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Scientific Notebook No. 561: Description of the Experiments (05/23/2003 through 12/10/2003)

LABORATORY NOTEBOOK

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NOTEBOOK NO. _____
ISSUED TO B. Hill / J. Phillips / T. Menand
ON 12/17 **20**02
DEPARTMENT _____
RETURNED _____ **20**____

This scientific notebook documents work performed to study the interaction of gas-bearing basaltic magma with a horizontal tunnel, CNWRA project # 06002.01.051

Initial entry by Dr. Jeremy C. Phillips

All entries are dated using the European format (day/month/year)

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Title of the experiments:
Buoyancy-driven circulation of bubbly magma within a horizontal tunnel due to density variations caused by separation of bubbles.

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Rational for the experiments:
Following intersection of the rising magma with a tunnel, a pathway will likely be established to the surface. Magma will then flow through this pathway for days to weeks, impacting the performance of engineered structures located along or near the flow path. Convective circulations may occur in magma-filled structures due to gas exsolution and segregation. A number of different flow regimes may develop, depending on the volume flux of magma through the system, the size of bubbles in the magma, and the geometry of flow system. The flux of magma through the dike may drive a recirculating flow within a drift, which may result in the entire volume of the tunnel being exchanged with the dike. Conversely, there may be stagnant regions where the magma has a long residence time. Vapor bubbles also will exsolve or grow from the magma. If the bubble size is large, the bubble rise speed may be large compared to the flow within a drift, resulting in significant melt-bubble separation in the drift and the formation of a coalesced foam at the drift roof. This process may result in foam collapse, which can drive fire-fountain eruptions. Along with the foam collapse, dense degassed magma may drain back into the dike/conduit system and possibly be re-entrained into the ascending magma flow. Time scales for foam collapse and flow recirculation may depend critically on the geometry of the dike-drift intersection and the angle of the tunnel to the dike.
The first series of experiments described in this notebook investigate the buoyancy-driven exchange flow between a vertical dyke abutting an open or closed, horizontal

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tunnel in the special case where the fluids in the dyke and the tunnel are bubble free and of different densities and viscosities. These experiments serve as a background study for the more realistic case where the fluid contains bubbles. The dynamics of this bubbly case is investigated by a second series of experiments and we anticipate that the presence of the bubbles will enhance the exchange flow between the dyke and the tunnel owing to their separation from the fluid in the tunnel.

Description of the analogue experimental system

Description of the apparatus

The apparatus consists of a series of interlocking glass process tube making a loop such that one of the vertical conduits of the loop, representing a dyke, is connected to a side arm tube, representing a tunnel (see figure below). The glass process tube has an internal diameter of 40 mm and the side arm length can be varied from 150 mm upwards. In some experiments a gate was fitted at the entrance to the side arm to separate the fluids prior to starting an experiment, in the case of the fluid in the side arm having a different density from that in the rest of the flow loop. The apparatus is filled with a salty aqueous solution and bubbles are generated by electrolysis using a nickel gauze as the anode and a platinum wire as the cathode that are both immersed into the vertical conduit well below the connection with the tunnel. Part of the loop is a pump such that the fluid can be made to flow with a controlled and constant flow rate.

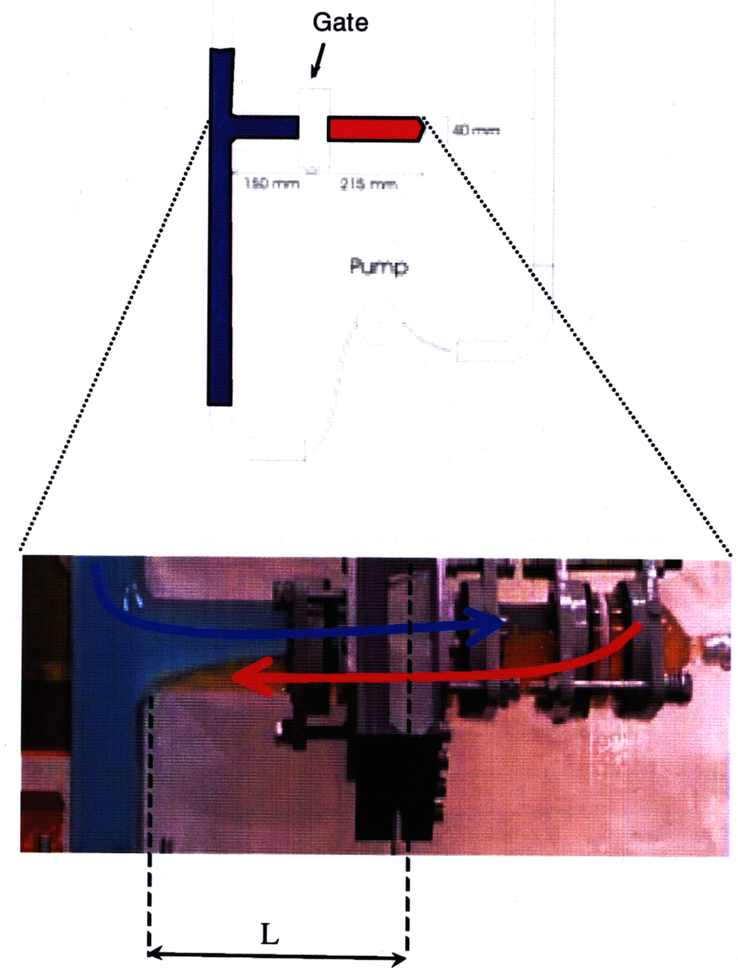
Experimental materials

Most of the working fluids are aqueous solutions containing various amounts of dissolved salt (Sodium Chloride) and Natrosol (hydroxyethylcellulose). The salt provides the drive for the electrolysis as well as a control on the density of the fluid while the natrosol is a food polymer that allow solution viscosities to be varied without affecting other properties. Densities are calculated by weighing a known volume of each fluid. Viscosities are measured over a range of shear rates with a Haake RV20 Rotovisco rotating cylinder viscosimetre using the sensor system M5/MV1.

Experimental method

The loop is first filled with this solution. A background fluid flow is set in the loop if required and the power supply connected to the nickel gauze and the platinum wire is switched on to start the electrolysis and generate bubbles. The flow patterns in the conduit and the side arm are recorded using a digital video camera. HP 02/01/03

Buoyancy-driven Flow



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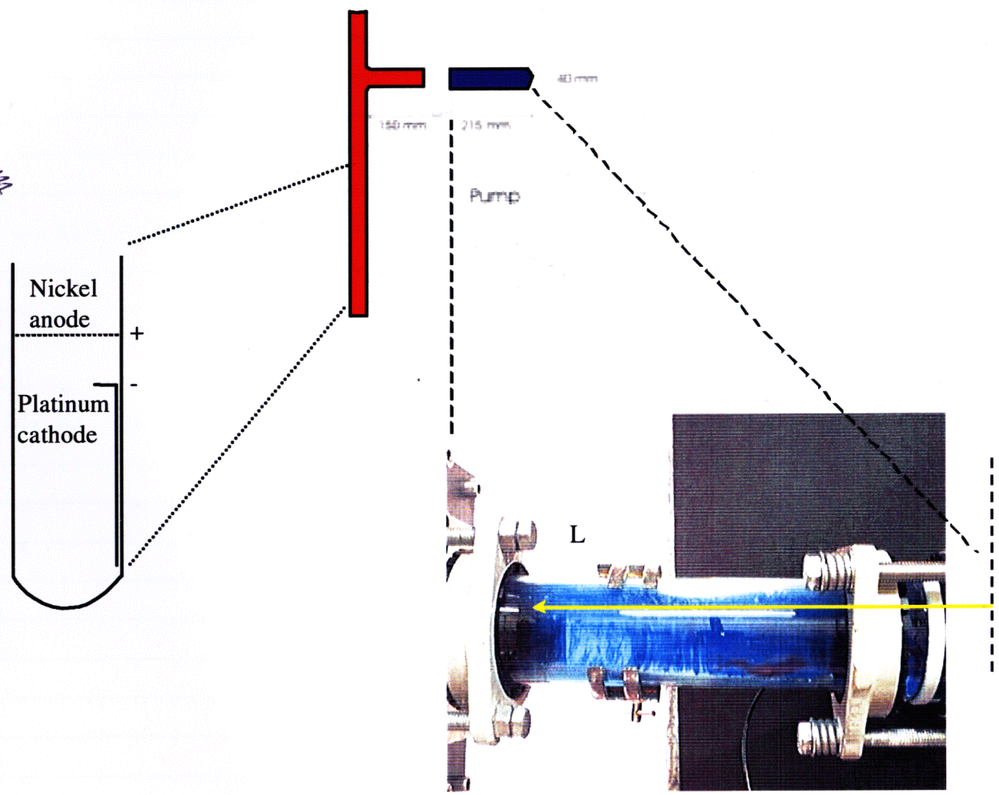
Buoyancy-driven Bubbly Flow

Bubble diameter ~ 50 µm

Gas flux: 32 - 185 mm³ s⁻¹



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		Exp N°	Rho1	Rho2	µ1	µ2	g'	mm/s	mm^3/s	A (mm)	B (mm)	C (mm)
IO FLOW	Newt fluid	77	1401.7	1360.9	2.67	1.14	0.30			150	215	40
		78	1401.6	1360.9	1.19	1.10	0.30			150	215	40
		79	1386.3	1345.9	1.20	0.62	0.30			150	215	40
		80	1360.9	1321.3	1.11	0.24	0.30			150	215	40
	µ2 v small →	81	1360.9	1321.3	1.28	0.01	0.30			150	215	40
		82	1411.3	1370.9	1.01	1.43	0.29			150	215	40
		83	1370.8	1350.9	0.94	0.57	0.15			150	215	40
		85	1390.0	1350.9	1.01	0.62	0.29			150	215	40
		87	1409.0	1350.9	1.13	0.58	0.43			150	215	40
	Natrosol®	16	1000.8	1044.0	0.46	0.42	0.43			150	190	40
		17	1015.2	1044.0	0.53	0.54	0.28			150	190	40
		18	1029.6	1044.0	0.57	0.62	0.14			150	190	40
		13	1044.4	1015.2	2.07	0.68	0.29			150	190	40
		14	1044.4	1015.4	1.84	1.43	0.29			150	190	40
		15	1044.4	1015.6	1.73	1.75	0.28			150	190	40
		28	1029.5	1000.7	0.23	0.25	0.29			150	290	40
		29	1015.2	1000.8	0.65	0.48	0.14			150	290	40
		30	1029.8	1000.8	1.36	0.62	0.29			150	290	40
		31	1029.6	1001.0	0.68	1.16	0.29			150	290	40
		32	1029.6	1000.8	0.91	0.83	0.29			250	190	40
		33	1029.6	1000.8	0.62	0.70	0.29			250	190	40
		34	1044.0	1000.8	1.01	0.96	0.43			250	190	40
		35	1044.2	1001.0	2.67	2.67	0.43			250	190	40
		36	1029.6	1000.8	0.49	0.49	0.29			150	390	40
		37	1044.0	1000.8	0.55	0.62	0.43			150	390	40
		38	1044.2	1000.8	1.21	0.63	0.43			150	390	40
		46	1044.4	1000.0	0.85	0.00	0.44			150	215	40
		47	1044.4	1000.8	1.40	0.55	0.43			150	215	40
		48	1044.7	1000.8	3.56	0.55	0.44			150	215	40
		49	1044.7	1015.2	3.30	0.55	0.29			150	215	40
		54	1044.0	1001.5	0.49	3.73	0.42			150	215	40
	small gate	50	1044.0	1000.8	0.45	0.54	0.43			150	190	28
		51	1044.7	1000.8	4.05	0.57	0.44			150	190	28
		52	1044.7	1015.2	3.01	0.45	0.29			150	190	28
BUBBLY FLOW	Natrosol®	59	1022.1	1019.7	0.08	1.80	0.02		185.00	150	190	40
		60	1022.1	1018.5	0.08	0.08	0.04		185.00	150	190	40
		61	1022.1	1015.6	0.05	2.43	0.06		187.00	150	190	40
		62	1022.1	1018.8	0.05	0.69	0.03		187.00	150	190	40
		63	1022.1	1015.2	0.06	0.67	0.07		187.00	150	190	40
		64	1022.1	1019.2	0.13	2.47	0.03		92.51	150	190	40
		65	1022.1	1018.5	0.09	0.12	0.04		92.51	150	190	40
		66	1022.1	1019.2	0.11	2.45	0.03		40.25	150	190	40
		67	1022.1	1018.5	0.07	0.04	0.04		40.11	150	190	40
FLOW LOOP	Newt fluid	84	1370.8	1350.9	0.95	0.60	0.15	9.44		150	215	40
		86	1390.0	1350.9	0.93	0.60	0.29	10.64		150	215	40
		88	1409.0	1350.9	0.94	0.64	0.43	10.85		150	215	40
	Natrosol®	39	1029.6	1000.8	0.36	0.36	0.29	25.81		150	190	40
		40	1029.6	1000.8	0.43	0.43	0.29	37.15		150	190	40
		41	1029.6	1000.8	0.54	0.63	0.29	16.03		150	190	40
		43	1029.6	1000.8	0.57	0.64	0.29	17.31		150	190	40
		44	1044.0	1000.8	0.39	0.46	0.43	25.50		150	190	40
		45	1044.0	1000.8	0.53	0.50	0.43	36.00		150	190	40

