APPENDIX B

SUMMARY OF DGD RESULTS FOR RUNS WITH FT DERIVED WAXES

Table B.1. Summary of dynamic gas disengagement results for FT-300 wax.
(Run 13-3, 0.051 m ID column, 1.85 mm orifice, 265°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (mm)	H_o (m)	n_S	n_M	n_L
0.01	0.81	1.81	09.4	5.6	0.45	0.23	0.32	1.40	2.17	$3.91X10^5$	$1.84X10^4$	179
0.02	0.37	0.42	28.7	20.8	0.59	0.27	0.13	0.44	2.59	$2.45X10^7$	$7.68X10^6$	12
0.03	0.33	0.35	18.2	26.3	0.65	0.19	0.16	0.39	2.79	$5.15X10^7$	$1.28X10^7$	73
0.04	0.32	0.35	17.1	27.9	0.56	0.22	0.22	0.42	2.87	$5.26X10^7$	$1.62X10^7$	137
0.05	0.32	0.35	17.3	25.7	0.49	0.20	0.32	0.48	2.79	$4.11X10^7$	$1.29X10^7$	168
0.07	0.33	0.36	25.1	22.5	0.32	0.16	0.52	0.69	2.69	$2.09X10^7$	$8.29X10^6$	77
0.09	0.33	0.37	43.5	22.7	0.27	0.11	0.62	0.88	2.72	$1.79X10^7$	$5.46X10^6$	18
0.12	0.33	0.41	73.8	25.8	0.25	0.05	0.69	1.10	2.85	$2.00X10^7$	$2.19X10^6$	5

Table B.2. Summary of dynamic gas disengagement results for FT-300 wax. (Run 13-2, 0.051 m ID column, 1.85 mm orifice, 200°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (mm)	H_o (m)	n_S	n_M	n_L
0.01	1.12	1.09	8.0	4.7	0.28	0.13	0.59	2.27	2.21	8.04×10^4	4.03×10^4	470
0.02	0.51	0.56	29.5	14.7	0.41	0.32	0.27	0.72	2.46	4.34×10^6	2.55×10^6	15
0.03	0.45	0.50	28.8	19.5	0.46	0.25	0.29	0.65	2.60	1.00×10^7	3.88×10^6	24
0.04	0.45	0.51	19.3	18.8	0.40	0.16	0.44	0.81	2.58	8.26×10^6	2.33×10^6	113
0.05	0.46	0.52	25.0	18.4	0.41	0.06	0.54	0.98	2.57	7.63×10^6	7.56×10^5	63
0.07	0.45	0.52	24.2	18.6	0.21	0.09	0.71	1.53	2.57	4.22×10^6	1.12×10^6	92
0.09	0.45	0.49	20.4	21.2	0.16	0.09	0.75	1.73	2.64	3.77×10^6	1.71×10^6	191
0.12	0.45	0.57	43.1	24.1	0.16	0.05	0.80	2.25	2.74	4.37×10^6	6.42×10^5	26

Table B.3. Summary of dynamic gas disengagement results for Sasol's Arge reactor wax.
(Run 8-4, 0.051 m ID column, 1.85 mm orifice, 265°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (mm)	H_o (m)	n_S	n_M	n_L
0.01	0.41	1.14	23.2	4.7	0.31	0.26	0.43	1.01	2.19	1.75×10^6	6.93×10^4	14
0.02	0.40	0.59	20.5	7.6	0.21	0.22	0.57	1.08	2.26	2.20×10^6	7.03×10^5	44
0.03	0.36	0.55	29.1	10.0	0.18	0.21	0.62	1.12	2.32	3.44×10^6	1.11×10^6	22
0.04	0.38	0.55	33.7	12.0	0.15	0.16	0.69	1.40	2.35	3.05×10^6	1.06×10^6	20
0.05	0.35	0.55	23.7	13.3	0.12	0.15	0.73	1.53	2.38	3.48×10^6	1.11×10^6	67
0.07	0.34	0.50	53.2	16.7	0.10	0.11	0.78	1.84	2.47	4.16×10^6	1.45×10^6	8
0.09	0.33	0.55	31.5	19.2	0.12	0.08	0.81	1.93	2.53	6.12×10^6	8.53×10^5	49

Table B.4. Summary of dynamic gas disengagement results for Mobil's reactor wax. (Run 9-3, 0.051 m ID column, 1.85 mm orifice, 265°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (mm)	H_o (m)	n_S	n_M	n_L
0.01	0.51	3.10	15.9	4.9	0.35	0.21	0.44	1.29	2.09	1.02×10^6	2.80×10^3	43
0.02	0.50	1.11	30.7	7.6	0.29	0.17	0.54	1.33	2.16	1.49×10^6	7.76×10^4	12
0.03	0.49	0.88	28.5	9.4	0.17	0.11	0.71	1.97	2.21	1.19×10^6	1.31×10^5	25
0.04	0.51	0.92	32.4	11.2	0.17	0.09	0.74	2.23	2.26	1.25×10^6	1.09×10^5	22
0.05	0.53	1.36	35.5	13.2	0.14	0.09	0.77	2.89	2.31	1.09×10^6	4.09×10^4	20
0.07	0.50	1.13	47.2	16.0	0.11	0.08	0.81	3.21	2.39	1.31×10^6	8.39×10^4	11
0.09	0.52	4.50	51.0	19.2	0.11	0.11	0.78	4.08	2.49	1.40×10^6	2.33×10^3	11
0.12	0.58	3.90	47.3	21.8	0.08	0.09	0.83	5.50	2.62	9.29×10^5	3.33×10^3	17

APPENDIX C

SUMMARY OF RUNS WITH NON-WAX LIQUID MEDIUMS

Table C.1. Summary of Run W-1

Date: 01-07-87
Column ID: 5.1 cm
Distributor: 1.85 mm

Liquid: Distilled water
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	207.0	204.5	203.2	201.3	200.7	197.5	196.8	196.2
Gas hold-up (%)	4.68	7.2	9.09	11.37	13.26	14.84	17.55	21.17
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	0.6	1.4	0.7	1.12	1.3	1.13	1.0	1.13
Height slugs observed (cm)	210.0	120.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.6	0.9	1.3	2.2	2.8	3.5	4.44	5.7

Table C.2. Summary of Run W-2

Date: 01-08-87
Column ID: 5.1 cm
Distributor: 1.85 mm

Liquid: Distilled water
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	12	9	7	5	4	3	2	1
Static Height (cm)	217.2	216.4	215.9	208.3	208.3	207.6	206.7	205.1
Gas hold-up (%)	21.14	17.29	14.66	12.76	10.87	8.86	7.0	4.72
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	1.1	1.4	1.3	1.3	1.28	1.3	1.08	0.7
Height slugs observed (cm)	30.0	120.0	120.0	120.0	120.0	120.0	210.0	210.0
Amplitude of Oscillation (cm)	5.4	4.4	3.5	2.5	2.2	1.7	0.9	0.5

Table C.3. Summary of Run W-3

Date: 01-09-87
Column ID: 5.1 cm
Distributor: SMP

Liquid: Distilled water
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	219.7	219.0	218.4	217.9	217.5	214.0	213.4	208.3
Gas hold-up (%)	4.16	7.13	8.99	10.65	12.63	15.75	17.85	21.9
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	1.1	1.2	1.5	1.4	1.5	1.16	1.0
Height slugs observed (cm)	-	210.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.5	0.8	1.1	1.9	3.2	4.3	5.7	6.4

Table C.4. Summary of Run W-4

Date: 02-19-87
Column ID: 22.9 cm
Distributor: 19×1.85 mm

Liquid: Distilled water
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	187.9	187.6	187.5	187.0	186.7	185.7	185.4	-
Gas hold-up (%)	3.3	5.3	7.2	8.5	9.7	11.4	12.6	-
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.6	0.6	1.6	1.6	3.8	5.1	5.1	

Table C.5. Summary of Run W-5

Date: 02-20-87 Column ID: 22.9 cm Distributor: 5×1.0 mm					Liquid: Distilled water Temperature: 24°C Gas: Nitrogen			
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	181.61	-	180.98	-	180.34	179.71	-	-
Gas hold-up (%)	2.05	-	6.09	-	8.4	10.7	-	-
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (cm)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.3	-	0.5	-	1.6	2.0	-	-

Table C.6. Summary of Run B-1

Date: 04-10-87 Column ID: 5.1 cm Distributor: 1.85 mm				Liquid: n-butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	201.9	201.8	201.8	201.0	200.0	198.8	194.6	193.7
Gas hold-up (%)	3.05	5.99	8.43	10.59	12.74	14.71	18.7	22.85
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	-	1.54	1.6	1.72	1.7	1.45	1.4
Height slugs observed (cm)	-	-	210.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	0.6	0.8	1.1	1.7	2.2	2.5	3.2

Table C.7. Summary of Run B-2

Date: 04-10-87 Column ID: 5.1 cm Distributor: SMP				Liquid: n-butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	208.3	208.3	207.6	207.6	207.0	206.7	205.7	203.8
Gas hold-up (%)	3.24	6.28	8.91	10.66	12.83	15.78	19.1	23.57
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	-	1.4	1.6	1.8	1.53	1.5	1.6
Height slugs observed (cm)	-	-	210.0	120.0	120.0	120.0	120.0	120.0
Amplitude of Oscillation (cm)	0.3	0.6	0.8	1.0	1.6	2.2	3.5	4.4

