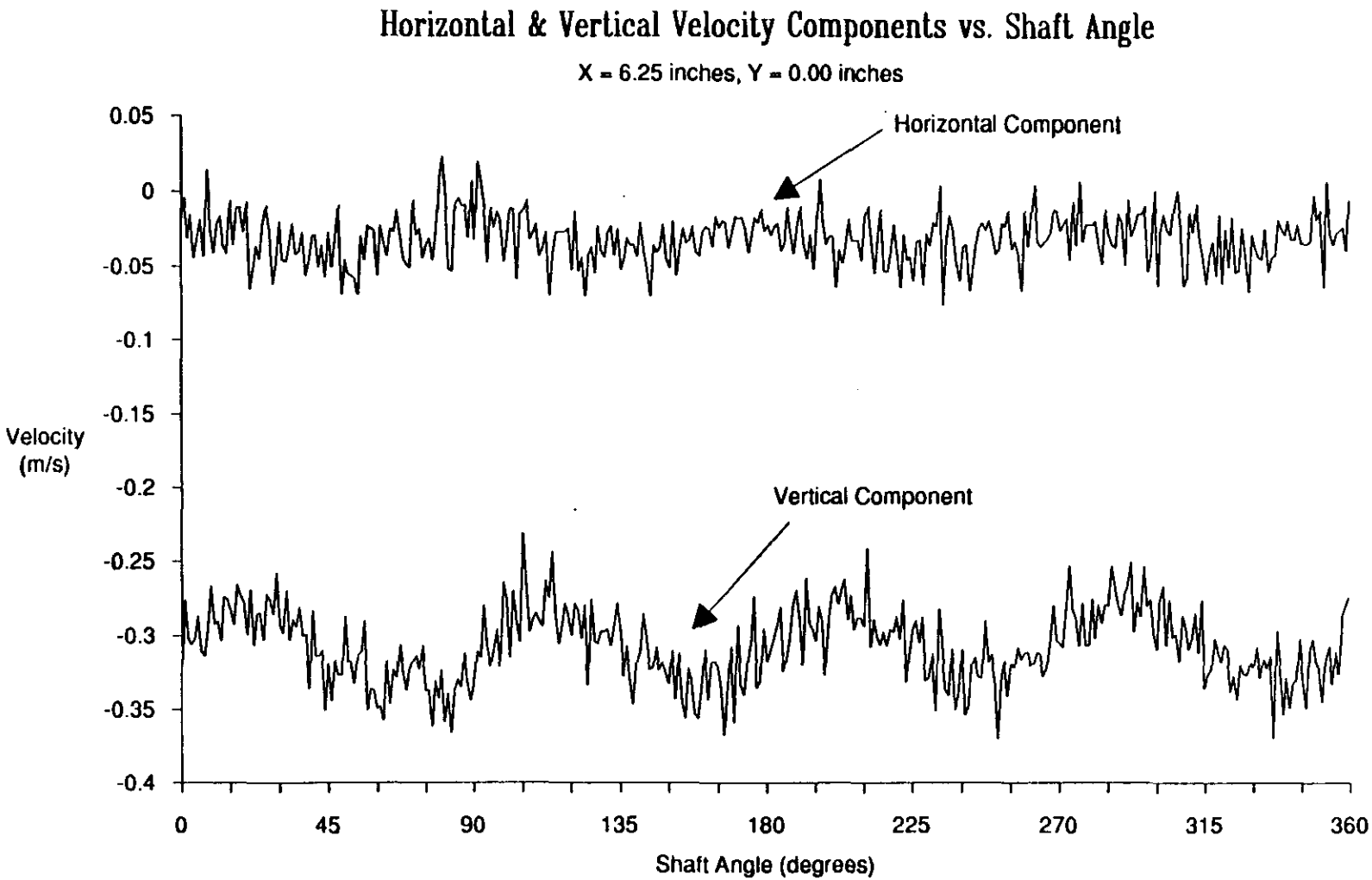


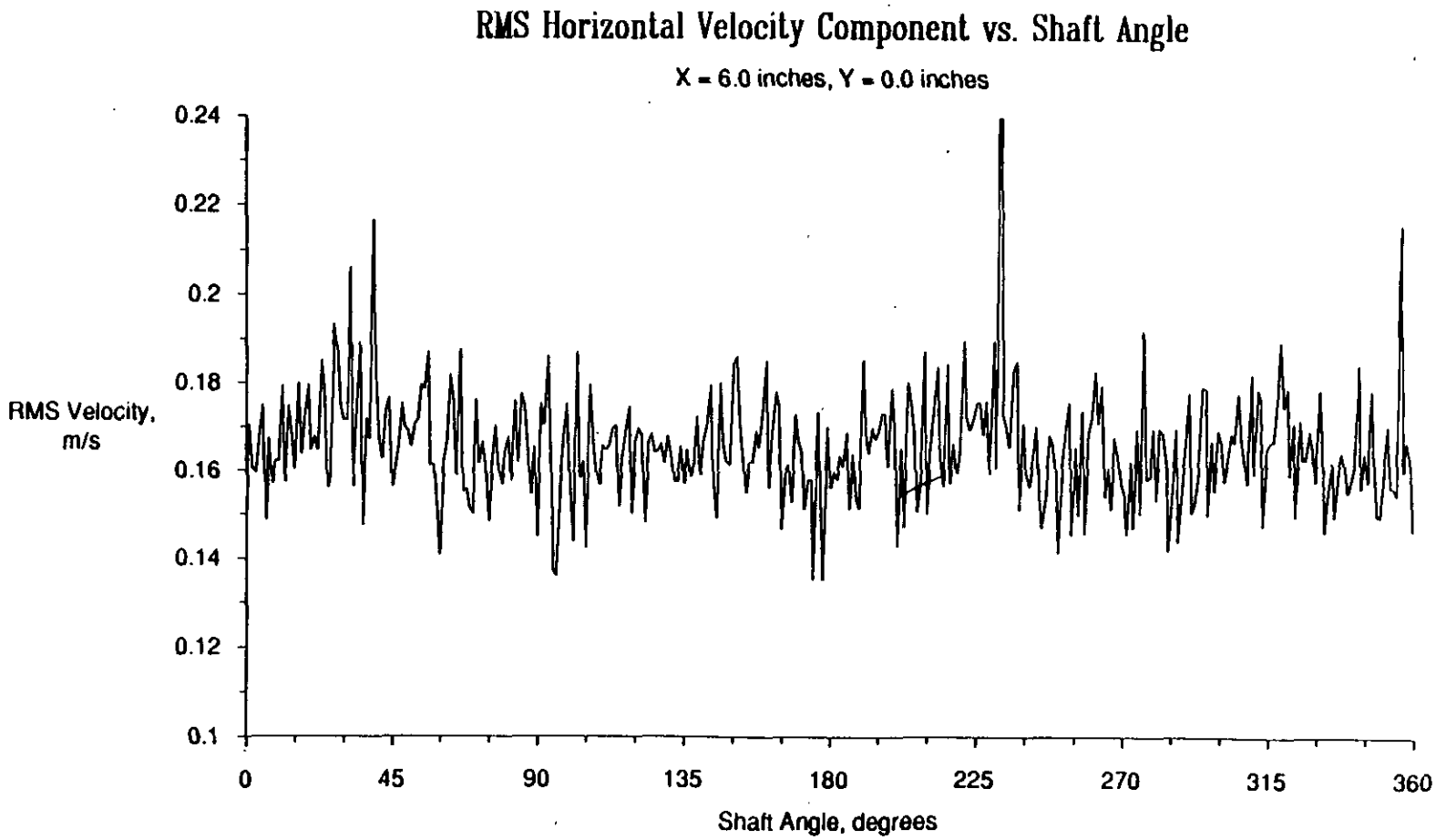
DuPont Slab Tank

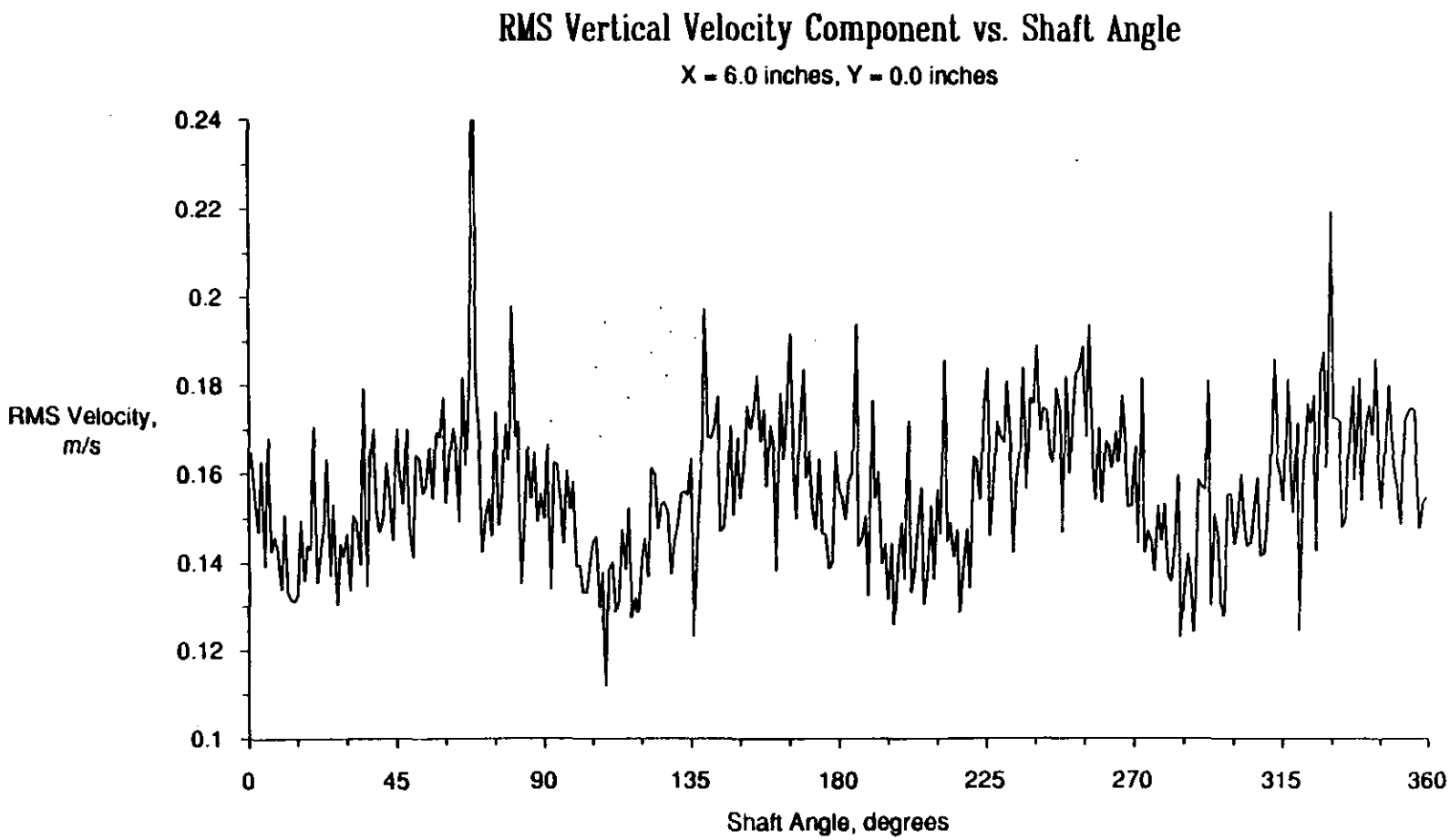

Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 6.0 inches, Y = 1.75 inches
Horizontal Component
Axial Component
Velocity (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)