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	14 t (s)	14 l (m)	15 t (s)	15 l (m)	29 t (s)	29 l (m)	30 t (s)	30 l (m)	31 t (s)	31 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	22.000	0.039000	27.000	0.044000	19.000	0.031000	21.000	0.032000	17.000	0.034000
2	52.000	0.070000	60.000	0.075000	43.000	0.065000	39.000	0.061000	33.000	0.060000
3	60.000	0.075000	70.000	0.080000	49.000	0.072000	50.000	0.072000	45.000	0.074000
4	70.000	0.082000	80.000	0.085000	56.000	0.076000	60.000	0.083000	55.000	0.082000
5	80.000	0.090000	90.000	0.091000	67.000	0.085000	70.000	0.090000	65.000	0.092000
6	90.000	0.095000	100.00	0.097000	75.000	0.092000	80.000	0.098000	75.000	0.10000
7	100.00	0.10100	110.00	0.10300	85.000	0.098000	90.000	0.10600	85.000	0.10700
8	110.00	0.10600	120.00	0.10900	95.000	0.10400	100.00	0.11200	95.000	0.11200
9	120.00	0.11200	130.00	0.11300	105.00	0.11000	110.00	0.11800	105.00	0.12000
10	130.00	0.11700	140.00	0.11900	115.00	0.11600	120.00	0.12200	115.00	0.12600
11	140.00	0.12300	150.00	0.12200	125.00	0.12100	130.00	0.12800	125.00	0.13200
12	150.00	0.12700	160.00	0.12600	140.00	0.12800	140.00	0.13300	135.00	0.13800
13	160.00	0.13100	170.00	0.13100	155.00	0.13500	150.00	0.14200	145.00	0.14300
14	170.00	0.13500	180.00	0.13500	170.00	0.14100			155.00	0.13700
15	180.00	0.13900	190.00	0.14000	183.00	0.14500				
16	190.00	0.14500	200.00	0.14300						
17	200.00	0.14700	210.00	0.14600						
18	210.00	0.15100	220.00	0.15000						
19	220.00	0.15500	230.00	0.15400						
20	230.00	0.16000	240.00	0.15800						
21	240.00	0.16300	250.00	0.16200						
22	250.00	0.16700	260.00	0.16500						
23	260.00	0.17100	280.00	0.17000						
24	270.00	0.17300	300.00	0.17700						
25	280.00	0.17700	320.00	0.18000						
26	293.00	0.18000								

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	32 t (s)	32 l (m)	33 t (s)	33 l (m)	34 t (s)	34 l (m)	35 t (s)	35 l (m)	36 t (s)	36 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	16.000	0.033000	16.000	0.032000	12.000	0.033000	26.000	0.034000	10.000	0.030000
2	28.000	0.056000	24.000	0.056000	23.000	0.058000	59.000	0.058000	19.000	0.052000
3	35.000	0.066000	28.000	0.064000	29.000	0.068000	76.000	0.067000	25.000	0.064000
4	44.000	0.077000	34.000	0.078000	35.000	0.077000	102.00	0.078000	30.000	0.071000
5	60.000		42.000		42.000	0.087000	116.00	0.087000	35.000	0.080000
6	70.000		57.000	0.11100	51.000		149.00		40.000	0.088000
7	80.000	0.10800	69.000	0.12700	62.000		167.00		45.000	0.094000
8	98.000	0.12300	82.000		72.000	0.11500	203.00	0.11000	50.000	0.10000
9	110.00		96.000	0.15000	83.000	0.12600	249.00	0.12600	57.000	0.10800
10	120.00		111.00	0.16300	102.00		284.00		63.000	0.11400
11	130.00		120.00	0.17100	121.00	0.15100	310.00		70.000	0.11800
12	140.00		130.00	0.17700	133.00	0.15800	346.00			
13	150.00	0.15200	140.00	0.18400	156.00	0.17200	381.00	0.15400		
14	160.00	0.15600	150.00	0.19000	171.00	0.17900	450.00	0.16500		
15	170.00	0.16200	160.00	0.19600	189.00	0.18800	510.00	0.17500		
16	180.00	0.16700	170.00	0.20200	209.00	0.19700	570.00	0.18500		
17	190.00	0.17100	180.00	0.20800	235.00	0.20800	630.00	0.19200		
18	200.00	0.17600	190.00	0.21400	256.00	0.21700	690.00	0.20200		
19	210.00	0.18000	200.00	0.22000	274.00	0.22700	780.00	0.21800		
20	225.00	0.18600	210.00	0.22600	300.00	0.23000	840.00	0.22500		
21	240.00	0.19100	218.00	0.22800			920.00	0.23000		
22	255.00	0.19900								
23	270.00	0.20400								
24	285.00	0.21000								
25	300.00	0.21300								
26	315.00	0.21900								
27	330.00	0.22500								
28	353.00	0.23000								

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	37 t (s)	37 l (m)	38 t (s)	38 l (m)	46 t (s)	46 l (m)	47 t(s)	47 l (m)	48 t (s)	48 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	13.000	0.029000	11.000	0.028000	3.3000	0.066000	4.1000	0.039000	8.5000	0.037000
2	20.000	0.052000	21.000	0.049000	4.2000	0.079000	16.900	0.082000	24.900	0.073000
3	24.000	0.064000	26.000	0.057000	5.2000	0.093000	25.630	0.091000	29.640	0.080000
4	28.000	0.072000	31.000	0.067000	5.8300	0.10100	30.300	0.10000	34.640	0.087000
5	32.000	0.082000	38.000	0.075000	7.3000	0.11700	34.270	0.10700	40.270	0.095000
6	36.000	0.088000	47.000	0.084000	8.4000	0.12700	40.200	0.11600	47.840	0.10300
7	40.000	0.094000	59.000	0.096000	9.3000	0.13700	47.470	0.12400	56.440	0.11300
8	44.000	0.10000	67.000	0.10200	10.300	0.14500	52.700	0.13300	64.840	0.12000
9	48.000	0.10600	74.000	0.11000	12.530	0.16100	58.200	0.13900	72.040	0.12800
10	52.000	0.11300	87.000	0.11800	14.230	0.16700	63.070	0.14500	79.400	0.13300
11	56.000	0.12000					69.000	0.15200	91.600	0.14300
12							74.130	0.15800	105.67	0.15200
13							80.100	0.16400	118.27	0.16100
14									125.67	0.16700
15									134.67	0.17000

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	41 t (s)	41 l (m)	43 t (s)	43 l (m)	44 t (s)	44 l (m)	45 t (s)	45 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	17.600	0.070000	5.1000	0.036000	6.0300	0.070000	2.7400	0.040000
2	20.560	0.075000	16.630	0.070000	7.3300	0.078000	7.4700	0.073000
3	23.800	0.083000	20.770	0.079000	9.5000	0.090000	8.9700	0.083000
4	27.430	0.090000	25.700	0.090000	12.070	0.10400	11.200	0.093000
5	30.930	0.097000	31.370	0.098000	14.070	0.11300	12.740	0.099000
6	35.500	0.10500	40.370	0.10200	17.030	0.12500	15.000	0.11000
7	40.900	0.11300	47.570	0.12400	20.030	0.13500	17.500	0.11800
8	45.600	0.12000	52.600	0.13100	22.730	0.14400	19.670	0.12700
9	52.800	0.13100	60.000	0.14000	26.530	0.15600	23.500	0.14000
10	57.730	0.13700	67.430	0.15100	30.770	0.16700	27.640	0.15200
11	63.860	0.14500	75.370	0.15900			30.870	0.16000
12	71.060	0.15400	81.470	0.16300			35.540	0.16800
13	79.000	0.16100	89.800	0.16700				
14	93.800	0.17000						

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	49 t (s)	49 l (m)	50 t (s)	50 l (m)	51 t (s)	51 l (m)	52 t (s)	52 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	16.000	0.036000	5.1000	0.038000	19.170	0.038000	20.840	0.037000
2	43.000	0.073000	16.900	0.074000	50.600	0.072000	52.640	0.071000
3	49.300	0.080000	19.600	0.080000	60.430	0.082000	59.540	0.075000
4	58.660	0.087000	23.100	0.088000	70.570	0.091000	67.900	0.082000
5	72.730	0.099000	26.930	0.096000	83.600	0.10000	78.540	0.088000
6	81.330	0.10500	30.900	0.10300	93.700	0.10700	89.700	0.096000
7	90.900	0.11200	36.630	0.11400	106.77	0.11500	100.74	0.10300
8	101.86	0.11800	40.660	0.12100	118.47	0.12300	112.67	0.11000
9	111.46	0.12500	45.730	0.12900	137.77	0.13300	125.67	0.11700
10	125.70	0.13300	49.860	0.13600	148.10	0.14000	141.67	0.12500
11	138.53	0.14000	53.700	0.14100	161.10	0.14600	156.87	0.13300
12	149.50	0.14500	58.600	0.14900	173.73	0.15300	173.60	0.13700
13	166.40	0.15200	63.000	0.15500	191.20	0.16000	191.27	0.14800
14	179.56	0.15900	68.000	0.16100	202.67	0.16500	202.04	0.15300
15	196.73	0.16600	72.160	0.16700	212.40	0.17000	220.80	0.15700
16	207.73	0.16800	76.830	0.17300	228.47	0.17300	237.60	0.16600
17			79.560	0.17600	233.23	0.17500	249.50	0.16700