Table C.8. Summary of Run B-3

Date: 04-15-87 Column ID: 5.1 cm Distributor: 1.85 mm				Liquid: 1.0% wt. butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	180.0	179.7	179.7	179.4	179.1	176.5	176.2	175.9
Gas hold-up (%)	3.24	7.21	9.87	12.8	15.57	20.8	33.29	41.8
Foam (cm)	0.3	0.6	1.0	1.3	2.54	6.4	40.6	86.4
Slug Frequency (1/s)	-	1.3	1.48	1.5	1.6	1.7	1.42	1.24
Height slugs observed (cm)	-	210.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	0.6	0.9	1.3	1.9	2.9	5.1	8.3

Table C.9. Summary of Run B-4

Date: 04-15-87 Column ID: 5.1 cm Distributor: 1.85 mm				Liquid: 1.0% wt. butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	12	9	7	5	4	3	2	1
Static Height (cm)	173.4	172.1	170.8	170.2	169.9	169.5	169.2	168.9
Gas hold-up (%)	42.2	37.27	22.03	17.41	13.98	10.70	7.46	3.6
Foam (cm)	81.3	63.5	15.2	2.9	1.9	1.3	0.6	-
Slug Frequency (1/s)	1.36	1.5	1.6	1.3	1.5	1.4	1.32	-
Height slugs observed (cm)	30.0	120.0	120.0	120.0	120.0	120.0	210.0	-
Amplitude of Oscillation (cm)	7.6	5.1	3.8	2.2	1.0	0.9	0.6	0.3

Table C.10. Summary of Run B-5

Date: 04-16-87
Column ID: 5.1 cm
Distributor: SMP

Liquid: 1.0% wt. butanol
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	149.9	149.9	149.9	149.9	149.2	148.9	148.6	148.0
Gas hold-up (%)	5.22	11.61	18.9	26.7	31.08	30.83	37.1	46.0
Foam (cm)	0.6	1.0	3.8	5.1	8.9	15.2	30.5	61.0
Slug Frequency (1/s)	-	-	-	-	0.6	1.1	1.08	1.0
Height slugs observed (cm)	-	-	-	-	210.0	120.0	120.0	120.0
Amplitude of Oscillation (cm)	0.3	0.3	0.3	0.3	0.6	1.3	2.5	5.1

Table C.11. Summary of Run B-6

Date: 04-20-87
Column ID: 5.1 cm
Distributor: 1.00 mm

Liquid: 1.0% wt. butanol
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	195.3	194.9	194.9	194.8	194.8	194.6	172.4	137.8
Gas hold-up (%)	3.30	6.97	10.23	13.83	17.10	22.6	38.57	52.83
Foam (cm)	0.3	0.6	1.0	1.3	1.9	10.2	45.7	114.3
Slug Frequency (1/s)	-	1.0	1.5	1.25	1.2	1.37	1.16	1.4
Height slugs observed (cm)	-	210.0	120.0	120.0	120.0	120.0	120.0	120.0
Amplitude of Oscillation (cm)	0.3	0.6	1.3	1.7	1.9	3.2	6.4	11.4

Table C.12. Summary of Run B-7

Date: 04-22-87 Column ID: 5.1 cm Distributor: 1.85 mm				Liquid: 0.5% wt. butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	176.5	176.4	175.9	175.6	175.3	174.6	174.3	173.7
Gas hold-up (%)	3.14	6.48	9.18	11.94	14.02	16.67	21.1	27.41
Foam (cm)	1.0	1.3	1.3	1.3	1.6	1.6	2.5	6.4
Slug Frequency (1/s)	-	1.2	1.2	1.5	1.5	1.3	1.3	1.43
Height slugs observed (cm)	-	210.0	210.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	1.0	1.3	1.7	1.9	2.5	3.8	4.5

Table C.13. Summary of Run B-8

Date: 04-22-87 Column ID: 5.1 cm Distributor: SMP				Liquid: 0.5% wt. butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	192.7	192.4	192.1	192.4	191.3	191.14	190.5	190.2
Gas hold-up (%)	3.65	7.9	11.81	13.98	16.09	18.65	23.86	28.35
Foam (cm)	0.63	1.3	1.6	1.6	1.9	2.2	3.8	6.4
Slug Frequency (1/s)	-	-	-	1.5	1.3	1.26	1.2	1.3
Height slugs observed (cm)	-	-	-	210.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	0.3	0.3	0.6	1.7	3.8	3.8	5.7

Table C.14. Summary of Run B-9

Date: 04-24-87

Column ID: 5.1 cm
Distributor: SMP

Liquid: 1.0% wt. butanol and 0.1% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	189.0	189.0	188.5	188.8	189.1	163.8	147.8	146.7
Gas hold-up (%)	4.03	6.74	10.87	23.38	31.06	43.8	49.83	51.75
Foam (cm)	0.6	0.6	1.3	35.6	66.0	99.0	122.0	137.0
Slug Frequency (1/s)	-	1.2	1.1	1.3	1.32	1.36	1.35	1.4
Height slugs observed (cm)	-	210.0	120.0	120.0	120.0	120.0	120.0	120.0
Amplitude of Oscillation (cm)	0.3	0.6	1.3	1.9	1.9	2.5	5.1	6.4

Table C.15. Summary of Run B-10

Date: 04-25-87

Column ID: 5.1 cm
Distributor: 1.85 mm orifice

Liquid: 1.0% wt. butanol and 0.1% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	175.9	175.6	175.3	174.4	173.5	172.6	171.7	170.8
Gas hold-up (%)	3.48	5.63	8.91	12.54	15.68	20.52	26.92	33.41
Foam (cm)	-	-	0.6	0.6	1.3	2.5	44.5	82.6
Slug Frequency (1/s)	0.6	1.0	1.1	1.2	0.9	1.3	1.3	1.4
Height slugs observed (cm)	210.0	120.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	0.6	2.0	2.2	2.5	3.8	5.1	7.6

Table C.16. Summary of Run B-11

Date: 04-27-87

Column ID: 5.1 cm
Distributor: 1.85 mm orifice

Liquid: 1.0% wt. butanol and 0.1% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	12	9	7	5	4	3	2	1
Static Height (cm)	222.6	220.3	219.1	218.8	217.8	216.9	216.5	216.2
Gas hold-up (%)	25.4	21.1	17.5	14.3	12.05	9.62	6.57	3.27
Foam (cm)	5.1	4.4	3.8	2.5	2.2	1.3	0.6	-
Slug Frequency (1/s)	1.2	1.1	1.3	1.1	0.9	1.0	0.9	0.6
Height slugs observed (cm)	30.0	120.0	120.0	120.0	120.0	120.0	120.0	210.0
Amplitude of Oscillation (cm)	7.6	7.0	4.4	3.8	2.5	2.0	1.3	0.5

Table C.17. Summary of Run B-12

Date: 04-28-87

Column ID: 5.1 cm
Distributor: 1.00 mm

Liquid: 1.0% wt. butanol and 0.1% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	186.4	185.9	185.7	185.3	184.9	184.5	184.2	183.7
Gas hold-up (%)	3.14	7.04	11.63	15.89	20.87	27.89	35.84	41.67
Foam (cm)	-	1.0	1.9	2.5	3.2	15.2	25.4	315.0
Slug Frequency (1/s)	0.54	0.9	1.0	1.2	1.0	1.2	1.0	1.2
Height slugs observed (cm)	210.0	210.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	0.6	1.3	1.9	3.2	4.4	5.1	8.9

Table C.18. Summary of Run B-13

Date: 05-5-87

Liquid: 1.0% wt. butanol and 0.5% wt. CMC

Column ID: 5.1 cm

Temperature: 24°C

Distributor: 1.85 mm

Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	194.6	194.3	194.1	193.9	193.7	193.5	193.3	193.0
Gas hold-up (%)	2.7	5.55	8.48	10.98	12.6	17.2	19.7	23.13
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	0.7	0.8	0.9	0.93	0.94	0.84	0.83	0.94
Height slugs observed (cm)	210.0	120.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	1.0	0.5	2.0	2.5	5.1	7.0	7.6	8.9

Table C.19. Summary of Run B-14

Date: 05-5-87

Liquid: 1.0% wt. butanol and 0.5% wt. CMC

Column ID: 5.1 cm

Temperature: 24°C

Distributor: SMP

Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	198.6	198.6	198.1	198.1	197.7	197.2	196.7	196.2
Gas hold-up (%)	2.87	6.64	10.08	13.33	15.64	18.72	22.36	27.8
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	0.53	0.84	0.87	0.94	0.98	0.94	0.91	0.832
Height slugs observed (cm)	210.0	120.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.6	1.0	1.3	2.5	3.8	6.4	8.9	11.4

Table C.20. Summary of Run B-15

Date: 05-7-87 Column ID: 5.1 cm Distributor: 1.00 mm	Liquid: 1.0% wt. butanol and 0.5% wt. CMC Temperature: 24°C Gas: Nitrogen							
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	195.6	195.6	195.6	195.6	195.4	195.3	195.1	194.9
Gas hold-up (%)	2.84	5.81	8.88	10.98	13.55	18.00	25.25	31.63
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	0.6	0.7	0.87	1.0	0.96	1.0	1.1	1.08
Height slugs observed (cm)	210.0	120.0	120.0	120.0	120.0	120.0	120.0	30.0
Amplitude of Oscillation (cm)	0.3	1.0	1.7	2.2	3.2	4.4	5.1	6.4

Table C.21. Summary of Run B-16

Date: 05-27-87 Column ID: 22.9 cm Distributor: 19x1.85 mm	Liquid: 1.0% wt. butanol Temperature: 24°C Gas: Nitrogen							
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	194.3	194.3	194.0	193.8	193.7	193.4	193.0	175.9
Gas hold-up (%)	4.67	9.73	13.46	17.05	21.8	29.2	33.04	42.3
Foam (cm)	0.3	1.3	3.1	3.8	5.0	20.1	27.6	35.1
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.3	0.6	1.3	1.3	1.3	2.5	3.8	5.0