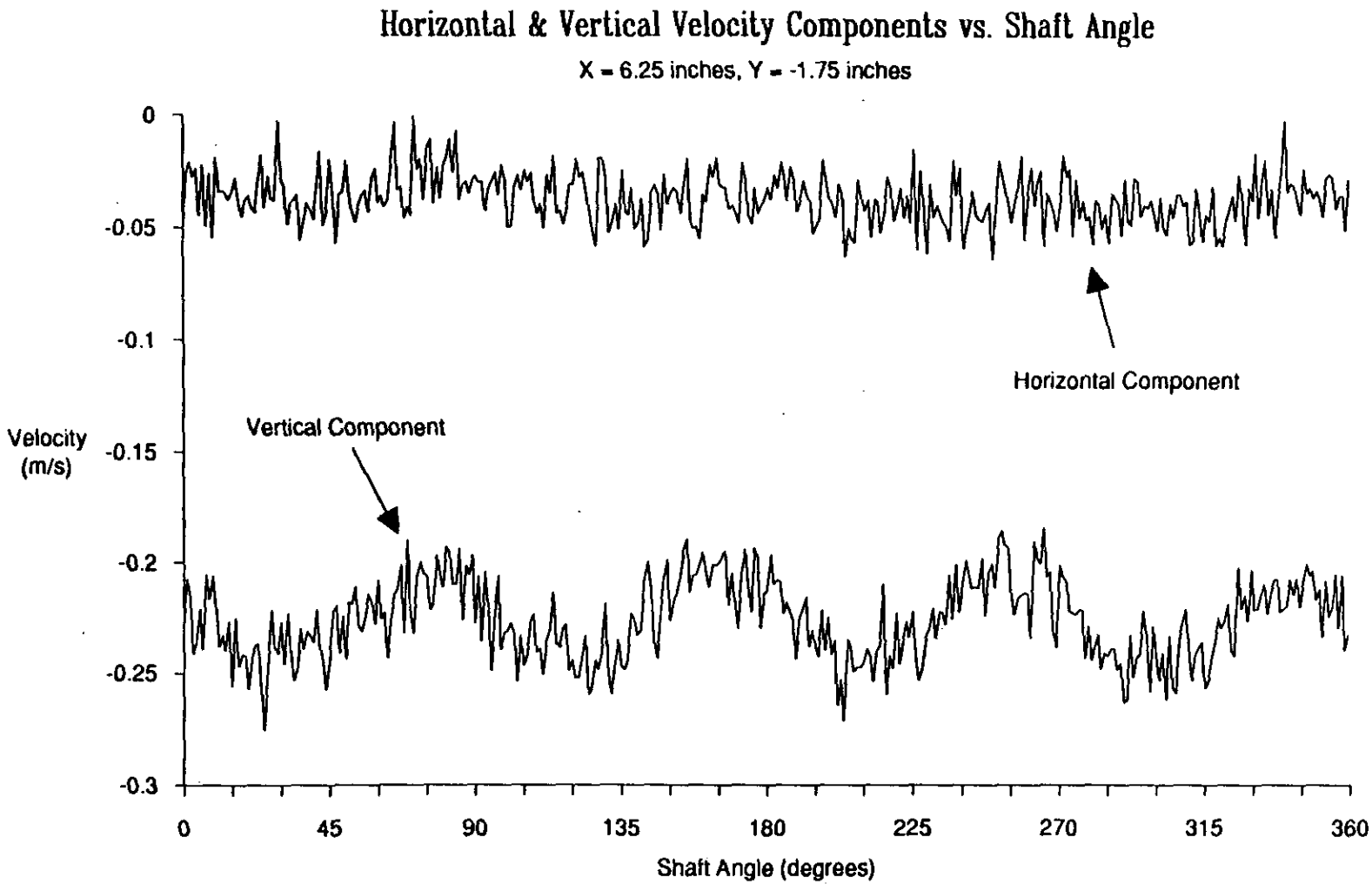

RMS Horizontal Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = 1.75 inches
RMS Velocity, m/s
0.34
0.3
0.26
0.22
0.18
0.14
0.1
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees