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	84 t (s)	84 l (m)	86 t (s)	86 l (m)	88 t (s)	88 l (m)	39 t (s)	39 l (m)	40 t (s)	40 l (m)
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	14.570	0.041000	9.5000	0.039000	6.4000	0.042000	4.0000	0.037000	4.8000	0.044000
2	40.300	0.078000	25.000	0.073000	18.070	0.074000	12.000	0.071000	11.300	0.073000
3	46.030	0.083000	30.770	0.080000	21.030	0.080000	17.000	0.083000	14.500	0.083000
4	52.330	0.088000	35.470	0.086000	26.100	0.090000	21.000	0.095000	17.030	0.091000
5	58.270	0.093000	42.700	0.095000	29.870	0.097000	25.000	0.10500	21.200	0.10400
6	67.330	0.10000	50.830	0.10500	33.300	0.10100	29.000	0.11300	24.800	0.11300
7	75.130	0.10700	57.670	0.11300	36.900	0.10700	34.000	0.12500	30.770	0.12800
8	87.200	0.11500	66.470	0.12000	42.730	0.11500	39.000	0.13500	33.170	0.13300
9	96.030	0.12000	72.770	0.12800	48.330	0.12200	43.000	0.14200	37.700	0.14300
10	108.87	0.12800	79.800	0.13400	52.370	0.12800	48.000	0.15000	42.800	0.15300
11	122.60	0.13700	88.600	0.14000	57.330	0.13500	53.000	0.15900	46.600	0.16000
12	137.53	0.14400	96.530	0.14700	62.730	0.14000	59.000	0.16100	50.470	0.16500
13	148.17	0.14800	107.67	0.15600	72.400	0.14800	69.000	0.17100	55.630	0.17000
14	161.90	0.15700	119.90	0.16600	77.330	0.15500				
15	180.07	0.16800			84.230	0.16500				
16	193.97	0.17400								

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	82 t (s)	82 I (m)	83 t (s)	83 I (m)	85 t (s)	85 I (m)	87 t (s)	87 I (m)
0	1.0000e-05	1.0000e-08	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	17.970	0.039000	15.700	0.042000	9.5000	0.039000	6.2700	0.041000
2	42.930	0.070000	38.130	0.074000	25.000	0.073000	15.830	0.071000
3	51.730	0.076000	44.270	0.078000	30.770	0.080000	20.500	0.081000
4	62.600	0.084000	49.670	0.084000	35.470	0.086000	23.800	0.087000
5	73.000	0.093000	56.570	0.091000	42.700	0.095000	28.130	0.097000
6	83.730	0.10000	63.300	0.097000	50.830	0.10500	31.500	0.10200
7	95.270	0.10900	70.730	0.10200	57.670	0.11300	36.000	0.11200
8	104.30	0.11800	81.000	0.11000	66.470	0.12000	40.800	0.11700
9	112.20	0.12000	90.730	0.11800	72.770	0.12800	46.930	0.12600
10	123.17	0.12600	103.17	0.12500	79.800	0.13400	53.670	0.13500
11	138.10	0.13400	116.13	0.13200	88.600	0.14000	59.800	0.14200
12	152.50	0.14100	132.33	0.14300	96.530	0.14700	64.470	0.14900
13	163.50	0.14500	145.63	0.15200	107.67	0.15600	73.830	0.15800
14	179.50	0.15500	162.23	0.15800	119.90	0.16600	81.930	0.16600
15	190.33	0.15700	177.80	0.16500				
16	200.07	0.16300	188.33	0.17300				

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	77 t (s)	77 I (m)	78 t (s)	78 I (m)	79 t (s)	79 I (m)	80 t (s)	80 I (m)	81 t (s)	81 I (m)
0	0.0000	0.0000	1.0000e-05	1.0000e-05	1.0000e-05	1.0000e-08	1.0000e-05	1.0000e-08	1.0000e-05	1.0000e-08
1	18.367	0.038000	14.867	0.039000	8.4667	0.039000	7.6667	0.040000	3.6667	0.041000
2	42.100	0.071000	40.233	0.074000	23.000	0.072000	17.067	0.073000	8.0000	0.072000
3	60.667	0.092000	47.433	0.082000	25.933	0.075000	20.367	0.081000	9.2333	0.079000
4	87.567	0.10300	58.067	0.091000	29.733	0.081000	23.767	0.088000	10.400	0.085000
5	117.63	0.12100	64.400	0.096000	36.567	0.090000	27.000	0.095000	11.933	0.095000
6			72.367	0.10200	41.967	0.098000	31.233	0.10300	13.367	0.10100
7			80.933	0.11000	47.200	0.10400	35.100	0.11000	15.167	0.11100
8			89.200	0.11500	54.200	0.11100	38.367	0.11800	17.867	0.12100
9			98.233	0.12000	59.733	0.11600	43.233	0.12300	19.900	0.12900
10			107.07	0.12700	67.567	0.12400	48.000	0.12800	22.833	0.13800
11			116.83	0.13300	74.900	0.13200	52.433	0.13500	25.367	0.14800
12			129.33	0.14100	82.467	0.13800	56.967	0.14300	29.100	0.16000
13			142.10	0.14700	91.333	0.14600	62.833	0.14900	32.333	0.17100
14			157.20	0.15500	99.233	0.15200	68.967	0.15600		
15			168.87	0.16200	106.97	0.15700	78.033	0.16500		
16			179.27	0.16700	117.87	0.16500	85.300	0.17300		
17			197.43	0.17300	128.47	0.17300				

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Exp#1 Solution: 1wt% NaCl + 0.2 wt% Natrosol + H_2O

→ 4 l of water + 40 g of NaCl + 8 g of Natrosol

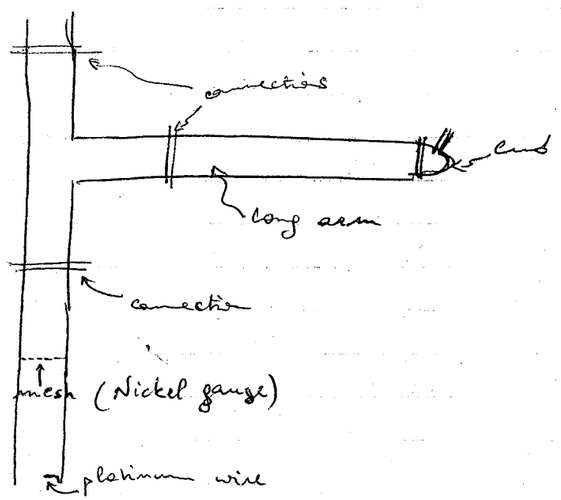
Viscosity measured with RoTovisco RV20 (system M5)
→ cup MV.St + sensor MV1St
measurements with software Rotatio 3.0
(Haake Rot 3.0)

$T° = 21°C$.

$\dot{\gamma}\,(s^{-1})$: 0 → 1150 s^{-1} in 10 min.
with 1 measurement/s ⇒ 600 data points

Data saved in TH1#1.ROT

solution displays a shear thinning behaviour with $\bar{\eta} \simeq 10$ mPas for the highest $\dot{\gamma}\,(s^{-1})$



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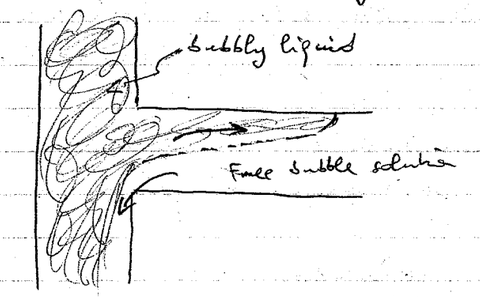
Bubbles have been generated with a current of $I \simeq 0.2 - 0.3$ A.

Bubbles rise through the main conduit and progressively, although very slowly, start to intrude the side arm creating a gravity current on top of it. This in turn drives a dense gravity current of bubble free liquid (the initial solution) that sinks back into the conduit.



On top of the gravity current in the side arm, bubbles rise and collect forming a foam layer.

As time goes on, the bubbly gravity current spreads more and more into the side arm and thickens as well, while the bubble free layer thins 11/2/04 and the foam layer grows sending bubbles back up into the conduit. Hence the lower part of the conduit feeds the side arm with both liquid and gas while the side arm feeds the conduit back with bubbles (nearly pure gas) from the foam layer, which rise up to the top of the conduit, and with free bubble liquid down the conduit.

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If a steady-state is achievable, we can envisioned a situation where the side arm contains three layers of approximately constant thickness: a foam layer, made of nearly pure gas, on top of a bubbly layer underlined by a layer of pure liquid. 11/2/04

The thickness of these layers ~~could~~ is presumably determined by the exchange of gas and liquid between the bubbly layer and the foam and pure liquid respectively. as well as the flux of gas and liquid coming from the conduit, flux which would be matched by the flux of gas from the foam layer and of liquid from the liquid layer so that the gas production rate is balanced by the gas loss at the top of the conduit. 11/2/04

What determine the thickness of these ~~bubbly~~ layers? 11/2/04

The foam thickness depends of the gas loss from the bubbly layer which depends on the gas concentration c in that layer, its extend (surface area) and the rising velocity of the individual bubbles (linked to their size). This would be balanced with the gas flux from the foam layer back into the conduit.

The thickness of the bubbly layer ~~depends~~ 11/2/04 is related also to the pure liquid layer as it also looses liquid which goes into the pure liq. layer.

We observe that 11/2/04 the exp ran out of steam before the 3 layers fully developped along the entire length of the side arm.

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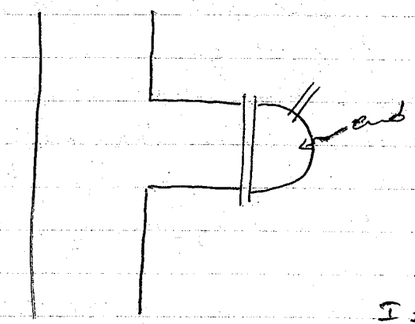
The electrolysis used all the NaCl before the exp reached a steady-state, presumably

→ New exp with more salt and a smaller side arm.

Exp #2

solution: 4 l of H_2O + 80 g of NaCl (2 wt%) + 8 g of Natrosol (0.2 wt%)

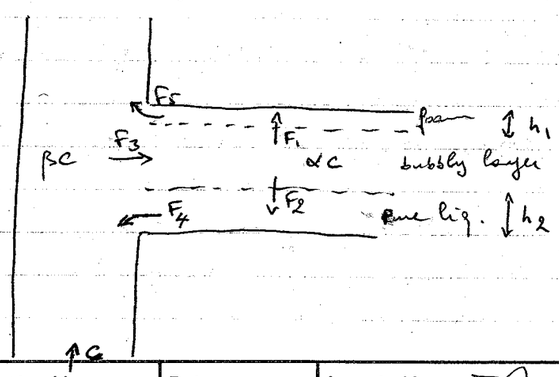


directly connected into the T tube

I = 0.3 A

The same structure with 3 layers in the side arm is observed with the foam on top of the bubbly layer and a bubble free layer at the bottom.

What determine the thickness of the 3 layers?



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A flux F_1 escapes from the bubbly layer ~~into~~ the foam layer and a flux F_2 into the liquid layer.

The bubbly layer has a concentration αc, c being the concentration produced at the bottom of the main tube.

A flux F_4 of liquid is going back down the conduit while a flux F_5 of gas is going back ~~and~~ into up the conduit.

A flux F_3 goes from the conduit into the side arm. At that level in the conduit, concentration is βc

By conservation of mass, we have

$$F_3 = F_4 + F_5$$

but we also have $F_1 = F_4$ (pure gas)

and $F_2 = F_5$ (pure liquid)

so that $F_3 = F_1 + F_2$

$F_1 = A \alpha c V_s$ where A is the area of the foam/bubbly interface, V_s the rising speed of the individual bubbles and αc the concentration of gas in the bubbly layer.