Table C.22. Summary of Run B-17

Date: 06-1-87 Column ID: 22.9 cm Distributor: 19x1.0 mm				Liquid: 1.0% wt. butanol Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	190.5	190.3	190.2	189.8	189.7	189.5	176.5	156.5
Gas hold-up (%)	4.15	9.17	13.94	19.20	23.6	31.22	34.12	43.2
Foam (cm)	0.3	2.0	3.8	6.4	8.3	15.2	23.0	28.0
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.16	0.3	0.6	1.3	1.3	2.5	3.8	5.1

Table C.23. Summary of Run B-18

Date: 06-03-87 Column ID: 22.9 cm Distributor: 19x1.00 mm				Liquid: 1.0% wt. butanol and 0.1% wt. CMC Temperature: 24°C Gas: Nitrogen				
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	187.9	187.9	187.9	187.9	187.9	187.9	187.9	171.5
Gas hold-up (%)	3.58	8.64	16.85	23.9	29.2	31.8	34.1	43.3
Foam (cm)	0.6	2.2	4.4	7.6	8.9	-	-	-
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.3	0.6	0.6	1.3	2.5	5.1	5.7	8.9

Table C.24. Summary of Run B-19

Date: 06-4-87

Column ID: 22.9 cm
Distributor: 19x1.85 mm

Liquid: 1.0% wt. butanol and 0.1% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	183.8	183.8	182.9	182.4	181.8	181.3	180.9	180.3
Gas hold-up (%)	3.5	9.53	19.55	25.0	28.6	32.82	34.31	41.32
Foam (cm)	0.3	1.9	5.1	7.6	8.9	-	-	-
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.6	1.3	1.3	1.7	3.2	5.1	7.0	8.9

Table C.25. Summary of Run B-20

Date: 06-5-87

Column ID: 22.9 cm
Distributor: 19x1.85 mm

Liquid: 1.0% wt. butanol and 0.5% wt. CMC
Temperature: 24°C
Gas: Nitrogen

Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	188.9	188.9	188.5	187.9	187.9	187.6	187.3	-
Gas hold-up (%)	1.81	3.72	5.48	7.21	8.64	10.45	12.46	-
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	0.6	2.5	5.1	7.6	8.9	9.5	10.2	-

Table C.26. Summary of Run B-21

Date: 06-7-87 Column ID: 22.9 cm Distributor: 19x1.00 mm					Liquid: 1.0% wt. butanol and 0.5% wt. CMC Temperature: 24° C Gas: Nitrogen			
Gas Velocity (cm/s)	1	2	3	4	5	7	9	12
Static Height (cm)	187.96	187.96	187.96	187.96	187.96	187.96	187.96	-
Gas hold-up (%)	2.63	4.36	6.92	8.92	11.90	16.38	18.9	-
Foam (cm)	-	-	-	-	-	-	-	-
Slug Frequency (1/s)	-	-	-	-	-	-	-	-
Height slugs observed (cm)	-	-	-	-	-	-	-	-
Amplitude of Oscillation (cm)	1.3	2.5	3.2	3.8	5.1	6.4	7.8	-

APPENDIX D

SUMMARY OF DGD RESULTS FOR RUNS WITH NON-WAX LIQUID MEDIUMS

Table D.1. Summary of dynamic gas disengagement results for Run B-1.
(n-butanol, 0.051 m ID column, 1.85 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	2.03	-	27.25	3.1	0.187	-	0.813	0.0082	0.2232	2.08	5.55×10^{3}	-	9.95
0.02	1.94	-	29.00	6.0	0.254	-	0.746	0.0064	0.5651	2.15	1.74×10^{4}	-	1.54
0.03	1.82	17.73	39.81	8.5	0.131	0.467	0.401	0.0092	0.5511	2.20	1.58×10^{4}	6.10×10^{1}	4.63
0.04	1.88	18.71	48.80	10.6	0.265	0.372	0.363	0.0059	1.0754	2.24	3.74×10^{4}	5.29×10^{1}	2.9
0.05	1.71	27.17	49.88	12.7	0.273	0.383	0.344	0.0055	1.3848	2.29	6.27×10^{4}	2.17×10^{1}	3.15
0.07	1.34	19.39	48.00	14.7	0.181	0.414	0.405	0.0061	1.4552	2.33	1.00×10^{5}	7.59×10^{1}	4.89
0.09	1.30	20.82	51.00	18.7	0.160	0.469	0.370	0.0065	1.7215	2.39	1.27×10^{5}	9.10×10^{1}	4.88
0.12	1.24	16.16	42.67	22.8	0.151	0.414	0.434	0.0063	2.1696	2.51	1.79×10^{5}	2.19×10^{2}	12.5

Table D.2. Summary of dynamic gas disengagement results for Run B-2.
(n-butanol, 0.051 m ID column, 40 μm SMP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	1.93	-	18.83	3.2	0.419	-	0.580	0.0040	0.4827	2.15	1.58×10^4	-	23.6
0.02	1.83	-	22.15	6.3	0.315	-	0.685	0.0049	0.7657	2.22	2.79×10^4	-	34.4
0.03	1.62	-	23.83	8.9	0.278	-	0.722	0.0050	1.0791	2.28	5.16×10^4	-	42.2
0.04	1.64	18.49	46.37	10.6	0.345	0.193	0.462	0.0043	1.4802	2.32	7.62×10^4	2.95×10^1	4.47
0.05	1.59	19.91	44.80	12.8	0.251	0.392	0.357	0.0054	1.4350	2.37	7.50×10^4	5.91×10^1	4.72
0.07	1.08	8.55	29.56	15.7	0.150	0.272	0.578	0.0053	1.7928	2.45	1.78×10^5	6.55×10^2	33.7
0.09	0.98	3.75	29.59	18.8	0.073	0.187	0.740	0.0067	1.6885	2.54	1.45×10^5	6.65×10^3	53.3
0.12	1.31	19.23	31.57	23.6	0.140	0.427	0.433	0.0070	2.0229	2.67	1.53×10^5	1.47×10^2	33.7

Table D.3. Summary of dynamic gas disengagement results for Run B-3.
(1.0 wt % butanol + 0.0 wt % CMC, 0.051 m ID column, 1.85 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	1.56	15.22	–	3.2	0.099	0.900	–	0.0081	0.2368	1.86	6.08×10^3	5.95×10^1	–
0.02	0.95	22.82	–	7.2	0.428	0.571	–	0.0021	2.0569	1.93	2.71×10^5	2.62×10^1	–
0.03	0.94	11.79	31.53	9.8	0.306	0.328	0.365	0.0027	2.1626	1.99	2.83×10^5	1.53×10^2	8.95
0.04	0.58	2.44	24.85	12.8	0.209	0.376	0.414	0.0019	4.1090	2.05	1.11×10^6	2.66×10^4	27.8
0.05	0.56	2.15	45.60	15.5	0.235	0.410	0.354	0.0016	5.7904	2.12	1.73×10^6	5.33×10^4	4.80

Table D.4. Summary of dynamic gas disengagement results for Run B-5.
(1.0 wt % butanol + 0.0 wt % CMC, 0.051 m ID column, 40 μm SMP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	1.43	–	–	5.2	1.000	–	–	0.0014	2.1882	1.58	1.09×10^5	–	–
0.02	1.24	–	–	11.6	1.000	–	–	0.0012	5.6281	1.69	4.04×10^5	–	–
0.03	0.93	–	–	18.9	1.000	–	–	0.0009	12.2047	1.84	1.69×10^6	–	–

Table D.5. Summary of dynamic gas disengagement results for Run B-6.
(1.0 wt % butanol + 0.0 wt % CMC, 0.051 m ID column, 1.0 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	1.56	–	31.8	3.3	0.139	–	0.860	0.0086	0.2308	2.02	9.59×10^3	–	6.93
0.02	1.10	0.99	27.47	6.9	0.299	0.283	0.417	0.0017	2.4030	2.09	1.28×10^3	1.65×10^3	11.4
0.03	0.74	2.04	22.55	10.2	0.270	0.316	0.412	0.0018	3.3251	2.17	5.90×10^5	3.22×10^4	31.1
0.04	0.73	1.55	31.63	13.8	0.275	0.319	0.405	0.0017	4.9336	2.26	8.53×10^5	1.04×10^5	15.6
0.05	0.54	1.74	34.99	17.1	0.262	0.401	0.336	0.0014	7.4632	2.35	2.63×10^6	1.20×10^5	12.3

Table D.6. Summary of dynamic gas disengagement results for Run B-7.
(0.5 wt % butanol + 0.0 wt % CMC, 0.051 m ID column, 1.85 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	2.41	16.48	-	3.1	0.440	0.5591	-	0.0046	0.4070	1.82	6.99×10^{3}	2.77×10^{1}	-
0.02	1.18	34.66	51.0	6.5	0.350	0.518	0.131	0.0032	1.2365	1.88	1.03×10^{5}	5.98	0.47
0.03	0.83	2.52	51.00	9.2	0.220	0.359	0.420	0.0024	2.2821	1.93	2.62×10^{5}	1.55×10^{4}	2.19
0.04	0.65	2.10	18.02	11.9	0.178	0.168	0.653	0.0026	2.8033	1.99	5.99×10^{5}	1.69×10^{4}	1.03
0.05	0.78	2.57	47.10	14.0	0.250	0.165	0.584	0.0025	3.3350	2.03	5.80×10^{5}	1.09×10^{4}	6.23
0.07	0.54	1.63	16.31	16.6	0.216	0.506	0.277	0.0014	7.2728	2.09	1.85×10^{6}	1.60×10^{5}	87.0
0.09	0.64	1.77	16.17	21.1	0.360	0.406	0.233	0.0012	10.1962	2.21	2.46×10^{6}	1.32×10^{5}	100.0