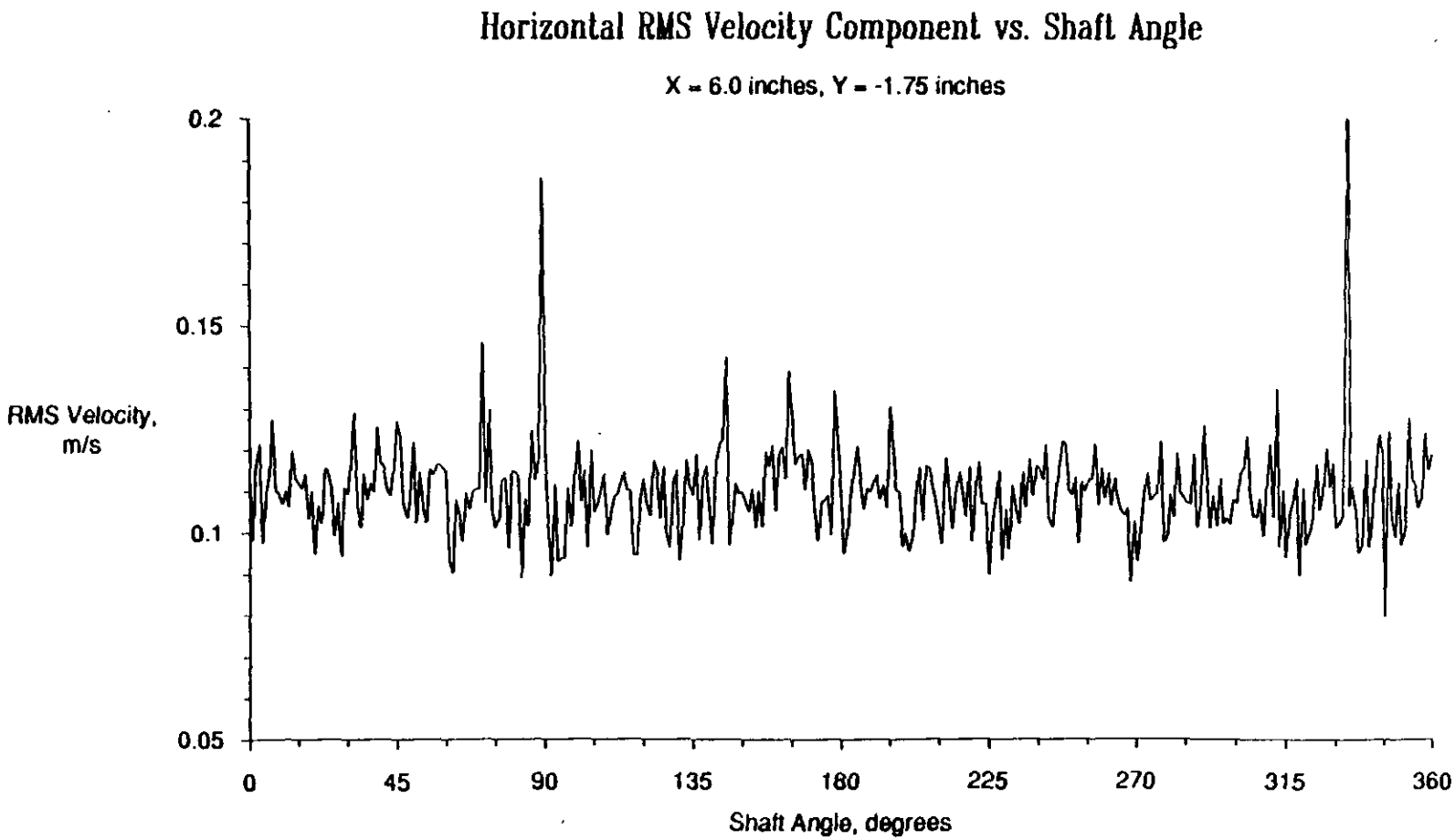

RMS Vertical Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = 1.75 inches
RMS Velocity, m/s
0.3
0.26
0.22
0.18
0.14
0.1
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees

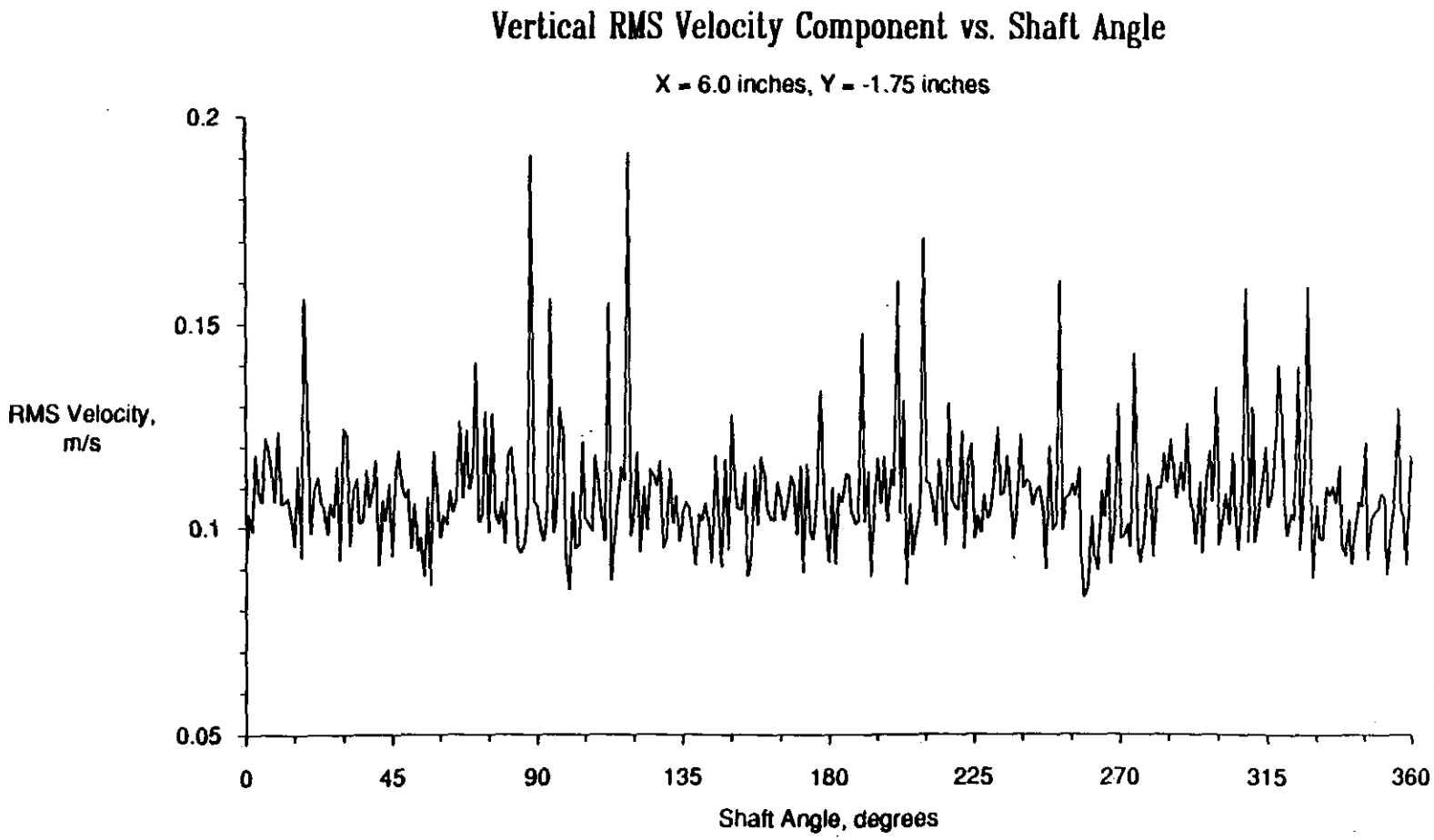

Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 6.25 inches, Y = 0.00 inches
Horizontal Component
Vertical Component
Velocity (m/s)
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)