11/2/04

Now if the concentration of gas is βc in main conduit then the gas flux from the conduit into the side arm is $\beta c F_3$ and must balance the gas flux from the side arm back into the conduit:

$$F_1 = \beta c F_3$$

likewise we must have the following relationship for the liquid flux:

$$F_2 = (1-\beta c) F_3$$

These 2 relationship are the one we wrote before: $F_1 + F_2 = F_3$

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Now, we assume that:

$$\alpha c = \beta c = c \quad : \text{Assumption ①}$$

$$\Rightarrow F_1 = A V_s c = c F_3$$

$$\Rightarrow F_3 = A V_s$$

and $F_2 = (1-c) F_3 = A(1-c) V_s$

02/03/03

Assumption ②:

Flow in both the foam layer and the pure liquid layer are driven by buoyancy owing to the density difference between the fluid in these layers and the fluid in the conduit.

So that $U_1 = (g' h_1)^{1/2}$ is the velocity scale in the foam layer and $U_2 = (g' h_2)^{1/2}$ is the velocity scale of the liquid layer.

h_1 and h_2 are the height of the foam layer and the liquid layer respectively.

and g' is defined as $g' = g \frac{\Delta \rho}{\rho}$ ← density difference of element by convection

so that $g'_1 = g\left(\frac{\rho_m - \rho_g}{\rho_g}\right)$

and $g'_2 = g\left(\frac{\rho_l - \rho_m}{\rho_m}\right)$

$\rho_m = c\rho_g + (1-c)\rho_l$

where ρ_l = density of liquid
ρ_g = ——— gas
ρ_m = ——— mixture $= \left(\frac{c}{\rho_g} + \frac{(1-c)}{\rho_l}\right)^{-1}$

mass fraction not volume fraction

T.7 02/03/03

11/2/04

In both layers (foam and liquid) the flux is the product of the velocity and the height

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$\Rightarrow \quad F_1 = v_1 h_1$ and $F_2 = v_2 h_2$

$\Rightarrow \quad h_1 = F_1^{2/3} g_1'^{-1/3}$

and $h_2 = F_2^{2/3} g_2'^{-1/3}$

Here everything is determined by c and the settling velocity V_s of the bubble.

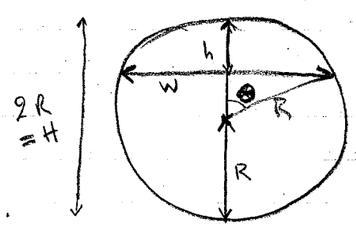
We have neglected any impact the viscosity difference between the 3 layers may have on the flow of the foam layer or the fluid layer

→ This issue must be addressed as the viscosities, or viscosity ratios, may have an impact on the velocity scalings.

02/10/03

⚠ We have bubbles!

⇒ the area A of the interface between the foam and the bubbly layer as well as the interface between the bubbly layer and the liquid layer are not constant but change with the height of the layers.



$R - h = R \sin\theta$

$\frac{W}{2} = R\cos\theta$

$\Rightarrow \left(\frac{R-h}{R}\right)^2 + \frac{W^2}{4R^2} = 1$

$\Leftrightarrow \quad W^2 = 4R^2\left[1 - \left(\frac{R-h}{R}\right)^2\right]$

$\Leftrightarrow \quad W = 2R\left[1 - \left(\frac{R-h}{R}\right)^2\right]^{1/2} = 2\left[R^2 - (R-h)^2\right]^{1/2}$

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$\Leftrightarrow \quad W = 2\sqrt{h(2R-h)} = 2\sqrt{h(H-h)}$

if $H = 2R$ is the height of the side arm (diameter of tube)

Hence the area of the interface is:

$A(h) = 2L\sqrt{h(H-h)}$

where L is the length of the side arm

$\Rightarrow \quad h_i = F_i^{2/3} g_i'^{-1/3} \qquad i = 1,2 \quad (1 = \text{foam}, 2 = \text{liquid})$

where $F_i = A(h_i) V_s c_i \qquad (c_1 = c;\ c_2 = 1-c)$

$\Leftrightarrow \quad F_i = 2L V_s c_i \left[h_i(H-h_i)\right]^{1/2}$

$\Rightarrow \quad h_i = \left[\frac{(2LV_s c_i)^2}{g_i'}\right]^{1/3}\left[h_i(H-h_i)\right]^{1/3}$

$\Leftrightarrow \quad h_i = \left[\lambda_i h_i (H-h_i)\right]^{1/3}$

where $\lambda_i = \frac{(2LV_s c_i)^2}{g_i'}$

Hence h_i is solution of the equation:

$h_i^3 = \lambda_i h_i (H-h_i)$

$\Leftrightarrow \quad h_i^3 + \lambda_i h_i^2 - \lambda_i H h_i = 0$

$\Leftrightarrow \quad h_i(h_i^2 + \lambda_i h_i - \lambda_i H) = 0$

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One solution is $h_i = 0$ but this is not physical as this means no flux: $F_i = 0$.

$$\Rightarrow \quad h_i^2 + d_i h_i - d_i H = 0$$

$$\Delta = d_i^2 + 4 d_i H$$

$$\Rightarrow \quad h_i = \frac{-d_i \pm (d_i^2 + 4 d_i H)^{1/2}}{2}$$

we want $h_i > 0$ ($h_i < 0$ is not physical)

$$\Rightarrow \quad \boxed{h_i = \frac{\sqrt{d_i^2 + 4 d_i H} - d_i}{2}}$$

with $d_i = \frac{(2 L V_s c_i)^2}{g'_i}$ $\qquad c_i = c$ (gas) $(i=1)$, $c_i = 1-c$ (liquid) $(i=2)$

$$g'_i = \begin{cases} g'_1 = g\left(\frac{\rho_m - \rho_g}{\rho_g}\right) \\ g'_2 = g\left(\frac{\rho_L - \rho_m}{\rho_m}\right) \end{cases}$$

TM 02/03/03

~~We look at h_i in steady-state $\Rightarrow$ once $h_i > 0$ has been reached, the other mathematical solution $h_i = 0$ cannot be reached.~~

$\longrightarrow$ Trying model with $c = 1\%$ or 10% doesn't work. It gives

$h_g \sim 3 10^{-10}$ and $h_L \sim 9 10^{-7}$ $(c = 1\%)$

and $h_g \sim 2 10^{-8}$ and $h_L \sim 3 10^{-7}$ $(c = 10\%)$

The question is to know what the velocity scales are in both the foam and bubble free layers.

<u>Assumption</u>:

Flow in both layer is driven by the density difference between fluid in the layers and the conduit and ~~can~~ ~~follow "Poiseuille"~~ behaves as a "Poiseuille" flow: TM 02/03/03

$$\bar{u} \sim \nabla p \frac{g h^2}{\mu} \quad (*)$$

μ is the ~~velocity~~ viscosity of the fluid in the layer (either bubble free, or foam) and $\nabla p = \Delta \rho$

Mass conservation (see p4-6):

$$\Rightarrow \quad F_1 = A N_s C$$
$$\text{and} \quad F_2 = A (1-c) N_s$$

} Influx of gas (F_1) and liquid (F_2) in layers

TM 02/03/03

<u>Note</u>: As seen on p7,8, A is a function of h

$$\Rightarrow \quad A = A(h) = L \times W(h)$$

where L is the length of the side arm and $W(h)$ is the in depth width of the interface that is considered.

Gas flux out of foam layer:

$$F_s = \bar{u}_g h W(h) \quad \cancel{= \bar{u} A}$$

AH 11/2/04

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Steady-state:

$\Rightarrow F_1 = F_5$

$\cancel{\Leftrightarrow A v_s c = \bar{u} A \Leftrightarrow \bar{u} =}$

$$\Leftrightarrow L\, \cancel{W(h)}\, v_s\, c = \bar{u}_g\, h_g\, \cancel{W(h)}$$

$$\Leftrightarrow \bar{u}_g = \frac{L}{h_g} c\, v_s$$

Likewise, for the bubble free layer we get

$$\bar{u}_L = \frac{L}{h_L}(1-c)\, v_s$$

Using expression ⊛, we get:

$$h_g = \left(\frac{\mu_f\, c\, L\, v_s}{\Delta\rho_f\, g}\right)^{1/3} = \left[\frac{\mu_f\, c\, L\, v_s}{(\rho_m-\rho_g)\, g}\right]^{1/3}$$

and

$$h_L = \left(\frac{\mu\, (1-c)\, L\, v_s}{\Delta\rho_L\, g}\right)^{1/3} = \left[\frac{\mu\, (1-c)\, L\, v_s}{(\rho_L-\rho_m)\, g}\right]^{1/3}$$

with $\rho_m = c\,\rho_g + (1-c)\,\rho_L$

and $\mu_f = \mu\,(1-\varepsilon)^{-5/2}$ is the foam thickness where ε is the gas volumetric fraction in the foam

$$\Rightarrow h_g = \left[\mu\, \frac{(1-\varepsilon)^{-5/2}\, c\, L\, v_s}{\Delta\rho_g\, (1-c)}\right]^{1/3}$$

and

$$h_L = \left[\mu\, \frac{(1-c)\, L\, v_s}{c\, \Delta\rho_g}\right]^{1/3} \quad \text{with } \Delta\rho = \rho_L - \rho_g.$$

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These expressions are strongly dependent on the gas concentration in both the bubbly layer and in the foam.

Taking a gas concentration of 90% in the foam and 20% in the bubbly layer gives $h_g \sim 0.8$ mm and $h_L \sim 0.3$ mm

These values are of order of magnitude less than the observed thicknesses

However the model does not take into account any viscous coupling between the 3 fluid layers, which could increase the thickness of the layers.

~~Indeed, a 90% gas in the foam layer implies an increase in viscosity by a factor ~200 while a 20% increase relative~~ TT 02/03/03

Indeed, a 20% gas content in the bubbly liquid would double the viscosity of the liquid while a 90% gas content in the foam layer implies an increase in viscosity by a factor ~200 relative to the bubbly viscosity

Moreover, such a coupling is observed in the experiments where the bubbles in the bubbly layer act ~~since~~ as tracers and show that part of the bubbly layer is experiencing some viscous drag close to the foam and the bubble free layer.

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To test the model, we need to know hence measure the gas concentration C in the liquid which is a function of the gas flux

⇒ Need to measure gas flux

The T junction of the apparatus is dismantled and the end of the side arm is mounted above the nickel gauze. A thin glass tube (1.8 mm of internal diameter) is protruding from the top.

Liquid is flown up to this thin glass tube. When gas is produced, bubbles rise and collect on the fluid surface where they form a foam. Measuring the time needed for bits of this foam to rise a distance L up the thin tube give the gas flux, or production rate, Q produced by a given current intensity I.

This measurement will be carried out for a wide range of NaCl content as well as a wide range of natrosol content to check whether viscosity plays a role on gas production.