Table D.7. Summary of dynamic gas disengagement results for Run B-8.
(0.5 wt % butanol + 0.0 wt % CMC, 0.0.051 ID column, 40 μ SMP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	1.45	14.00	–	3.6	0.194	0.8060	–	0.0052	0.4195	2.00	1.80×10^4	8.39×10^1	–
0.02	1.65	2.31	11.63	7.9	0.230	0.409	0.359	0.0029	1.6472	2.08	3.28×10^4	2.14×10^4	1.46
0.03	1.46	2.03	51.00	11.8	0.236	0.436	0.326	0.0026	2.7189	2.17	7.64×10^4	5.22×10^4	2.47
0.04	1.27	2.00	44.05	13.9	0.496	0.314	0.188	0.0018	4.6235	2.22	2.91×10^5	4.77×10^4	2.68
0.05	0.83	1.63	45.25	16.0	0.238	0.390	0.370	0.0019	5.1488	2.28	5.87×10^5	1.28×10^5	5.72
0.07	0.71	1.08	24.45	18.6	0.267	0.519	0.212	0.0012	9.6780	2.35	1.27×10^6	6.98×10^5	24.8
0.09	0.65	1.03	30.20	23.8	0.195	0.512	0.292	0.0012	12.0970	2.50	1.65×10^6	1.09×10^6	24.6
0.12	0.74	1.12	27.10	28.3	0.462	0.248	0.289	0.0011	15.8152	2.65	1.33×10^6	5.17×10^5	42.5

Table D.8. Summary of dynamic gas disengagement results for Run B-13.
(1.0 wt % butanol + 0.5 wt % CMC, 0.051 m ID column, 1.85 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	7.54	–	51.00	2.7	0.468	–	0.531	0.0138	0.1189	2.00	$2.32X10^2$	–	0.85
0.02	6.60	–	41.96	5.5	0.352	–	0.648	0.0145	0.2298	2.05	$5.48X10^2$	–	3.91
0.03	–	26.89	–	8.5	–	1.000	–	0.0139	0.3680	2.12	–	$3.61X10^1$	–
0.04	–	16.32	–	11.0	–	1.000	–	0.0113	0.5833	2.17	–	$2.15X10^2$	–
0.05	–	16.73	–	12.6	–	1.000	–	0.0120	0.6306	2.21	–	$2.33X10^2$	–
0.07	2.15	14.30	–	17.2	0.103	0.897	–	0.0090	1.1398	2.33	$1.61X10^4$	$4.80X10^2$	–
0.09	1.61	17.70	–	19.7	0.103	0.896	–	0.0087	1.3571	2.40	$4.60X10^4$	$2.99X10^2$	–
0.12	0.85	15.17	–	23.1	0.112	0.888	–	0.0053	2.6331	2.50	$4.12X10^5$	$5.73X10^2$	–

Table D.9. Summary of dynamic gas disengagement results for Run B-14.
(1.0 wt % butanol + 0.5 wt % CMC, 0.051 m ID column, 40 μm SMP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	7.85	–	44.55	2.8	0.276	–	0.723	0.0194	0.0883	2.04	1.30×10^2	–	8.6
0.02	3.89	19.69	–	6.6	0.081	0.918	–	0.0148	0.2686	2.12	7.61×10^2	6.61×10^1	–
0.03	1.96	16.35	–	10.0	0.110	0.890	–	0.0090	0.6695	2.20	1.26×10^4	1.76×10^2	–
0.04	1.65	16.93	–	13.3	0.196	0.803	–	0.0060	1.3319	2.28	5.19×10^4	1.96×10^2	–
0.05	1.73	16.30	–	15.6	0.208	0.791	–	0.0059	1.5933	2.34	5.81×10^4	2.61×10^2	–
0.09	1.14	4.30	7.39	22.4	0.184	0.430	0.385	0.0032	4.2209	2.53	2.75×10^5	1.20×10^4	2.11×10^3
0.12	1.24	4.28	7.41	27.8	0.163	0.601	0.235	0.0033	5.0741	2.71	2.54×10^5	2.26×10^4	1.69×10^3

Table D.10. Summary of dynamic gas disengagement results for Run B-15. (1.0 wt % butanol + 0.5 wt % CMC, 0.051 m ID column, 1.0 mm orifice, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	12.68	25.17	–	2.8	0.434	0.565	–	0.0176	0.0862	2.00	4.22×10^1	7.74	–
0.02	5.94	20.25	–	5.8	0.191	0.809	–	0.0139	0.2514	2.07	4.29×10^2	4.58×10^1	–
0.03	5.79	12.03	–	8.8	0.107	0.893	–	0.0108	0.4940	2.14	4.08×10^2	3.81×10^2	–
0.04	4.52	14.92	51.00	10.9	0.071	0.562	0.366	0.0165	0.3994	2.19	7.24×10^2	1.59×10^2	2.59
0.05	4.23	15.90	51.00	13.5	0.163	0.546	0.289	0.0127	0.6390	2.26	2.57×10^3	1.62×10^2	2.60
0.07	1.30	4.42	13.67	18.0	0.241	0.323	0.435	0.0034	3.1557	2.38	1.85×10^5	6.26×10^3	2.86×10^2
0.09	0.31	6.00	12.37	25.2	0.099	0.573	0.327	0.0023	6.6267	2.61	8.17×10^6	6.80×10^3	4.44×10^2
0.12	1.08	4.54	6.62	31.6	0.374	0.148	0.477	0.0022	8.5687	2.85	1.04×10^6	5.58×10^3	5.79×10^3

Table D.11. Summary of dynamic gas disengagement results for Run B-20.
(1.0 wt % butanol + 0.5 wt % CMC, 0.229 m ID column, 19X1.85 mm PP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	–	–	155.93	1.8	–	–	1.000	0.1559	0.0068	1.92	–	–	0.710
0.02	–	76.17	–	3.7	–	1.000	–	0.0762	0.0291	1.96	–	1.28×10^1	–
0.03	1.41	37.42	94.98	5.5	0.138	0.135	0.726	0.0091	0.3608	1.99	4.26×10^5	2.21×10^1	7.28
0.04	1.26	22.00	97.51	7.2	0.238	0.087	0.674	0.0050	0.8656	2.02	1.36×10^6	9.42×10^1	8.35
0.05	2.11	58.67	107.71	8.6	0.363	0.097	0.539	0.0056	0.9280	2.05	5.41×10^5	6.73	6.03
0.07	0.76	26.46	177.70	10.5	0.330	0.103	0.566	0.0023	2.7960	2.09	1.30×10^7	9.70×10^1	1.75
0.09	1.08	6.33	185.13	12.5	0.197	0.038	0.764	0.0051	1.4670	2.14	3.28×10^6	3.14×10^3	2.52

Table D.12. Summary of dynamic gas disengagement results for Run B-21.
(1.0 wt % butanol + 0.5 wt % CMC, 0.229 m ID column, 19X1.00 mm PP, 24°C)

u_g (m/s)	d_{BS} (mm)	d_{BM} (mm)	d_{BL} (mm)	ϵ_{go} (%)	f_S	f_M	f_L	d_s (m)	a_g (cm^2/cm^3)	H_e (m)	n_S	n_M	n_L
0.01	5.65	–	105.17	2.6	0.448	–	0.551	0.0118	0.1335	1.93	9.91×10^3	–	1.89
0.02	2.58	73.83	–	4.4	0.398	0.601	–	0.0061	0.4288	1.96	1.57×10^5	1.01×10^1	–
0.03	1.29	–	196.02	6.9	0.476	–	0.523	0.0027	1.5474	2.01	2.44×10^6	–	0.76
0.04	0.87	–	125.21	8.9	0.501	–	0.498	0.0017	3.1254	2.06	1.12×10^7	–	3.68
0.05	0.77	5.56	123.11	11.9	0.465	0.049	0.485	0.0016	4.4321	2.13	2.07×10^7	5.76×10^3	5.19
0.07	0.50	3.71	57.52	16.4	0.580	0.016	0.403	0.0009	11.5624	2.24	1.35×10^8	9.00×10^3	61.4

APPENDIX E

PROCEDURES FOR MEASURING PHYSICAL PROPERTIES OF NON-WAX LIQUID MEDIUMS

A. Surface Tension Measurements

1. Apparatus

Surface tension of aqueous mixtures were measured using Fisher surface tensiometer model 20. The tensiometer employs the ring method. A platinum-iridium ring of precisely known dimensions is suspended from a horizontal lever arm clamped on a torsion wire. Increasing the torsion in the wire raises the arm and the ring. The surface tension is measured as the force necessary to pull the test ring free from the surface film.

2. Calibration

The tensiometer was calibrated by placing known weights on the ring, (more description is found in the users manual). The surface tension, S, was calculated as:

$$S = \frac{m\,g}{2l} \qquad (E.1)$$

where: m is the mass (g), g is the acceleration due to gravity (cm/s^2), l is the ring circumference = 6.0000 cm, and S is the calculated apparent surface tension (dynes/cm).

If the value of S does not match the observed surface tension (P) on the dial, then some adjustments of the weights on the lever arm was done. This procedure was repeated until the calculated value matched the dial value, then different weights were placed to check the accuracy of

values.