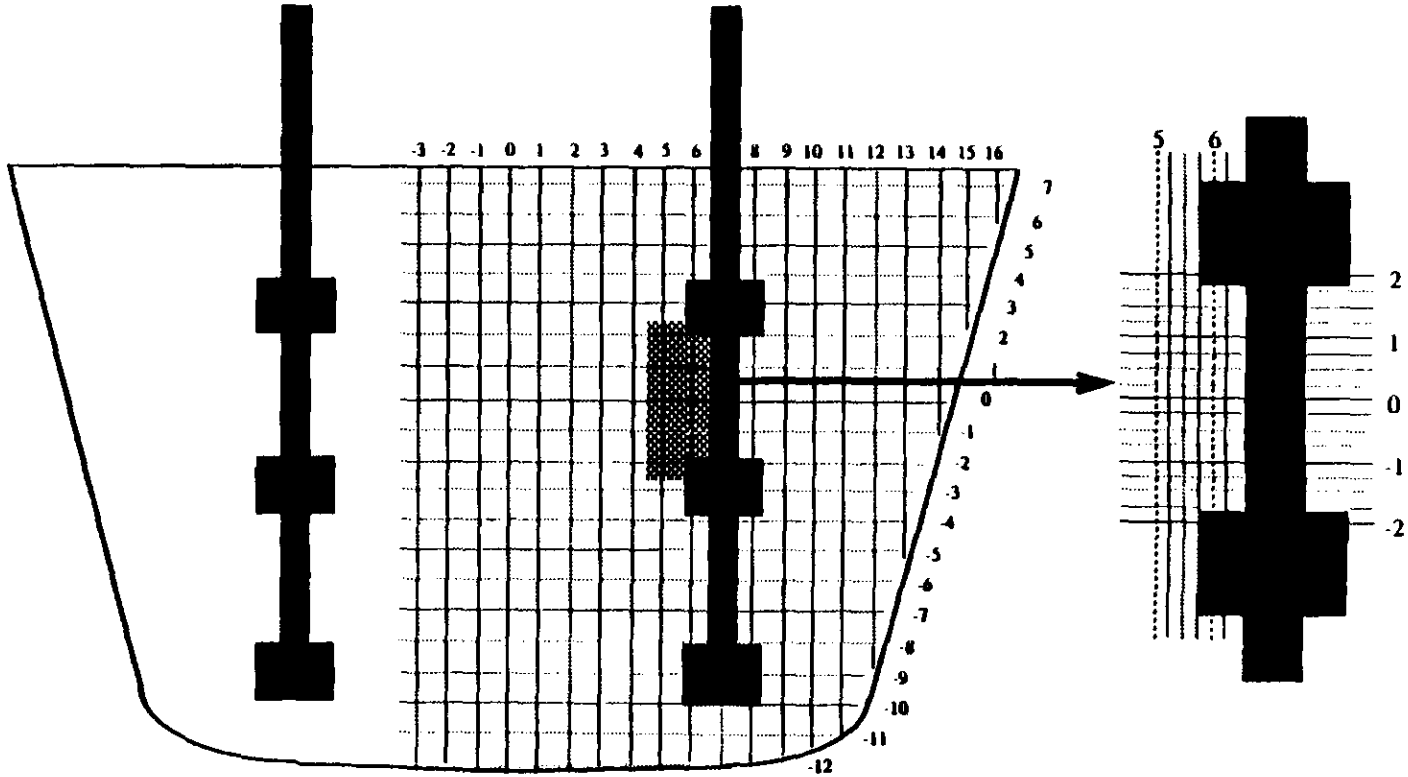

RMS Horizontal Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = 0.0 inches
RMS Velocity, m/s
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees


RMS Vertical Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = 0.0 inches
RMS Velocity, m/s
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees

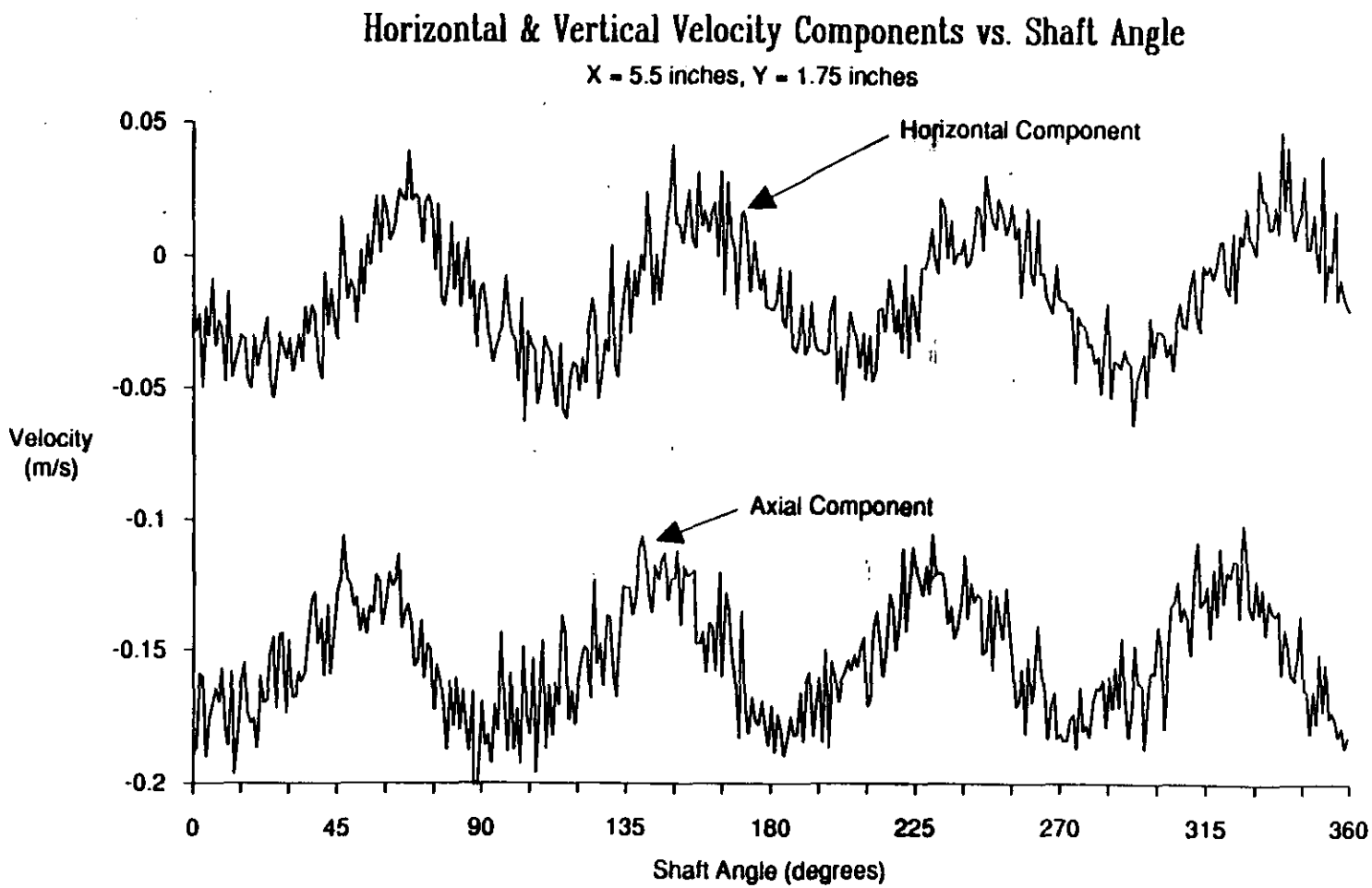

Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 6.25 inches, Y = -1.75 inches
Velocity (m/s)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Horizontal Component
Vertical Component
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)

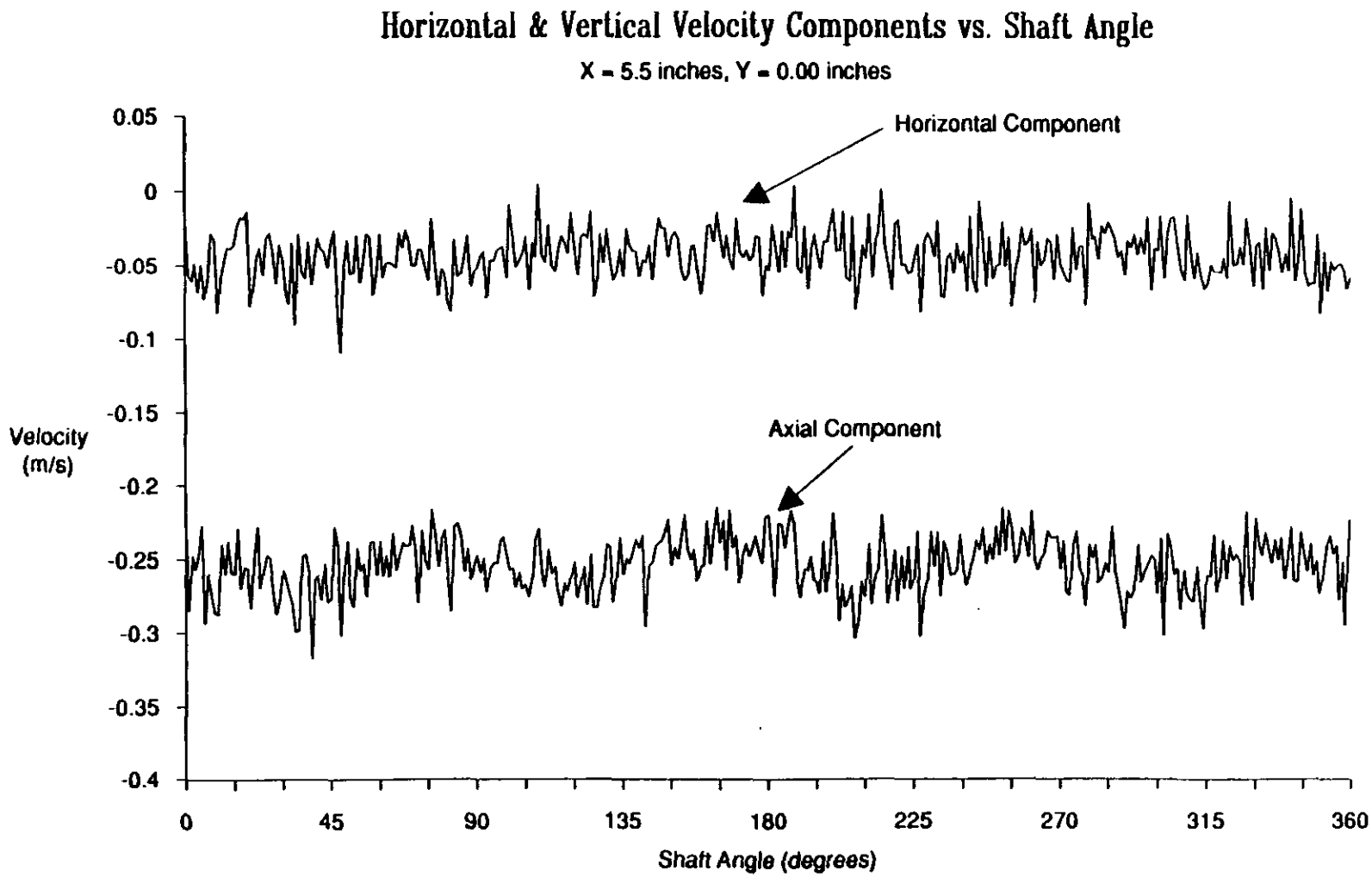

Horizontal RMS Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = -1.75 inches
RMS Velocity, m/s
0.2
0.15
0.1
0.05
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees

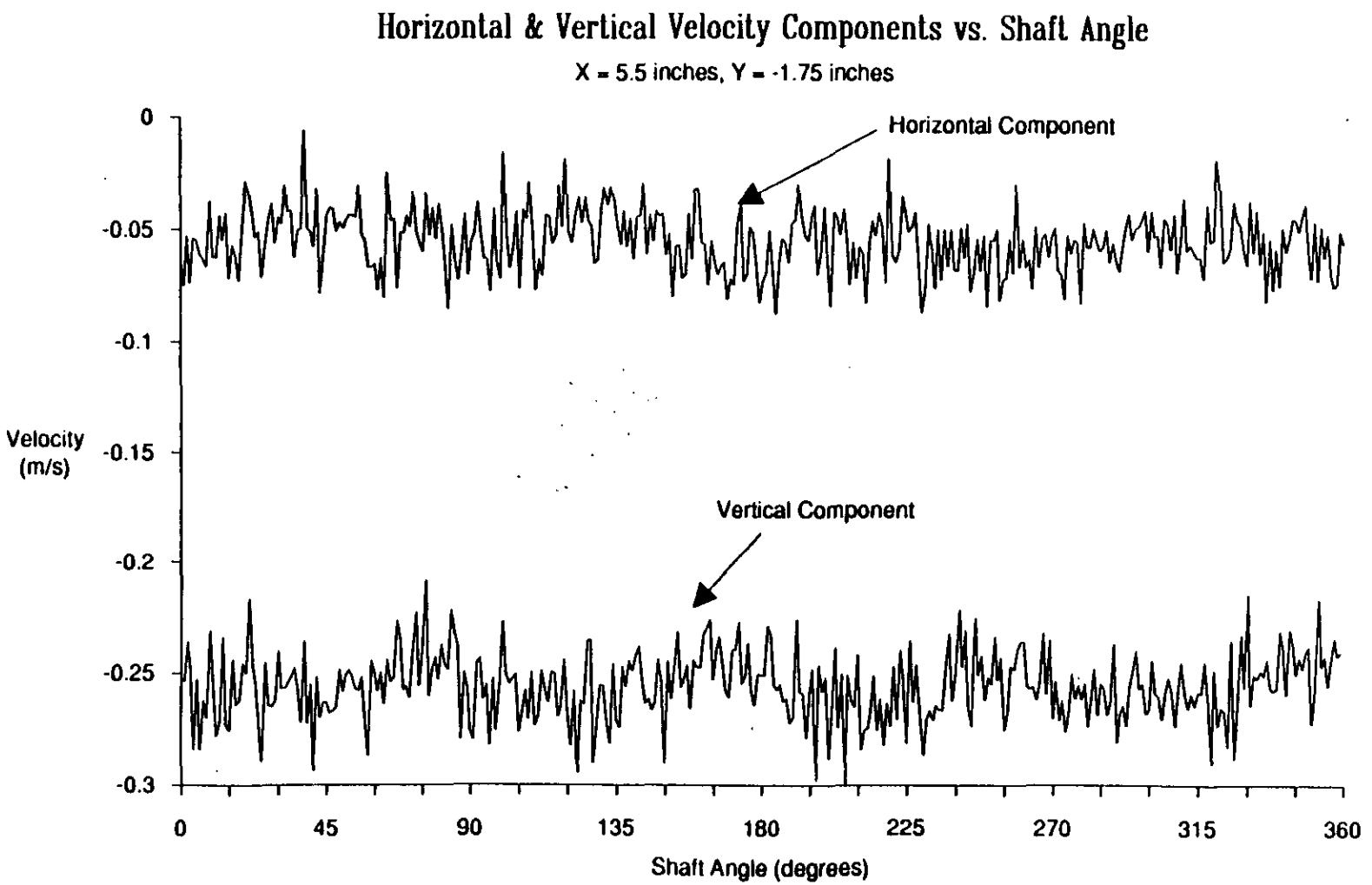

Vertical RMS Velocity Component vs. Shaft Angle
X = 6.0 inches, Y = -1.75 inches
RMS Velocity, m/s
0.2
0.15
0.1
0.05
0
45
90
135
180
225
270
315
360
Shaft Angle, degrees



DuPont Slab Tank


Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 5.5 inches, Y = 1.75 inches
Horizontal Component
Axial Component
Velocity (m/s)
0.05
0
-0.05
-0.1
-0.15
-0.2
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)


Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 5.5 inches, Y = 0.00 inches
Horizontal Component
Axial Component
Velocity (m/s)
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)


Horizontal & Vertical Velocity Components vs. Shaft Angle
X = 5.5 inches, Y = -1.75 inches
Horizontal Component
Vertical Component
Velocity (m/s)
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
45
90
135
180
225
270
315
360
Shaft Angle (degrees)

Conclusions

- There is a general three-dimensional circulation throughout the tank.

- Mean velocity measurements show several stagnation regions throughout the tank. Furthermore, the bottom impeller is not an effective contributor to the total pumping.

- *RMS Turbulent Velocities are relatively uniform* throughout the tank and are generally greater than the mean velocity.