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Solution 1: 2wt% NaCl + 0.2wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt
	2.74	4.67	6.37	13.04	42.23
	2.9	4.41	6.85	11.64	38.64
	3.07	4.2	5.82	12.73	41.65
	2.94	4.4	5.96	12.27	46.8
	3.01	4.35	7.7	11.98	37.77
mean Δt	2.932	4.406	6.540	12.332	41.418
uncertainty	0.056	0.076	0.341	0.252	1.592
Q (m3/s)	8.68E-08	5.78E-08	3.89E-08	2.06E-08	6.14E-09
δQ (m3/s)	2.53E-09	1.57E-09	2.42E-09	6.27E-10	2.98E-10

Solution 2: 2wt% NaCl + 0.1wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt
	3.96	5.2	7.34	12.09	21.67
	3.5	5.27	7.5	13.5	22
	3.24	6.18	8.24	13.5	22.45
	3.64	5.11	7.44	11.7	21.89
	3.25	6.64	7.84	11.47	23.6
mean Δt	3.518	5.680	7.672	12.452	22.322
uncertainty	0.134	0.308	0.165	0.439	0.344
Q (m3/s)	7.23E-08	4.48E-08	3.32E-08	2.04E-08	1.14E-08
δQ (m3/s)	3.48E-09	2.88E-09	1.05E-09	9.25E-10	2.90E-10

02/10/03
TJ

Solution 2: 2wt% NaCl + 0.1wt% natrosol
2nd set of measurements due to leaks in 1st.

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.5	0.4	0.3	0.2	
	Δt	Δt	Δt	Δt	not enough
	3.49	4.64	5.66	9.81	NaCl left in
	3.15	4.07	6.44	10.51	solution for
	3.14	4.5	5.94	10.24	measurement
	3.11	4.03	6.11	10.7	at I = 0.1 A
	2.91	4.66	6.25	9.34	
mean Δt	3.160	4.380	6.080	10.120	
uncertainty	0.093	0.138	0.133	0.246	
Q (m3/s)	8.05E-08	5.81E-08	4.19E-08	2.51E-08	
δQ (m3/s)	3.18E-09	2.41E-09	1.34E-09	8.62E-10	

Witnessed | Recorded by TJ TJ 04/03/03

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Solution 3: 2wt% NaCl + 0.3wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.52	0.41	0.3	0.21	0.1
	Δt	Δt	Δt	Δt	Δt
	3.27	4.37	7.25	11.11	28.41
	3.4	5	6.89	9.88	24.3
	3.16	4.45	6.44	10.49	24.6
	3.25	4.16	6.61	12.79	26.71
		4.4	6.77	11.22	26.94
mean Δt	3.270	4.476	6.792	11.098	26.192
uncertainty	0.038	0.140	0.137	0.486	0.770
Q (m3/s)	7.78E-08	5.69E-08	3.75E-08	2.29E-08	9.72E-09
δQ (m3/s)	1.69E-09	2.35E-09	1.13E-09	1.23E-09	3.83E-10

Solution 4: 2wt% NaCl + 0.4wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt
	5.14	7.19	10	22.76
	4.84	7.36	10.75	21.08
	5.61	6.96	10.79	21.7
	4.6	6.59	10.44	21.14
	4.44	6.95	9.67	21
mean Δt	4.926	7.010	10.330	21.536
uncertainty	0.208	0.130	0.217	0.330
Q (m3/s)	5.17E-08	3.63E-08	2.46E-08	1.18E-08
δQ (m3/s)	2.70E-09	1.04E-09	7.65E-10	2.99E-10

02/10/02

Solution 5: 3wt% NaCl + 0.1wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.61	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt
	2.79	3.75	4.5	5.64	9.08	19.32
	2.81	3.54	4.44	5.95	9.18	19.18
	2.66	3.46	4.78	6.04	9.38	18.48
	2.94	3.5	4.74	5.77	8.84	18.68
	2.7	3.76	4.58	5.94	9	18.88
mean Δt	2.780	3.602	4.608	5.868	9.096	18.908
uncertainty	0.049	0.064	0.066	0.072	0.090	0.155
Q (m3/s)	9.15E-08	7.06E-08	5.52E-08	4.34E-08	2.80E-08	1.35E-08
δQ (m3/s)	2.52E-09	1.96E-09	1.35E-09	9.64E-10	5.57E-10	2.45E-10

Witnessed & Understood by me,	Date	Invented by TD	Date 05/03/03
		Recorded by TD	

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Solution 6: 3wt% NaCl + 0.2wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.61	0.51	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt
	2.76	3.6	5	6.88	9.87	22.14
	2.78	3.62	5.14	6.84	10.18	23.46
	2.79	3.37	4.85	6.26	9.81	22.81
	2.68	3.68	4.8	6.69	10.14	21.61
	2.64	3.48	5.04	6.87	10.04	21.31
mean Δt	2.730	3.550	4.966	6.708	10.008	22.266
uncertainty	0.030	0.055	0.062	0.117	0.073	0.393
Q (m3/s)	9.32E-08	7.17E-08	5.12E-08	3.79E-08	2.54E-08	1.14E-08
δQ (m3/s)	1.94E-09	1.84E-09	1.16E-09	1.04E-09	4.39E-10	3.16E-10

Solution 7: 3wt% NaCl + 0.3wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.61	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt
	2.81	3.5	5.14	7	10.97	23.7
	2.85	4.06	5.39	7.19	11.04	23.65
	2.78	4.01	4.76	6.94	10.97	23.55
	2.89	3.94	4.84	6.96	11.04	23.24
	2.74	3.78	4.54	7.05	10.89	24.81
mean Δt	2.814	3.858	4.934	7.028	10.982	23.790
uncertainty	0.026	0.101	0.149	0.045	0.028	0.267
Q (m3/s)	9.04E-08	6.60E-08	5.16E-08	3.62E-08	2.32E-08	1.07E-08
δQ (m3/s)	1.75E-09	2.39E-09	2.07E-09	5.92E-10	2.90E-10	2.27E-10

09/10/02

Solution 8: 3wt% NaCl + 0.4wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt
	2.9	3.17	4.6	6.36	9.83	24.6
	2.31	3.13	4.25	6.18	9.34	24.09
	2.5	3.42	4.44	6.17	9.7	24.33
	2.75	3.37	4.37	5.78	8.12	24.49
	2.66	3.32	4.34	5.93	8.53	24.43
mean Δt	2.624	3.282	4.400	6.084	9.104	24.388
uncertainty	0.102	0.057	0.059	0.102	0.334	0.086
Q (m3/s)	9.70E-08	7.75E-08	5.78E-08	4.18E-08	2.80E-08	1.04E-08
δQ (m3/s)	4.73E-09	2.11E-09	1.35E-09	1.12E-09	1.31E-09	1.41E-10

Witnessed & Understood by me,	Date	Invented by TD	Date 09/03/03
		Recorded by TD	

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Solution 9: 3wt% NaCl + 0.5wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.5	0.4	0.29
	Δt	Δt	Δt
	3.43	4.03	5.19
	3.36	3.97	5.59
	3.1	3.85	5.62
	3.37	3.79	5.77
	2.9	3.87	5.94
mean Δt	3.232	3.902	5.622
uncertainty	0.101	0.043	0.125
Q (m3/s)	7.87E-08	6.52E-08	4.53E-08
δQ (m3/s)	3.24E-09	1.37E-09	1.46E-09

Difficulties to keep intensity constant.
Ultimately, not enough NaCl left in solution.

Solution 10: 2wt% NaCl + 0.5wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.51	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt
	2.97	4.21	6.11	8.96	21.69
	3.59	4.01	5.56	8.07	21.46
	3.41	4.17	5.63	8.77	21.34
	2.95	4.23	6.39	8.54	21.53
	2.73	4.11	5.44	8.57	22.03
mean Δt	3.130	4.146	5.826	8.582	21.610
uncertainty	0.159	0.040	0.181	0.149	0.119
Q (m3/s)	8.13E-08	6.14E-08	4.37E-08	2.97E-08	1.18E-08
δQ (m3/s)	4.95E-09	1.20E-09	1.80E-09	8.10E-10	1.83E-10

Solution 11: 1wt% NaCl + 0.1wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.2	0.1
	Δt	Δt
	10.31	20.17
	10.26	21.49
	10.96	19.73
	9.99	19.96
	10.12	21.03
mean Δt	10.328	20.476
uncertainty	0.168	0.336
Q (m3/s)	2.46E-08	1.24E-08
δQ (m3/s)	6.46E-10	3.28E-10

Witnessed & Understood by me, | Date | Invented by T.7 | Date 19/03/03
Recorded by T.7

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Solution 12: 1wt% NaCl + 0.2wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.3	0.2	0.1
	Δt	Δt	Δt
	6.26	9.68	22.644
	5.43	10.07	21.24
	5.89	9.7	20.52
	5.8	9.98	20.69
	6.03	9.66	20.78
mean Δt	5.882	9.818	21.175
uncertainty	0.137	0.086	0.386
Q (m3/s)	4.33E-08	2.59E-08	1.20E-08
δQ (m3/s)	1.44E-09	4.86E-10	3.39E-10

Solution 13: 1wt% NaCl + 0.3wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.2	0.1
	Δt	Δt
	8.89	21.51
	8.6	21.68
	8.59	20.88
	8.66	22.03
	9.22	20.74
mean Δt	8.792	21.368
uncertainty	0.120	0.244
Q (m3/s)	2.89E-08	1.19E-08
δQ (m3/s)	6.84E-10	2.55E-10

Solution 14: 1wt% NaCl + 0.4wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.2	0.1
	Δt	Δt
	9	20.77
	9.07	20.77
	9.07	21.57
	8.73	21.73
	8.83	20.09
mean Δt	8.940	20.986
uncertainty	0.068	0.299
Q (m3/s)	2.85E-08	1.21E-08
δQ (m3/s)	5.02E-10	2.94E-10

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Witnessed & Understood by me, | Date | Invented by T.7 | Date 22/03/03
Recorded by T.7

Solution 15: 1wt% NaCl + 0.5wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.2	0.1
	Δt	Δt
	9	20.77
	8.69	20.34
	8.69	20.37
	8.91	21.23
	8.72	20.55
mean Δt	8.802	20.652
uncertainty	0.064	0.164
Q (m3/s)	2.89E-08	1.23E-08
δQ (m3/s)	5.00E-10	2.21E-10

Solution 16: 4wt% NaCl + 0.1wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.81	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.37	2.63	2.83	3.39	5.69	6.46	9.89	21.33
	2.13	2.5	2.91	3.45	5.77	6.15	9.74	20.93
	1.97	2.4	2.93	3.63	5.78	6.64	9.98	21.43
	2.16	2.4	2.91	3.5	5.2	6.05	9.8	20.83
	2.06	2.6	2.97	3.82	5.17	6.62	9.95	21.32
mean Δt	2.138	2.506	2.910	3.558	5.522	6.384	9.872	21.168
uncertainty	0.067	0.048	0.023	0.077	0.139	0.121	0.045	0.120
Q (m3/s)	1.19E-07	1.02E-07	8.74E-08	7.15E-08	4.61E-08	3.99E-08	2.58E-08	1.20E-08
δQ (m3/s)	4.90E-09	2.97E-09	1.56E-09	2.25E-09	1.62E-09	1.15E-09	3.76E-10	1.88E-10

Solution 17: 4wt% NaCl + 0.2wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.04	2.53	2.97	3.88	4.75	6.58	10.26	24.29
	2.17	2.33	2.88	3.59	4.84	6.27	9.25	24.97
	2.04	2.25	2.99	3.85	5.17	5.74	10.17	24.56
	2.13	2.87	3.08	3.77	5.23	6.15	9.77	24.34
	1.99	2.53	2.89	3.87	5.18	6.33	10.2	23.33
mean Δt	2.074	2.502	2.962	3.792	5.034	6.214	9.930	24.298
uncertainty	0.033	0.107	0.037	0.054	0.099	0.138	0.191	0.270
Q (m3/s)	1.23E-07	1.02E-07	8.59E-08	6.71E-08	5.06E-08	4.10E-08	2.56E-08	1.05E-08
δQ (m3/s)	3.18E-09	5.38E-09	1.92E-09	1.63E-09	1.50E-09	1.32E-09	7.48E-10	2.21E-10