3. Measurements

Apparent surface tension, P, was measured for different mix

this study. In order to obtain the true surface tension the apparent valu

multiplied by a correction factor as supplied by the manufacturer (for more detail

refer to the users manual).

Results of surface tension measurements are shown in Tables 7-9.

B. Viscosity Measurements

1. Introduction

Fluids which exhibit a linear relationship between shear stress and shear rate are described as Newtonian fluids. The ratio of shear stress to shear rate is constant for Newtonian fluids and is defined as:

$$\mu = \frac{\tau}{\dot{\gamma}} \qquad (E.2)$$

where: μ is the viscosity, τ is the shear stress, and $\dot{\gamma}$ is the shear rate.

Aqueous solutions of CMC are non-Newtonian mixtures, they are considered to be pseudoplastic. Their relationship between shear stress and shear rate is characterized by a power law, Ostwald-de Waele model. This model is defined as:

$$\tau = K \dot{\gamma}^{n} \qquad (E.3)$$

For non-Newtonian fluids the apparent fluid viscosity is defined as:

$$\mu_a = \frac{\tau}{\dot{\gamma}} = K\,\dot{\gamma}^{n-1} \qquad (E.4)$$

where: μ_a is the apparent viscosity, K is the fluid consistency index, i.e. is the measure of fluid 'thickness' and n is the flow behavior index, i.e. is the measure of degree of non-Newtonian behavior of the fluid when $n = 1$ the fluid is Newtonian in nature.

2. Apparatus

Viscosities of aqueous solutions were measured using a Fann model 50C viscometer. This is a concentric cylinder rotating viscometer. A force is imparted on the fluid by the rotation of the outer cylinder while the inner cylinder is held stationary. The fluid can be visualized as infinitely thin cylinders slipping past each other (Couette flow).

Schematic diagram of the viscometer is shown in Figure E.1. The outer cylinder is filled with 30 ml of sample to be measured. The rotation of the outer cylinder (cup) results in the formation of shear stress within the fluid. This shear stress is then transmitted to the inner cylinder (bob) in the form of torsional force. The force causes the bob to rotate and the degree of rotation is measured by the transducer which converts the deflection into a voltage signal. The voltage signal is fed into the microcomputer via a digital analog converter. The output voltage is considered to be linearly related to the shear stress.

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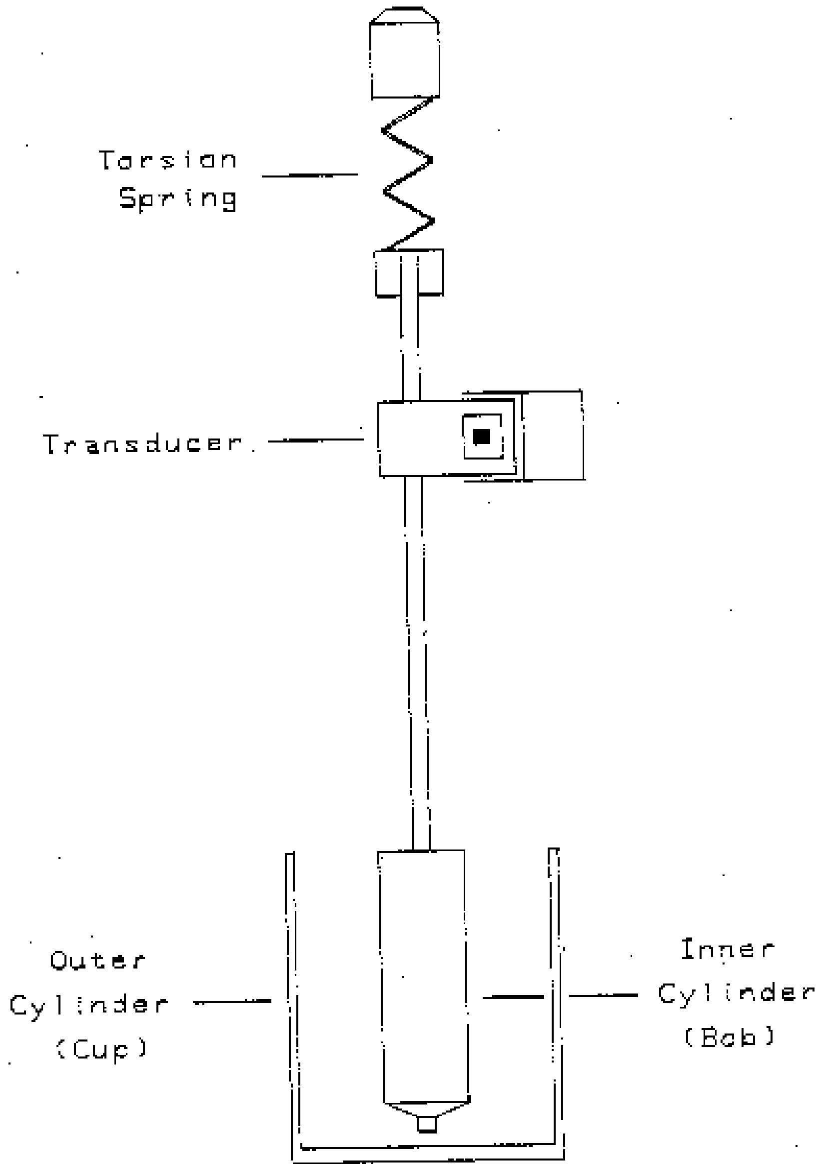

Figure E.1. Schematic diagram of Fann model 50C viscometer.

3. Calibration of the Viscometer

Calibration of viscometer requires a Newtonian fluid of known viscosity at a given temperature. During these measurements standard silicone oils of 5.1 cP and 8.9 cP at 25 °C were used for calibrations. Distilled water was used to check the accuracy of the calibration. Shear stress (voltage signals) were measured at ten different shear rates, 42.6, 85.2, 127.7, 170.3, 340.7, 511.0, 681.3, 766.5, 851.6, and 1001.5 s^{-1}. These shear rates cover the range of shear rates which were observed in the bubble column i.e., Nishikawa *et al.* (1977) estimated that shear rates in bubble column are given by:

$$\dot{\gamma} = 5000 \, u_g \tag{E.5}$$

where u_g is the superficial gas velocity in the column, (m/s). During this study u_g was varied from 0.01 m/s to 0.12 m/s which corresponds to shear rates of 50 to 600 s^{-1}. The same definition of shear rate has been used by Nakanoh and Yoshida (1980), Schumpe and Deckwer *et al.* (1982), Godbole *et al.* (1984), and by Haque *et al.* (1986).

The following linear equation between voltage, V (mv) and shear stress was obtained from calibration liquids.

$$\tau = 24704.312 \, V - 2.1994 \tag{E.6}$$

This equation was used to convert voltage signals into shear stress for all measurements in this study. Results of viscometer calibration using standard liquids are shown in Figure E.2. The accuracy of calibration equation was re-checked after every 10 measurements to see if there was any offset.

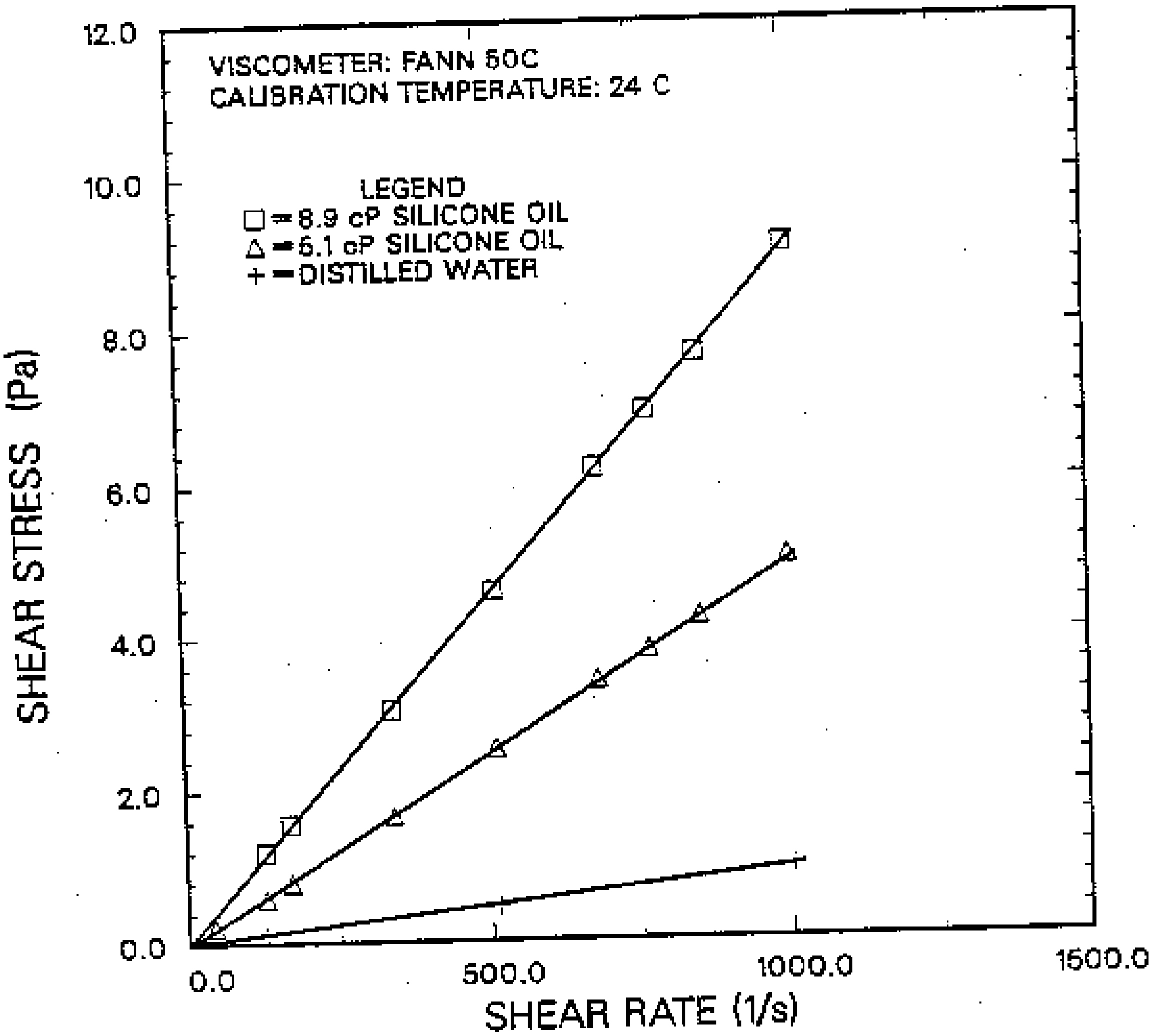

Figure E.2. Calibration curves for viscometer using standard liquids.