- The slab tank scales approximately with tip speed (RPM), particularly at higher impeller speeds.

- The flow close to the middle impeller is highly periodic, indicating the presence of trailing vortices or well defined wakes. In this region vertical mean velocities are much greater than in the horizontal but RMS turbulent velocity components are of similar order.

Work in Progress

Flow Visualization Studies

Microbubbles and Sand
Test different impeller operating strategies

Circulation Time Studies

Follow neutrally buoyant particle via a video
camera technique
Determine probability of different particle paths
Standard configuration versus up and down pumping

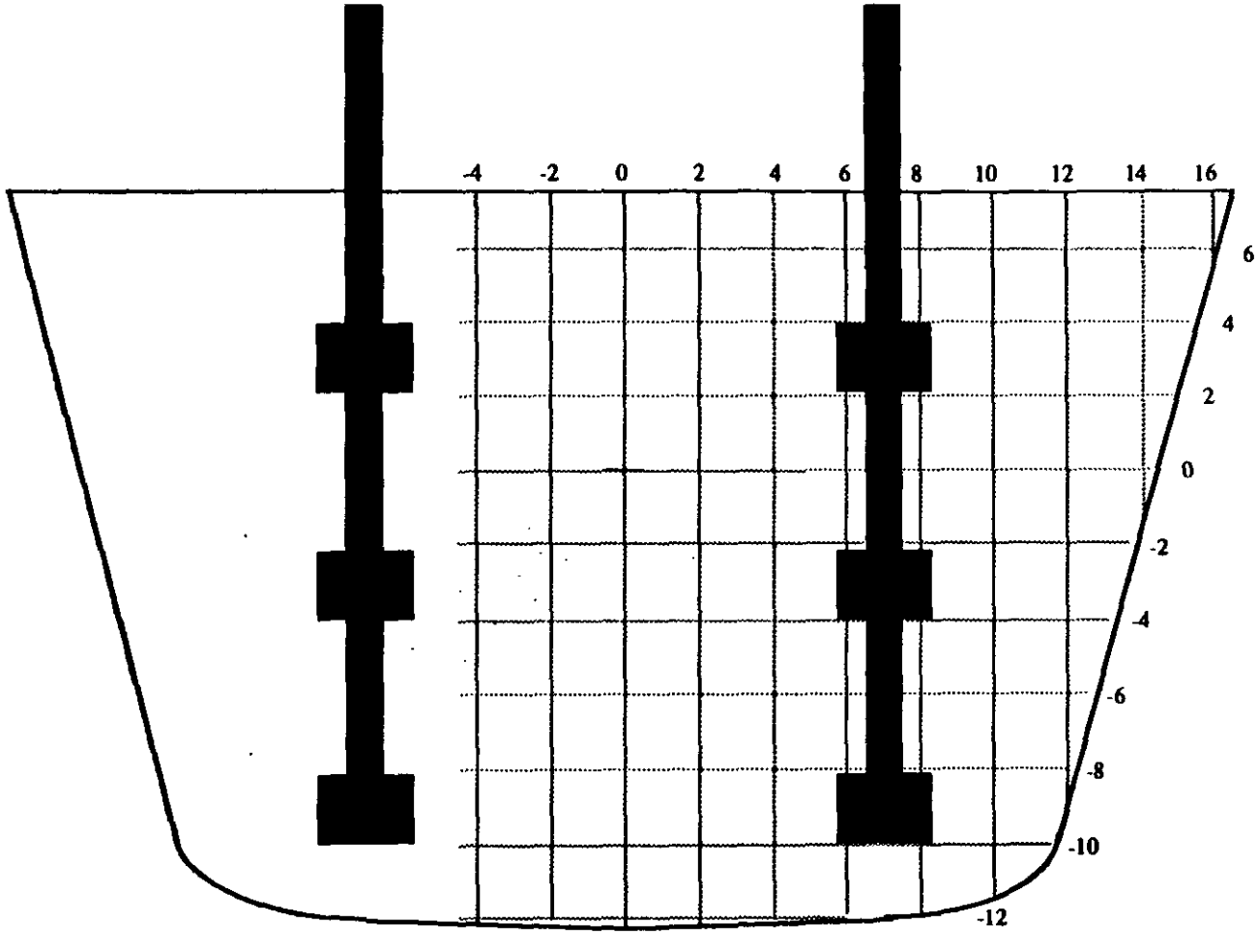
Measurement of Power Input

Power Number versus Impeller Speed
Distribution of Energy Dissipation Rates
Power No.:

$$N_P = \frac{P}{\rho N^3 D^5}$$

Distribution of Energy Dissipation Rates

Viscous Dissipation
Turbulent Dissipation



DuPont Slab Tank

Mean Velocity Gradients

Obtained via 3 point Lagrangian Interpolation

Second Invariant of Rate of Deformation Tensor

$$\mathbf{\Delta} : \mathbf{\Delta} = \sum_i \sum_j \left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i} \right)^2$$

Deformation Rate

$$\dot{\gamma} = \sqrt{\frac{1}{2} \mathbf{\Delta} : \mathbf{\Delta}}$$

Viscous Dissipation

$$\frac{\tau : \nabla \bar{v}}{\rho} = \nu \dot{\gamma}^2$$

Turbulent Energy

Turbulent Kinetic Energy $KE = \frac{1}{2}q^2$

Turbulent Energy Dissipation

$$\boxed{\epsilon = \frac{c(KE)^{3/2}}{l}}$$

Integral Length Scale $l = [l_x^2 + l_z^2]^{1/2}$

$$l_i = \sqrt{\overline{v_i^2}}\, T_i$$

Integral Time Scale

$$T_i = \int_0^\infty \rho_i(\tau) d\tau$$

Correlation Coefficient

$$\rho_i(\tau) = \frac{\overline{v_i'(t) v_i'(t+\tau)}}{\overline{v_i'^2}}$$