Solution 18: 4wt% NaCl + 0.3wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	1.95	2.69	3.28	4.29	4.97	5.41	11.1	24.67
	2.15	2.68	3.24	3.85	5.09	5.71	11.33	25.37
	1.94	2.4	2.93	3.84	4.71	6.66	10.92	23.43
	1.97	2.57	3.12	4	5.47	6.67	10.78	23.53
	2.18	2.92	2.99	3.73	4.96	6.07	11.2	24.65
mean Δt	2.038	2.652	3.112	3.942	5.040	6.104	11.066	24.330
uncertainty	0.052	0.085	0.068	0.097	0.124	0.252	0.098	0.371
Q (m3/s)	1.25E-07	9.60E-08	8.18E-08	6.46E-08	5.05E-08	4.17E-08	2.30E-08	1.05E-08
δQ (m3/s)	4.45E-09	4.03E-09	2.61E-09	2.23E-09	1.75E-09	2.14E-09	4.34E-10	2.64E-10

Solution 19: 4wt% NaCl + 0.4wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.01	2.32	2.89	3.61	4.69	6.71	11.51	27.29
	2.1	2.37	2.75	3.68	4.49	6.57	11.89	25.93
	1.82	2.49	2.97	3.73	4.5	6.46	10.83	24.61
	1.75	2.43	2.91	3.66	5.01	6.8	11.17	26.05
	1.95	2.31	3.05	3.57	4.59	6.69	11.11	26.32
mean Δt	1.926	2.384	2.914	3.650	4.656	6.646	11.302	26.040
uncertainty	0.063	0.034	0.050	0.028	0.096	0.059	0.182	0.430
Q (m3/s)	1.32E-07	1.07E-07	8.73E-08	6.97E-08	5.47E-08	3.83E-08	2.25E-08	9.77E-09
δQ (m3/s)	5.66E-09	2.59E-09	2.36E-09	1.23E-09	1.67E-09	7.24E-10	5.89E-10	2.59E-10

Solution 20: 4wt% NaCl + 0.5wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	1.95	2.41	2.6	3.04	4	5.58	10.49	22.62
	1.88	2.14	2.71	3.38	3.63	5.59	10.03	23.04
	1.75	2.47	2.63	3.01	3.99	5.53	10.32	22.87
	2.05	2.34	2.43	3.23	4.19	5.47	10.48	23.61
	2.23	2.17	2.78	3.52	3.92	5.88	9.8	23.92
mean Δt	1.972	2.306	2.630	3.236	3.946	5.610	10.224	23.212
uncertainty	0.081	0.065	0.059	0.098	0.091	0.071	0.135	0.240
Q (m3/s)	1.29E-07	1.10E-07	9.68E-08	7.86E-08	6.45E-08	4.54E-08	2.49E-08	1.10E-08
δQ (m3/s)	6.58E-09	4.22E-09	3.14E-09	3.16E-09	2.13E-09	1.03E-09	5.77E-10	2.23E-10

Solution 21: 5wt% NaCl + 0.1wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.29	2.62	3.07	4.17	4.62	6.46	10.61	23.16
	2.32	2.57	3.14	4.05	4.77	6.52	10.49	22.94
	2.29	2.46	3.13	3.83	4.69	6.58	10.63	22.56
	2.28	2.47	3.04	4.07	4.83	6.55	10.64	22.91
	2.18	2.53	3.13	3.73	4.76	6.76	10.36	22.6
mean Δt	2.272	2.530	3.102	3.970	4.734	6.574	10.546	22.834
uncertainty	0.024	0.030	0.020	0.082	0.036	0.051	0.054	0.112
Q (m3/s)	1.12E-07	1.01E-07	8.20E-08	6.41E-08	5.38E-08	3.87E-08	2.41E-08	1.11E-08
δQ (m3/s)	2.30E-09	2.21E-09	1.35E-09	1.96E-09	9.48E-10	6.85E-10	3.64E-10	1.66E-10

Solution 22: 5wt% NaCl + 0.2wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.15	2.87	3.33	4.58	5.63	6.74	11.22	22.59
	2.12	2.93	3.17	4.3	5.8	6.69	11.15	22.74
	2.33	2.69	3.29	4.29	5.87	7.17	10.85	22.77
	2.17	2.69	3.25	4.45	6.13	7.27	10.86	22.29
	2.28	2.53	3.52	4.42	5.2	6.62	10.95	22.22
mean Δt	2.210	2.742	3.312	4.408	5.726	6.898	11.006	22.522
uncertainty	0.040	0.071	0.058	0.053	0.154	0.134	0.076	0.114
Q (m3/s)	1.15E-07	9.28E-08	7.68E-08	5.77E-08	4.44E-08	3.69E-08	2.31E-08	1.13E-08
δQ (m3/s)	3.25E-09	3.35E-09	2.12E-09	1.28E-09	1.64E-09	1.08E-09	3.91E-10	1.70E-10

Solution 23: 5wt% NaCl + 0.3wt% natrosol

Tube: ID = 1.8 mm and L = 10 cm

Intensity	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	Δt	Δt	Δt	Δt	Δt	Δt	Δt	Δt
	2.04	2.45	3.04	4.73	5.78	7.46	11.67	20.63
	2.03	2.44	3.77	4.1	5.73	8.65	11.93	23.19
	2.14	2.33	3.39	4.29	5.73	8.83	11.68	22.16
	2.01	2.31	3.76	4	5.56	8.59	10.58	22.59
	2.04	2.51	3.53	4.07	5.61	8.53	11.83	24.78
mean Δt	2.052	2.408	3.498	4.238	5.682	8.412	11.538	22.670
uncertainty	0.023	0.038	0.135	0.132	0.041	0.243	0.244	0.676
Q (m3/s)	1.24E-07	1.06E-07	7.27E-08	6.00E-08	4.48E-08	3.03E-08	2.21E-08	1.12E-08
δQ (m3/s)	2.61E-09	2.72E-09	3.54E-09	2.47E-09	7.74E-10	1.18E-09	6.88E-10	4.47E-10

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The Viscosity of these solutions is measured with a Haake rheometer Rotovisco RV20 with sensor system MS/MV1

Software Rotation 3.0 (Haake Rot 3.0)

For each fluid, 2 files are created

1st file:

Strain rate $\dot{\gamma}$ (s^{-1}) goes from 0 to 500 s^{-1} by 50 s^{-1} step. Each step is reached in 1 minute. Then $\dot{\gamma}$ is kept constant for 2 minutes during which 100 stress measurements (τ in Pa) are made.

2nd file:

Same as above but $\dot{\gamma}$ goes from 550 s^{-1} to 1000 s^{-1}

2 files are needed because of space/memory limitation for such a number of steps.

Then for each steps, both $\bar{\dot{\gamma}}$ and $\bar{\tau}$ (mean values) are calculated along with their uncertainty. Then the viscosity η (Pa.s) of the fluid for a given $\dot{\gamma}$ is calculated as $\eta = \frac{\bar{\tau}}{\bar{\dot{\gamma}}}$ along with its uncertainty.

Uncertainty on $\bar{\dot{\gamma}}$ and $\bar{\tau}$ are the standard deviation of the 100 data points distribution for each step.

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Solution 1: 2wt% NaCl + 0.2wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0202	0.0017
100.7	0.0171	0.0009
150.4	0.0158	0.0007
200.9	0.0151	0.0008
250.7	0.0141	0.0004
301.2	0.0133	0.0002
351.1	0.0129	0.0002
400.9	0.0125	0.0002
451.2	0.012	0.0002
500.9	0.0118	0.0002
551.3	0.0116	0.0002
600.9	0.0115	0.0002
651.1	0.0113	0.0003
701	0.0112	0.0002
751.4	0.0111	0.0002
801.2	0.0109	1.00E-04
850.9	0.0108	1.00E-04
901.2	0.0106	0.0002
951	0.0105	0.0003
1001	0.0104	0.0004

Solution 2: 2wt% NaCl + 0.1wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0107	0.0014
100.7	0.0081	0.0008
150.5	0.0076	0.0006
201.1	0.0071	0.0004
250.9	0.0069	0.0002
301.4	0.0067	0.0002
351.1	0.0067	0.0002
400.9	0.0067	0.0002
451.2	0.0063	1.00E-04
500.9	0.0062	0.0002
551.3	0.0063	0.0002
601	0.0063	0.0003
651.3	0.0062	0.0002
701.1	0.0062	1.00E-04
751.4	0.006	0.000
801.2	0.006	0.000
850.9	0.006	1.00E-04
901.2	6.10E-03	2.00E-04
951	6.20E-03	3.00E-04
1001	0.0065	0.0003

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Solution 3: 2wt% NaCl + 0.3wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0378	0.0016
100.7	0.0349	0.001
150.3	0.0308	0.0008
200.7	0.0277	0.0006
250.5	0.0255	0.0003
300.8	0.024	0.0002
350.5	0.0229	0.0002
400.3	0.0221	1.00E-04
450.6	0.0213	1.00E-04
500.4	0.0204	0.0002
550.7	0.0199	0.0003
600.4	0.0194	0.0003
650.8	0.0189	0.0003
700.5	0.019	0.000
750.8	0.018	0.000
800.6	0.0177	1.00E-04
850.3	1.74E-02	2.00E-04
900.7	1.70E-02	2.00E-04
950.4	1.67E-02	0.0003
1001	0.0164	0.0003

Solution 4: 2wt% NaCl + 0.4wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
0.0503	0.0873	0.0023
0.1007	0.0666	0.0009
0.1499	0.057	0.0009
0.2003	0.0504	0.0007
0.2502	0.0458	0.0005
0.3007	0.0421	0.0003
0.3505	0.0393	0.0002
0.4003	0.037	1.00E-04
0.4506	0.0351	1.00E-04
0.5004	0.0334	1.00E-04
0.5507	0.0319	0.0002
0.6003	0.0308	0.0002
0.6505	0.0297	0.0002
0.7004	0.0287	0.0002
0.7508	0.028	0.000
0.8006	0.027	0.000
0.8503	0.0263	0.0002
0.9007	2.57E-02	2.00E-04
0.9504	2.51E-02	3.00E-04
1.001	2.45E-02	3.00E-04

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Solution 5: 3wt% NaCl + 0.1wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0003	0.000547
100.7	0.0033	0.000962
150.4	0.0043	0.000705
200.7	0.004	0.000428
250.5	0.0041	0.000378
300.8	0.0042	0.000279
350.5	0.0042	0.000259
400.3	0.0046	0.000275
450.6	0.0044	0.000238
500.6	0.0044	0.000213
551.3	0.0045	0.000351
600.4	0.0046	0.000354
650.8	0.005	0.000
700.5	0.005	0.000
750.9	0.0046	0.000163
800.8	4.90E-03	1.20E-04
850.7	5.20E-03	1.91E-04
901	0.0055	0.00027
950.9	5.80E-03	5.71E-04
1001	0.0059	0.00048

Solution 6: 3wt% NaCl + 0.2wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.021	0.0015
100.7	0.018	0.001
150.4	0.0162	0.0006
200.7	0.0152	0.0008
250.5	0.0138	0.0003
300.8	0.0133	0.0002
350.6	0.0127	0.0002
400.5	0.0123	0.0002
451.2	0.0118	0.0002
500.9	0.0114	0.0003
551.3	0.0108	0.0002
600.6	0.0108	0.0002
650.9	0.011	0.000
700.8	0.011	0.000
751.2	0.0105	1.00E-04
801.2	0.0103	1.00E-04
850.9	0.0101	1.00E-04
901.2	0.0101	0.0002
951	9.90E-03	2.00E-04
1001	9.90E-03	3.00E-04