4. Analysis of non-Newtonian Mixtures

Shear rate and shear stress of aqueous solutions of CMC are characterized by:

$$\tau = K \dot{\gamma}^{n} \tag{E.3}$$

Using measured values of τ and $\dot{\gamma}$, values of K and n were obtained by plotting $ln\tau$ against $ln\dot{\gamma}$. K was obtained from the intercept and n from the slope of the straight line fitted to experimental data points. Measured values of K and n for different mixtures used in this study are reported in Tables 8 and 9.

APPENDIX F

DYNAMIC GAS DISENGAGEMENT TECHNIQUE

A. Theory and Procedure

Sriram and Mann (1977) developed the dynamic gas disengagement (DGD) technique for obtaining the swarm bubble rise velocity and the bubble size distribution in bubble columns. This technique requires the knowledge of the change in liquid level as a function of time, once the gas flow to the bubble column is shut off.

Sriram and Mann showed that the gas hold-up, $\epsilon_g(t)$, after a time, t, is given by

$$\epsilon_g(t) = \epsilon_{go} \int_0^{\infty} \left[f(d_B) \left(1 - \frac{tu(d_B)}{H(t)} \right) \right] d(d_B) \tag{F.1}$$

where $(1 - tu(d_B)/H(t))$ is the fraction of the volume fraction of the volume of bubbles in the dispersion after an elapsed time, t, ϵ_{go} is the average gas hold-up at time zero, $f(d_B)d(_B)$ is the volume fraction of the bubbles having size between d_B and $d_B + d(d_B)$, and $u(d_B)$ is the rise velocity associated with a bubble of size d_b. Theoretically, equation (F.1) assumes that bubble size distribution is initially axially homogeneous and that no interactions between bubbles occurs during the disengagement process.

1. Classification for N classes of Bubbles

A theory for obtaining the bubble size distribution from DGD can be found elsewhere (Bukur *et al.* 1987), only the final equations are given here. Equation

(F.1) is valid for a continuous bubble size distribution, and its discretized version for N classes of bubbles is given by:

$$\epsilon_g(t) = \epsilon_{go} \sum_{i=1}^{N} f_i \left[1 - \frac{tu(d_{Bi})}{H(t)}\right] \qquad (F.2)$$

where i represents the individual bubble classes, f_i is the volume fraction of bubbles in class i, and u_{Bi} is the rise velocity associated with this class of bubbles. It is assumed that class N comprises of the largest bubbles and class 1 contains the smallest bubbles. After a time, t_1^*, all of the bubbles in class N will have disengaged along with some bubbles in the other N-1 classes. Similarly, after a time t_2^* ($t_2^* > t_1^*$) all of the bubbles in class N-1 will have disenganged, and so on until all bubbles have disengaged (see Figure F.1). By this assumption, the term $(1 - tu_{BN}/H)$ becomes zero at time t^*_1 and the term $(1 - \frac{t}{H} u_{BN-1})$ at $(t^*_2 > t^*_1)$ becomes zero at time t^*_2 leading to the following general equation for the dynamic hold-up, $\epsilon_g(t)$:

$$\epsilon_g(t) = \epsilon_{go} \sum_{i=1}^{N} f_i \left[1 - \frac{tu(d_{Bi})}{H(t)}\right] \qquad t_{N-k+1} \geq t > t^*_{N-k} \qquad (F.3)$$

Equation (F.3) can be rearranged so as to relate the normalized liquid level (H/H_e) to time elapsed (t) to obtain the following equation:

$$\frac{H}{H_e} = \frac{H_s/H_e}{1 - \sum_{i=1}^{k} \epsilon_{goi}} - t\frac{\sum_{i=1}^{k} \epsilon_{goi} u_{Bi}}{H_e\left[1 - \sum_{i=1}^{k} \epsilon_{goi}\right]} \qquad t_{N-k+1} \geq t > t^*_{N-k} \qquad (F.4)$$

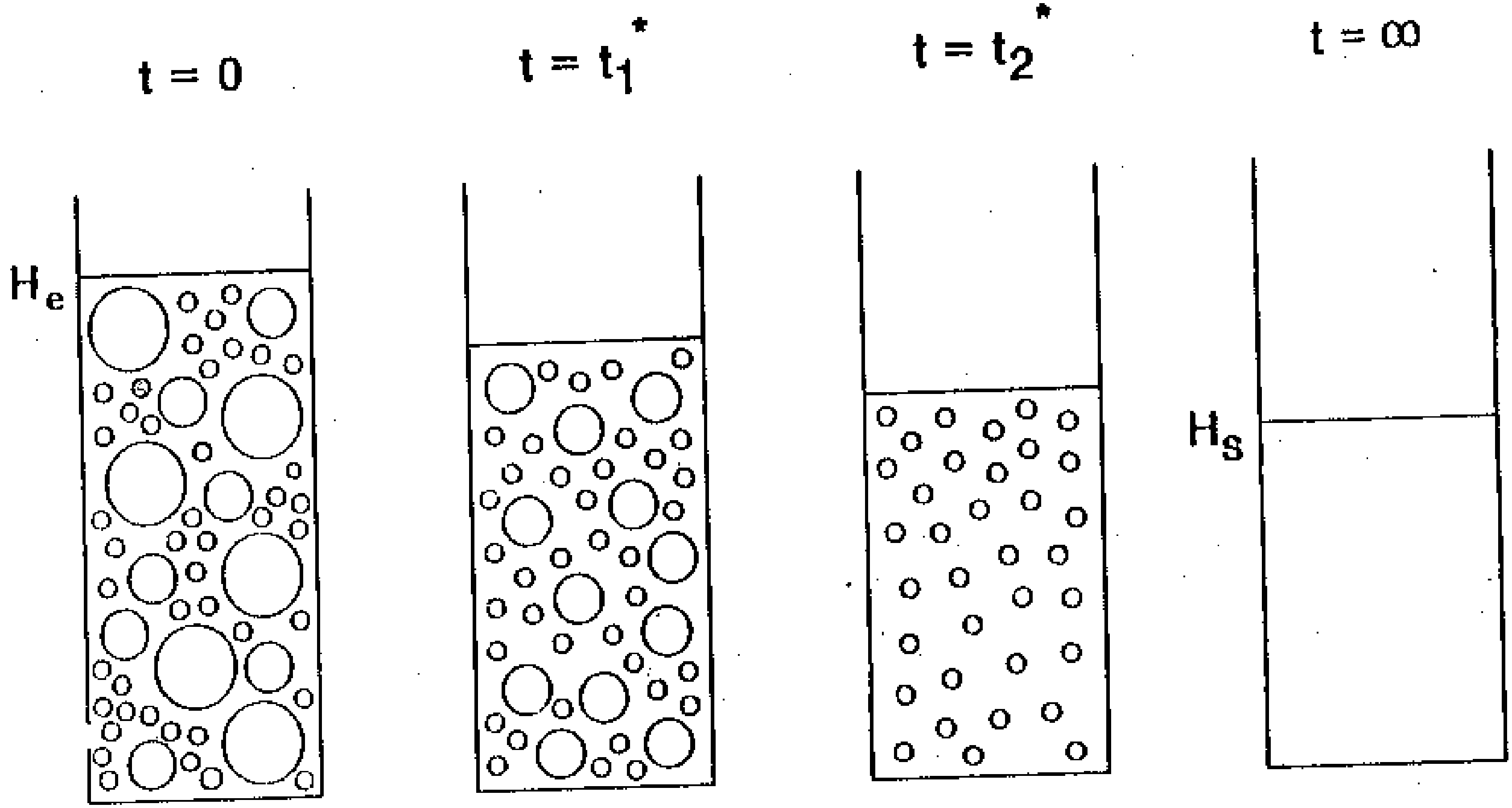

Figure F.1. Disengagement of bubbles after the gas flow is cutoff.

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where $\epsilon_{goi} = \epsilon_{go} f_i$, and H_s is the static height. A plot of normalized liquid level (H/H_e) versus time elapsed (t) would result in a series of straight lines as shown in Figure F.2.

2. Procedure for Obtaining ϵ_{goi}, u_{Bi}, and f_i

Estimates of ϵ_{goi} and u_{Bi} are obtained from the experimental plot of normalized liquid level versus time. Assuming t_N^* is the time when all bubble have disenganged from the liquid. The line beyond this time represents the static liquid height and has a zero slope, s_o. and the intercept is H_s/H_e.