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Solution 7: 3wt% NaCl + 0.3wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0469	0.0043
100.7	0.0382	0.0019
150.4	0.034	0.0012
200.8	0.0309	0.0009
250.7	0.0284	0.0005
301.3	0.0265	0.0003
351.1	0.0252	0.0002
400.9	0.024	0.0002
451.2	0.0229	0.0002
500.9	0.0221	1.00E-04
551.3	0.0212	0.0002
601	0.0206	0.0003
651.2	0.02	0.0003
701.1	0.0195	0.0003
751.4	0.019	0.0002
801.2	0.019	0.000
850.9	0.018	0.000
901.2	0.0178	0.0002
951	1.73E-02	3.00E-04
1001	1.70E-02	3.00E-04

Solution 8: 3wt% NaCl + 0.4wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0997	0.0033
100.7	0.0748	0.0018
150.4	0.0633	0.0017
200.7	0.0555	0.0011
250.5	0.0497	0.0007
300.8	0.0453	0.0005
350.6	0.042	0.0003
400.4	0.0394	0.0002
451	0.037	0.0002
500.9	0.0353	0.0002
551.3	0.0334	0.0002
600.7	0.0321	0.0002
650.9	0.0309	0.0002
700.7	0.0299	0.0002
751.2	0.029	0.0002
801.2	0.028	0.000
850.9	0.027	0.000
901.2	0.0267	0.0002
951	2.62E-02	3.00E-04
1001	2.55E-02	3.00E-04

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Solution 9: 3wt% NaCl + 0.5wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.4	0.1598	0.004
100.8	0.1154	0.003
150.4	0.094	0.0018
200.9	0.0807	0.0011
250.8	0.0715	0.0007
301.4	0.0649	0.0005
351.1	0.0596	0.0004
400.9	0.0554	0.0002
451.2	0.0522	1.00E-04
500.9	0.0494	1.00E-04
551.3	0.0468	0.0002
601	0.0448	0.0002
651.2	0.043	0.0002
701.1	0.0414	0.0002
751.4	0.0401	1.00E-04
801.2	0.039	0.000
850.9	0.038	0.000
901.2	0.0365	0.0002
951	3.55E-02	2.00E-04
1001	3.49E-02	2.00E-04

Solution 10: 2wt% NaCl + 0.5wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.4	0.1575	0.0033
100.7	0.1155	0.0034
150.4	0.0946	0.002
201	0.0809	0.0013
250.9	0.0718	0.0008
301.3	0.065	0.0005
351.1	0.0598	0.0003
400.9	0.0558	0.0002
451.2	0.0522	1.00E-04
500.9	0.0493	0.0002
551.3	0.0466	0.0002
601	0.0446	0.0002
651.3	0.0429	0.0002
701.1	0.0412	0.0002
751.4	0.0399	1.00E-04
801.2	0.038	0.000
850.9	0.037	0.000
901.2	0.0363	0.0002
951	3.51E-02	2.00E-04
1001	3.43E-02	3.00E-04

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Solution 11: 1wt% NaCl + 0.1wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0052	0.0012
100.7	0.0055	0.0009
150.6	0.0057	0.0008
201.2	0.0056	0.0006
251	0.0055	0.0003
301.4	0.005	0.0003
351.1	0.005	0.0003
400.9	0.0049	0.0004
451.2	0.0047	0.0002
500.9	0.0047	0.0002
551.3	0.0047	0.0003
601	0.0046	0.0003
651.3	0.0046	0.0003
701.1	0.0046	0.0003
751.4	0.0047	0.0003
801.2	0.005	0.0002
850.9	0.0053	0.0002
901.2	0.0056	0.0003
951	0.0058	0.0003
1001	0.0072	0.0011

Solution 12: 1wt% NaCl + 0.2wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0199	0.0015
100.7	0.0167	0.0008
150.4	0.0149	0.0008
200.7	0.0136	0.0007
250.5	0.0129	0.0003
300.8	0.0123	0.0002
350.5	0.0119	0.0002
400.4	0.0115	1.00E-04
451	0.0112	1.00E-04
500.9	0.0109	1.00E-04
551.3	0.0108	0.0003
600.4	0.0106	0.0003
650.8	0.0105	0.0004
700.5	0.0104	0.0003
750.9	0.0103	0.0003
800.8	0.010	0.000
850.6	0.010	0.000
900.9	0.0101	0.0002
950.9	9.90E-03	2.00E-04
1001	9.90E-03	3.00E-04

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Solution 13: 1wt% NaCl + 0.3wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.044	0.0019
100.7	0.036	0.001
150.4	0.0311	0.0007
200.7	0.0277	0.0005
250.5	0.0257	0.0004
300.9	0.024	0.0002
350.8	0.023	0.0002
400.8	0.0219	1.00E-04
451.2	0.0211	1.00E-04
500.9	0.0204	1.00E-04
551.3	0.0197	0.0002
600.7	0.0192	0.0002
650.9	0.0188	0.0002
700.7	0.0182	0.0002
751.2	0.0179	1.00E-04
801.2	0.018	0.000
850.9	0.017	0.000
901.2	0.0168	0.0002
951	1.64E-02	3.00E-04
1001	1.62E-02	4.00E-04

Solution 14: 1wt% NaCl + 0.4wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.1038	0.0024
100.7	0.0767	0.002
150.4	0.0645	0.0014
200.7	0.0565	0.0009
250.5	0.0507	0.0007
300.9	0.0461	0.0005
350.8	0.0429	0.0003
400.7	0.0401	0.0002
451.2	0.0378	1.00E-04
500.9	0.0359	0.0002
551.3	0.0343	0.0002
600.7	0.033	0.0002
650.9	0.0318	0.0002
700.6	0.0308	0.0002
751.1	0.0299	1.00E-04
801.2	0.029	0.000
850.9	0.028	0.000
901.2	0.0274	1.00E-04
951	2.68E-02	2.00E-04
1001	2.62E-02	2.00E-04

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Solution 15: 1wt% NaCl + 0.5wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.1646	0.0059
100.7	0.1194	0.0044
150.4	0.0976	0.0023
200.7	0.0835	0.0016
250.6	0.0738	0.0009
301.1	0.0667	0.0006
351	0.0613	0.0004
400.9	0.057	0.0002
451.2	0.0532	0.0002
500.9	0.0505	0.0002
551.3	0.0479	0.0002
600.8	0.0458	0.0002
651	0.044	0.0002
701	0.0424	1.00E-04
751.4	0.0408	1.00E-04
801.2	0.039	0.000
850.9	0.038	0.000
901.2	0.0371	0.0002
951	3.61E-02	2.00E-04
1001	3.52E-02	3.00E-04

Solution 16: 4wt% NaCl + 0.1wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0062	0.0015
100.7	0.0066	0.0008
150.4	0.0062	0.0007
200.9	0.0059	0.0005
250.7	0.0058	0.0003
301.2	0.0055	0.0002
351.1	0.0054	0.0002
400.9	0.0054	1.00E-04
451.2	0.0051	1.00E-04
500.9	0.0051	0.0002
551.3	0.0051	0.0002
600.9	0.005	0.0003
651	0.0051	0.0003
701	0.005	0.0002
751.4	0.005	1.00E-04
801.2	0.005	0.000
850.9	0.005	0.000
901.2	0.0057	0.0002
951	6.00E-03	2.00E-04
1001	6.20E-03	3.00E-04

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Solution 17: 4wt% NaCl + 0.2wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0151	0.0016
100.7	0.017	0.0009
150.5	0.0158	0.0007
201	0.0149	0.0008
250.8	0.0143	0.0003
301.3	0.0137	0.0002
351.1	0.0131	1.00E-04
400.9	0.0126	1.00E-04
451.2	0.0122	1.00E-04
500.9	0.0121	0.0002
551.3	0.0119	0.0003
601	0.0119	0.0003
651.1	0.0117	0.0004
701.1	0.0116	0.0003
751.4	0.0114	0.0003
801.2	0.011	0.000
850.9	0.011	0.000
901.2	0.0111	0.0002
951	1.10E-02	2.00E-04
1001	1.09E-02	3.00E-04

Solution 18: 4wt% NaCl + 0.3wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0536	0.0017
100.7	0.0428	0.0008
150.4	0.0371	0.0006
200.8	0.0335	0.0005
250.6	0.0308	0.0003
301.1	0.0287	0.0002
351.1	0.0272	0.0002
400.9	0.026	0.0002
451.2	0.0249	0.0002
500.9	0.0237	0.0002
551.3	0.023	0.0003
600.9	0.0223	0.0003
651	0.0217	0.0003
701	0.0212	0.0003
751.4	0.0206	0.0002
801.2	0.020	0.000
850.9	0.020	0.000
901.2	0.0193	0.0002
951	1.88E-02	3.00E-04
1001	1.85E-02	4.00E-04

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Solution 19: 4wt% NaCl + 0.4wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0945	0.0075
100.7	0.0758	0.0038
150.4	0.065	0.0022
200.8	0.0571	0.0013
250.7	0.0513	0.0008
301.2	0.0469	0.0005
351.1	0.0435	0.0003
400.9	0.0409	0.0002
451.2	0.0386	1.00E-04
500.9	0.0367	0.0002
551.3	0.035	0.0002
600.9	0.0336	0.0002
651	0.0324	0.0002
701	0.0314	0.0002
751.4	0.0305	1.00E-04
801.2	0.030	0.000
850.9	0.029	0.000
901.2	0.0281	0.0002
951	2.75E-02	2.00E-04
1001	2.69E-02	3.00E-04

Solution 20: 4wt% NaCl + 0.5wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.4	0.1849	0.0079
100.8	0.1316	0.005
150.5	0.1056	0.0028
200.9	0.0896	0.0016
250.8	0.079	0.001
301.3	0.0712	0.0006
351.1	0.0652	0.0004
400.9	0.0606	0.0002
451.2	0.0567	0.0002
500.9	0.0535	0.0002
551.3	0.0506	0.0002
600.9	0.0484	0.0002
651.1	0.0464	0.0002
700.9	0.0447	0.0002
751.4	0.043	1.00E-04
801.2	0.042	0.000
850.9	0.040	0.000
901.2	0.0392	0.0002
951	3.82E-02	3.00E-04
1001	3.74E-02	2.00E-04

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Solution 21: 5wt% NaCl + 0.1wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0116	0.0014
100.7	0.0088	0.001
150.4	0.0079	0.0007
200.9	0.0075	0.0006
250.8	0.0071	0.0004
301.3	0.0067	0.0003
351.1	0.0065	0.0003
400.9	0.0063	0.0003
451.2	0.0061	0.0002
500.9	0.0059	0.0003
551.3	0.0056	0.0003
601	0.0057	0.0004
651.2	0.0056	0.0003
701	0.0056	0.0003
751.4	0.0055	0.0002
801.2	0.006	0.000
850.9	0.006	0.000
901.2	0.006	0.0002
951	6.30E-03	3.00E-04
1001	6.80E-03	2.00E-04

Solution 22: 5wt% NaCl + 0.2wt% natrosol

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Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0251	0.0019
100.7	0.0206	0.0009
150.4	0.0185	0.0005
201	0.0169	0.0006
250.8	0.0154	0.0004
301.3	0.0145	0.0003
351.1	0.0142	0.0002
400.9	0.0137	0.0002
451.2	0.0132	0.0002
500.9	0.013	0.0002
551.3	0.0127	0.0002
600.9	0.0126	0.0003
651.1	0.0124	0.0004
701	0.0123	0.0003
751.4	0.0122	0.0002
801.2	0.012	0.000
850.9	0.012	0.000
901.2	0.0117	0.0002
951	1.16E-02	3.00E-04
1001	1.13E-02	3.00E-04

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Solution 23: 5wt% NaCl + 0.3wt% natrosol

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.3	0.0517	0.0028
100.7	0.041	0.0009
150.4	0.0361	0.0008
201	0.0326	0.0006
250.8	0.0302	0.0005
301.3	0.0284	0.0003
351.1	0.027	0.000
400.9	0.026	0.000
451.2	0.0245	1.00E-04
500.9	2.35E-02	2.00E-04
551.3	2.26E-02	2.00E-04
601	0.022	0.0002
651.2	0.0214	0.0002
701.1	0.0209	0.0003
751.4	0.0203	1.00E-04
801.2	0.0199	1.00E-04
850.9	0.0194	0.0002
901.2	0.019	0.0002
951	0.0186	0.0002
1001	0.0182	0.0003

02/10/03 T.J

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		Recorded by T.J	25/03/03

The viscosity measurements show that solutions with Natrosol are shear thinning, hence non Newtonian.