The first step is to obtain the slopes and the intercepts of the N straight line segments (see Figure F.2). Let s_1 to s_N represent the slopes of these lines, and let b_1 to b_N represent the intercepts of these lines. Equation F.4 can be used to obtain the expressions for the slope and intercept of the straight lines.

For the k^{th} straight line the following expressions represent the slope and the intercept:

$$\text{slope :} \qquad s_k = \frac{\sum_{i=1}^{k} \epsilon_{goi} u_{Bi}}{H_e\left[1 - \sum_{i=1}^{k} \epsilon_{goi}\right]} \tag{F.5}$$

$$\text{intercept :} \qquad b_k = \frac{H_s/H_e}{1 - \sum_{i=1}^{k} \epsilon_{goi}} \tag{F.6}$$

These equations can be manipulated to obtain the following expressions for ϵ_{goi} and u_{Bi}

$$\epsilon_{goi} = \frac{H_s}{H_e}\left[\frac{1}{b_i - 1} - \frac{1}{b_i}\right] \qquad i = 1 \rightarrow N \tag{F.7}$$

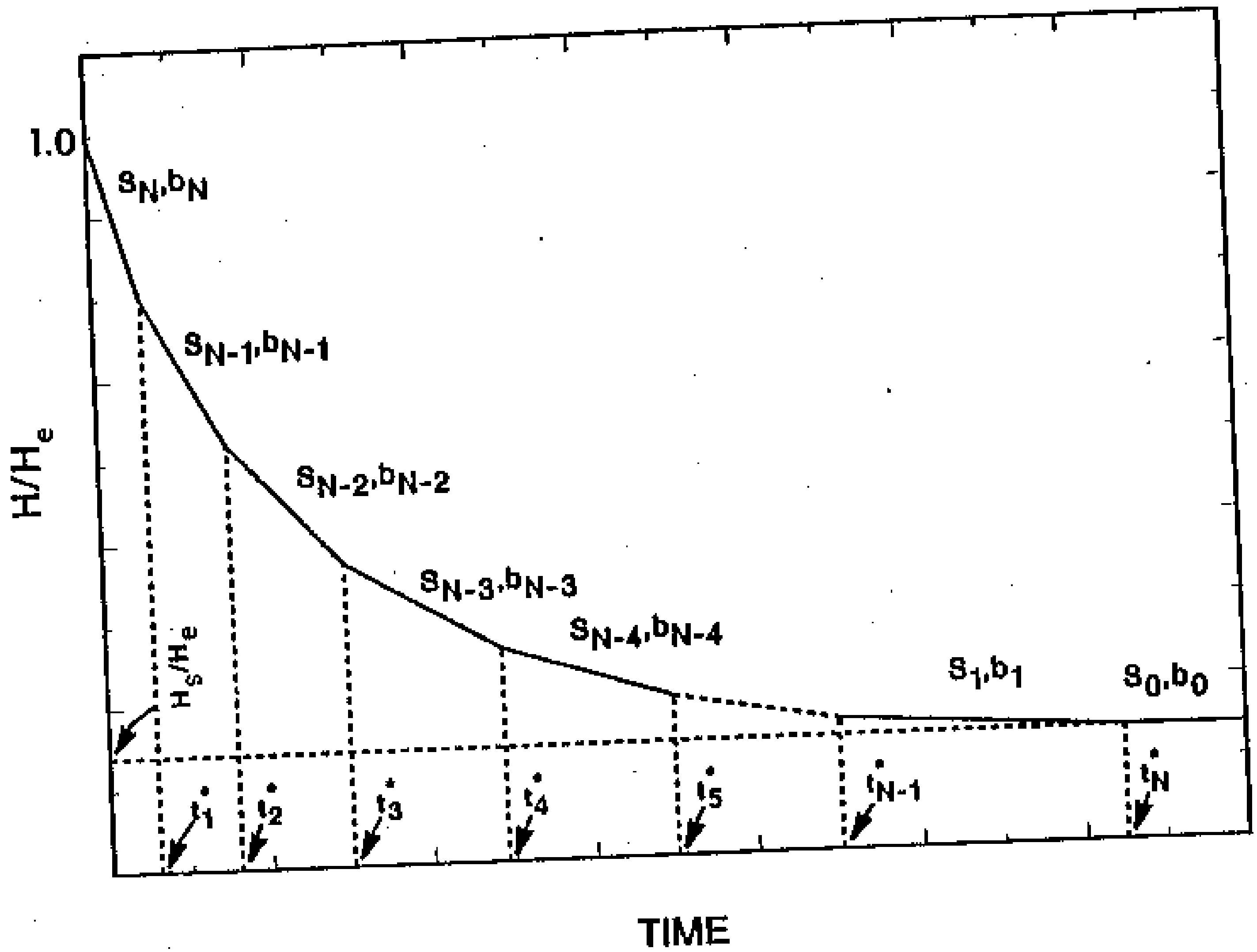

Figure F.2. Normalized height as a function of time.

$$u_{Bi} = \frac{H_e \left[b_i s_{i-1} - b_{i-1} s_i\right]}{b_i - b_{i-1}} \qquad i = 1 \rightarrow N \tag{F.8}$$

Equations F.7 and F.8 are used to estimate ϵ_{goi} and u_{Bi} for the N classes of bubble sizes. The fraction of bubbles of class i, is given by:

$$f_i = \frac{\epsilon_{goi}}{\epsilon_{go}} \qquad i = 1 \rightarrow N \tag{F.9}$$

The number of bubbles, n_i, of size d_{Bi} were calculated as follows:

$$n_i = \frac{\epsilon_{goi} V_T}{V_i} = \frac{3\epsilon_{goi} d_c{}^2 H_e}{2 d_{Bi}^3} \tag{F.10}$$

where V_T is the total volume of dispersion and V_i is the volume due to bubbles of size d_{Bi}.

Literature correlations were used to obtain bubble sizes based on the bubble rise velocity. With the knowledge of bubble size and fraction of bubbles the Sauter mean bubble diameter and specific gas-liquid interfacial area can be calculated as follows:

Sauter Mean Diameter

Sauter mean diameter, d_s, is given by:

$$d_s = \frac{\sum_{i=1}^{N} n_i d_{Bi}{}^3}{\sum_{i=1}^{N} n_i d_{Bi}{}^2} \tag{F.11}$$

which after substitution of equation F.10 gives:

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$$d_s = \frac{\sum_{i=1}^{N} \epsilon_{goi}}{\sum_{i=1}^{N} \epsilon_{goi}/d_{Bi}} \quad (F.12)$$

Specific gas-liquid interfacial area is given by:

$$a_g = \frac{6\epsilon_{go}}{d_s} \quad (F.13)$$

B. Sample Calculation for DGD Analysis (Run B-20, u_g=0.09 m/s)

The following sample calculation illustrates how the DGD (Dynamic Gas Disengagement) method was used to obtain results for bubble dynamics (bubble size distribution and Sauter bubble diameter) and specific gas-liquid interfacial area. The data selected were from a run with non-Newtonian mixture. Similar procedure was used for waxes and for Newtonian mixtures applying the appropriate equations.

The mixture used for Run B-20 in the 0.229 m ID column contained 1.0 wt % butanol with 0.5 wt % CMC. The mixture had the following physical properties

ρ=997.0 kg/m^3

σ=0.0489 N/m

K=0.773 Pa.s^n

n=0.575

Using the correlation by Nishikawa, the viscosity of the mixture is calculated as:

$$\mu_a = K(5000\ u_g)^{(n-1)} = 0.0576 \text{ Pa.s}$$

At 0.09 m/s the expanded height (H_e) was 214.0 cm and the static height (H_s) was 187.3 cm giving the average gas hold-up of 12.46 %.

1. Replaying the video tape to obtain liquid height at different time intervals after the gas flow rate was cut off. The following values were obtained:

t (s)	H (cm)	$\frac{H}{H_e}$
0.0	214.0	1.0
0.2	212.0	0.991
0.5	209.0	0.977
0.7	206.0	0.963
1.2	202.5	0.946
1.4	200.3	0.936
1.6	198.0	0.925
1.9	196.0	0.916
2.5	193.6	0.905
5.0	192.4	0.899
10.0	192.0	0.897
20.0	190.6	0.891
70.0	190.0	0.887
100.0	189.3	0.885

2. Plot normalized height, H/H_e, versus time, t, as illustrated in Figure F.3.
3. Approximate the curve by straight lines and estimate slopes (s_i) and the intercepts (b_i). For this set of data the curve was approximated by three straight lines representing a trimodal bubble size distribution: small, medium, and large bubble sizes. The following values of slopes and intercepts were obtained:

$s_1 = -0.000125$ $\quad$ $s_2 = -0.000544$ $\quad$ $s_3 = -0.049$

$b_1 = 0.8973$ $\quad$ $b_2 = 0.9017$ $\quad$ $b_3 = 1.0051$

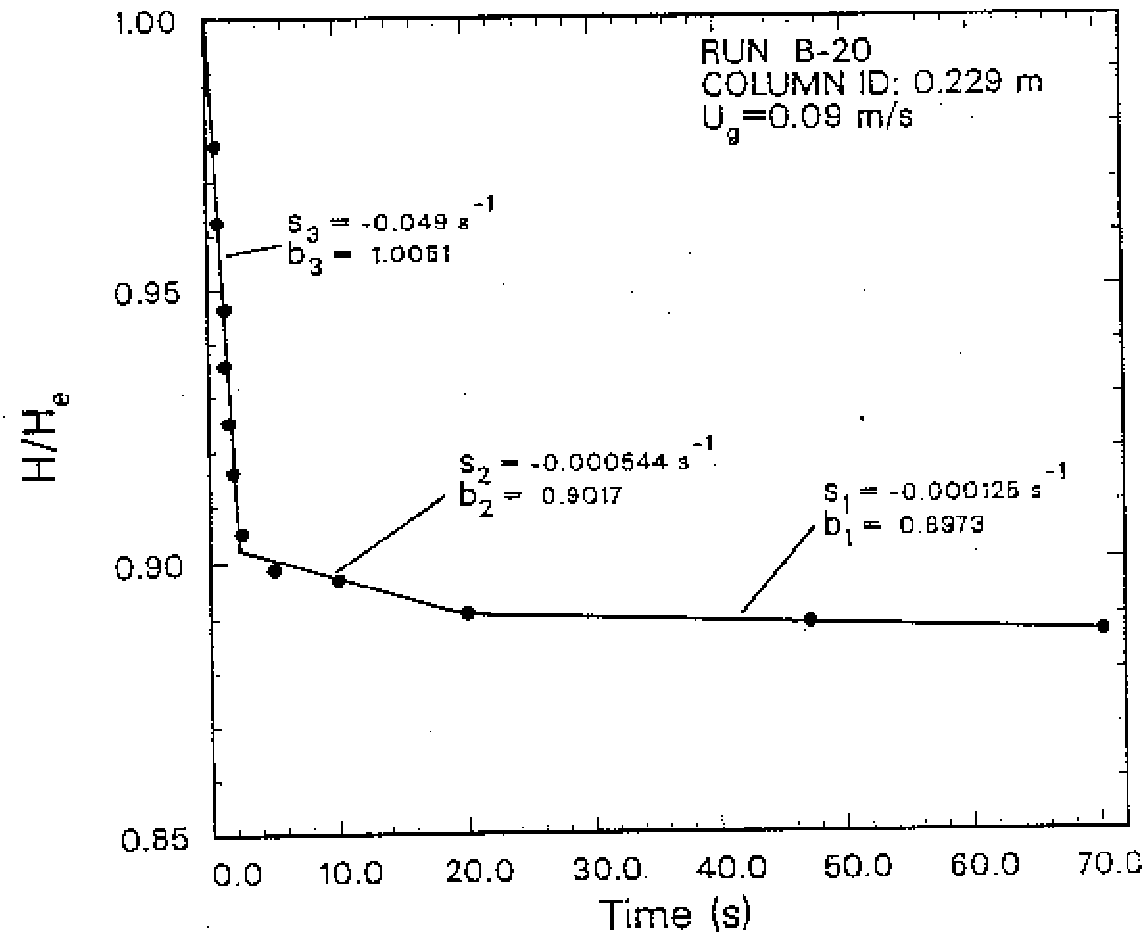

Figure F.3. Plot of normalized height versus time for dynamic gas disengagement analysis (Run B-20, u_g = 0.09 m/s).

4. Estimation of bubble swarm velocities (u_{bi}) and fractions of gas hold-up for each bubble group (ϵ_{goi}).

$$\epsilon_{go1} = \frac{1 - H_s}{b_1 H_e} = 0.0246$$

$$\epsilon_{go2} = \frac{H_s}{H_e}\left[\frac{1}{b_1} - \frac{1}{b_2}\right] = 0.0048$$

$$\epsilon_{go3} = \frac{H_s}{H_e}\left[\frac{1}{b_2} - 1\right] = 0.0952$$

$$u_{b1} = \frac{H_s s_1}{\left[b_1 - \frac{H_s}{H_o}\right]} = 1.06 \text{ cm/s}$$

$$u_{b2} = \frac{H_o\left[b_2 s_1 - b_1 s_2\right]}{b_2 - b_1} = 18.26 \text{ cm/s}$$

$$u_{b3} = \frac{H_o\left[s_2 - b_2 s_3\right]}{1 - b_2} = 95.32 \text{ cm/s}$$

5. Estimation of volume fractions for each bubble group: small, medium, and large bubbles;

$$f_i = \frac{\epsilon_{goi}}{\epsilon_{go}}$$

where: ϵ_{go}=12.46 %

$$f_1 = \frac{0.0246}{0.1246} = 0.197$$

$$f_2 = \frac{0.0048}{0.1246} = 0.038$$

$$f_3 = \frac{0.0952}{0.1246} = 0.764$$

6. Estimation of bubble sizes.

a. Estimation of bubble rise velocity ($u_{bi\infty}$) from the swarm velocity. (for small and medium bubble sizes) using the correlation by Marrucci (1965), Equation (5.1)

$$u_{bi\infty} = u_{bi} \frac{1 - \epsilon_{goi}^{5/3}}{(1 - \epsilon_{goi})^2}$$

thus

$$u_{b1\infty} = \frac{1.06(1 - 0.0246)^{5/3}}{(1 - 0.0246)^2} = 1.11 \text{ cm/s}$$

$$u_{b2\infty} = \frac{18.26(1 - 0.0048)^{5/3}}{(1 - 0.0048)^2} = 18.43 \text{ cm/s}$$

b. Estimation of small bubble size using Stokes law, Equation (5.8)

$$d_{b1} = \sqrt{\frac{0.011 \times 18 \times 0.0576}{9.81 \times (997 - 1.82)}} = 0.00108 \text{ m}$$

where: 1.82 kg/m^3 is the density of nitrogen.

Checking if $N_{Re} < 2$

$$N_{Re} = \frac{997 \times 0.011 \times 0.00108}{0.0576} = 0.2$$

which is within the range. If N_{Re} was to be greater than 2.0, then the correlation by Clift *et al.*, 1978 would have been used to estimate the bubble size.

c. Estimation of medium bubble size using the correlation by Clift *et al.* To obtain the bubble size, initial range of H has to be assumed in order to start calculations. The calculated bubble size is then substituted back to check if all conditions are satisfied. If not, another range is tried.

Assuming: $2 < H > 59.2$ Equation (5.7)

$$u_{bi\infty} = \frac{\mu_l}{\rho_l d_{bi}} M^{-0.149} (J - 0.857)$$

Solving this equation numerically, gives d_{b2}=0.00633 m and

$$M = \frac{g\ \mu_l^4\ (\rho_l\ -\ \rho_g)}{\rho_l^2\ \sigma^3} = 0.00091$$

which is less than 0.001.

$$N_{Re} = \frac{d_{bi}\ v_{bi\infty}\ \rho_l}{\mu_l} = 20.2$$

which is greater than 0.1

$$E_o = \frac{g\ (\rho_l\ -\ \rho_g)\ d_{bi}^2}{\sigma} = 8.0$$

which is less than 40.0

Cheking if the assumed range of H is valid

$$H = \frac{4}{3}\ E_o\ M^{-0.149}\ (\frac{\mu_l}{\mu_w})^{-0.14}\ = 16.91$$

Therefore the assumed range of H is valid. Thus the value of J is

$$J = 0.94\ H^{0.747}\ = 7.77 \qquad (2\ <\ H\ \geq\ 59.3)$$

With all conditions for M, E_o, N_{Re}, and H satisfied, then the calculated bubble size represents the bubble size for the medium group.

d. Estimation of large bubble size.

Applying the correlation by Mendelson (1967), the large bubble size is given by:

$$d_{b3} = \frac{u_{b3\infty}{}^2 + \sqrt{u_{b3\infty}{}^4 - \frac{4g\sigma}{\rho}}}{g}$$

$$d_{b3} = \frac{0.9532^2 + \sqrt{0.9532^2 - \frac{4\times 9.81\times 0.049}{997}}}{9.81}$$

$$= 0.185 \text{ m}$$

8. Estimation of number of bubbles, N_i.

Total volume of dispersion is given by:

$$V_T = \frac{\pi dc^2 H_e}{4} = 0.0881 \text{ m}^3$$

and

$$\epsilon_{goi} = \frac{V_i}{V_T} = \frac{3N_i d_{bi}{}^3}{2H_e d_c{}^2}$$

or

$$N_i = \frac{3\epsilon_{goi} d_c{}^2 H_e}{2d_{bi}{}^3}$$

Using the above equation the calculated values are:

$$N_1 = 3.28 \times 10^6$$

$$N_2 = 3.18 \times 10^2$$

$$N_3 = 2.5$$

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9. Estimation of Sauter mean bubble diameter, d_s.

Sauter mean bubble diameter is given by:

$$d_s = \frac{\epsilon_{go}}{\sum_{i=1}^{3}\left[\frac{\epsilon_{goi}}{d_{bi}}\right]}$$

substituting the hold-up values and the bubble size values one obtains,

$$d_s = \frac{0.1246}{\frac{0.0246}{0.00108} + \frac{0.0048}{0.00633} + \frac{0.0952}{0.165}} = 0.0051 \text{ m}$$

10. Estimation of specific gas-liquid interfacial area, a_g.

a_g is given by:

$$a_g = \frac{6\epsilon_{go}}{d_s} = \frac{6 \times 0.1246}{0.0051} = 146.6 \text{ m}^2/\text{m}^3$$

VITA

Matheo Lue Raphael was born in February 11, 1960 in Singida, Tanzania. After completion of his high school in 1978, he joined the University of Dar-es-Salaam in Tanzania. He graduated with B.Sc. first class in Chemical Engineering in September, 1984. He joined the department of Chemical and Process Engineering at the University of Dar-es-Salaam as a Tutorial Assistant. He worked for one year before joining the Department of Chemical Engineering at Texas A&M in January 1986 for M.S. degree.

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