An alternative would be to use Golden Syrup.

11:00 GS solution 1:

H_2O = 1920g (48 wt%)
GS = 1920g (48 wt%)
NaCl = (4 wt%) 160g

GS is first poured into a beaker containing a magnetic stirrer, then salty water is added.

GS at bottom of beaker is too viscous for magnetic stirrer to work ⇒ need to stir manually for a start.

15:05 Viscosity is measured with protocole as before.

Data in 48-4-GS1.txt and 48-4-GS2.txt

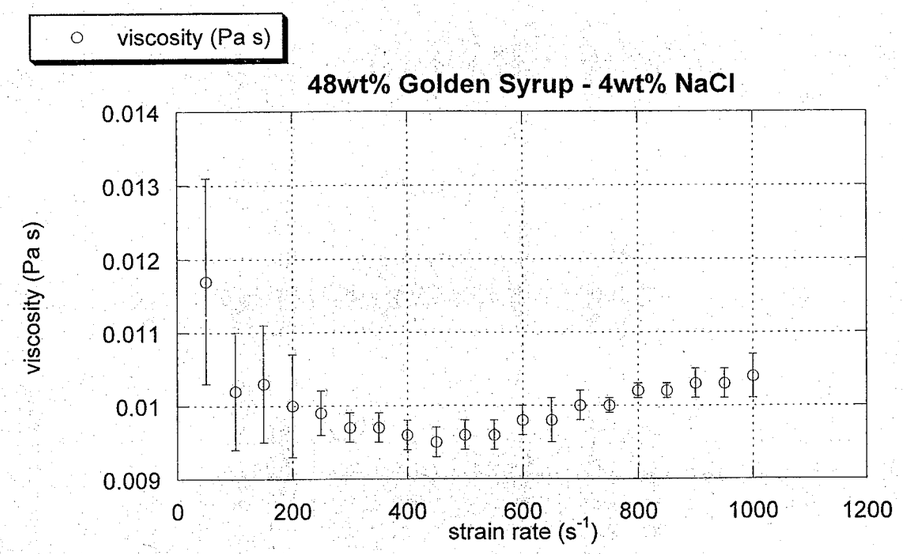
This solution should be Newtonian but its viscosity appears to rise with $\dot{\gamma}$ for $\dot{\gamma} > 500\,s^{-1}$

The viscosity is $\mu \simeq 10$ mPa s so it is likely that this apparent rise is an experimental artefact due to the low viscosity of the solution like what is observed when measuring the viscosity of water.

11/12/2003 T.7

GS Solution 1: 48wt% Golden Syrup + 4wt% NaCl

Strain rate (s-1)	Viscosity (Pa s)	Uncertainty (Pa s)
50.2	0.0117	0.0014
100.6	0.0102	0.0008
149.8	0.0103	0.0008
200.1	0.01	0.0007
249.9	0.0099	0.0003
300.2	0.0097	0.0002
350	0.0097	0.0002
399.7	0.0096	0.0002
450.1	0.0095	0.0002
500	0.0096	0.0002
550.6	0.0096	0.0002
599.9	0.0098	0.0002
650.2	0.0098	0.0003
699.9	0.01	0.0002
750.3	0.01	1.00E-04
800	0.0102	1.00E-04
849.8	0.0102	1.00E-04
900.1	0.0103	0.0002
950	0.0103	0.0002
1000.5	0.0104	0.0003



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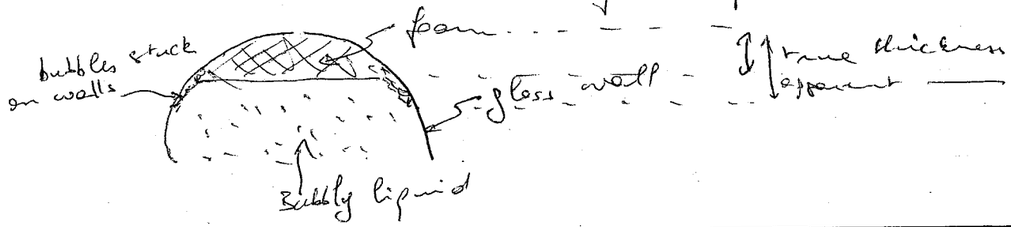
Experiment

Exp Current = 0.3 A

Note: Nickel gauge has to be connected to ⊖ of power supply and Platinum wire to ⊕.
This gives tiny bubbles (~ 50μm according to Jeremy)
If gauge and wire are connected to the power supply the other way around, then bubbles are produced from wire (mainly) rather than gauge and as wire is bigger than gauge mesh, bubbles are bigger by ~ 1 order of magnitude (eye estimation)

C estimated by variation in liquid height at top of apparatus ⇒ C ≃ 1%
Bubbles are produced for ~ ½ hour.
After that, solution ran out of NaCl

Steady-state:
Bubble free layer at bottom of side arm is ~ 5mm thick
Foam layer at top of side arm is 0.5 – 1 cm thick. This is more difficult to measure than the bubble free layer as bubbles stick to glass walls and side arm is cylindrical so this can (but does it?) lead to an overestimation of the foam thickness:



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According to Huppert (1982, JFM 121), the boundary condition at the surface of a gravity current flowing into a fluid of different density and viscosity can be a zero shear stress if the viscous dissipation in the current is much more important than viscous dissipation in the ambient fluid.

Let's look at the foam layer in our experiments.
If the flow of the foam layer induce some viscous dissipation in the bubbly layer then it will diffuse over the thickness of the bubbly layer h in a time $t \sim \frac{\rho h^2}{\mu}$ $\left(\Leftrightarrow h \sim \sqrt{\frac{\mu}{\rho} t}\right)$

With a gas volumetric fraction > 1%, this time is less than 10 s ($h \sim 1$ cm)
Therefore, the whole of the bubbly layer is, almost instantaneously, involved in the dissipation process.
Following, Huppert, the ratio of the shear stress S in the ambient fluid to that in the foam is given by

$$S \sim \frac{\mu_a}{\mu_f} \times \frac{h_f}{h_a}$$

where μ_a is the viscosity of the ambient bubbly fluid, μ_f that of the foam, h_f it's thickness and h_a that of the bubbly layer.

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$h_f \sim h_a$ (at most $\frac{h_f}{h_a} \sim 10^{-1}$)

So that $S \sim \frac{\mu_a}{\mu_f}$ is an upperbound for the stress ratio.

Conservative case: { Gas fraction in the foam: $\varepsilon \sim 0.8$; Gas fraction in the bubbly layer: $\varepsilon \sim 10\%$

$$\Rightarrow \quad S \sim \frac{(1-0.2)^{-5/2}}{(1-0.8)^{5/2}} \approx 3\,10^{-2} \ll 1 .$$

A smaller/higher concentration ε in bubbly layer/foam would give an even smaller S.

Therefore the shear stress in the current is the dominant one and the shear stress at the top of the gravity current may be set equal to zero.

This simplifies the problem a lot, as it enables to "decouple" the flow of foam at the top of the side arm from the rest of the flow: The foam can be treated as a gravity current in a "passive" ambient.

For the rest of the side arm flow, things are more delicate because the ratio of bubbly to bubble free shear stress $\sim \frac{\mu_b}{\mu_c} \sim 1$. Indeed, 25% bubbles in the bubbly layer increases the viscosity of the bubbly fluid by only a factor 2 relative to the viscosity of the pure liquid. Therefore, shear stress in the bubble free current is comparable to the shear stress in the ambient bubbly fluid and the viscous coupling between the 2 layers has to be accounted for.

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However, this situation is very similar to the one experienced by Jeremy in the case of exchange flow between 2 non miscibly liquids of different density and viscosity so it might be worth looking at the theory for those experiments.

Foam gravity current:

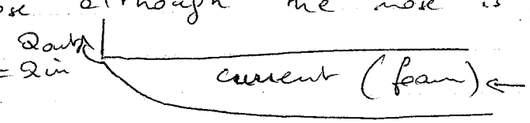
Following Huppert, the thickness of the current can be expressed as

$$h(x,t) = \eta_N^{2/3} \left(\frac{3 g Q \mu}{\Delta\rho g}\right)^{1/5} t^{1/5} \phi\left(\frac{1}{\eta_N}\right)$$

with $\eta = \left(\frac{3\mu}{\Delta\rho g \eta^3}\right)^{1/5} x \; t^{-4/5}$

and η_N is the ~~non~~ dimensionless length of the current at time t.

In our exps, we are looking at a steady-state that can be viewed as Huppert's case stopped at time t^*, say, after which any flux entering the current goes out at its nose although the nose is fixed in space:



Note that in Huppert's case, Q_{in} is feeding the current at its tail whereas in our case it is feeding the current along the whole of its length, but this shouldn't alter the picture to leading order.

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With that in mind, the thickness of the foam layer can be estimated using Huppert approach on calculating $h(0)$, the tail thickness of his gravity current.

In the case of a constant flux q feeding the current (our steady-state case),

$$h(0) \sim \eta_N^{8/3} \left(\frac{3\mu q^2}{\Delta\rho g}\right)^{1/5} \phi(0)\, t^{*\,1/5}$$

and $$t^* = \left(\frac{L}{\eta_N}\right)^{5/4} \left(\frac{3\mu}{\Delta\rho g q^3}\right)^{1/4}$$

where L is the length of the side wall, hence of the foam layer.

Huppert gives $\eta_N \simeq 1$ and $\phi(0) \simeq 1.3$ for a constant flux

so we get $$h(0) \sim \eta_N^{5/12} L^{1/4} \left(\frac{3\mu q}{\Delta\rho g}\right)^{1/4} \phi(0)$$

$$\Leftrightarrow h(0) \sim 1.3\, L^{1/4} \left(\frac{3\mu q}{\Delta\rho g}\right)^{1/4}$$

In the exp, $L \simeq 15\,10^{-2}$ m,
$q = L c v_s \simeq 15\,10^{-2} \times 10^{-2} \times 5\,10^{-5} = 75\,10^{-9}\ m^2 s^{-1}$, $\Delta\rho \simeq 900\ kg/m^3$ and $\mu \simeq 3$ Pa s

This assume 90% of gas in the foam and 1% in the bubbly layer (as estimated during exp on 08/10/03)

$\Rightarrow h(0) \simeq 4\,10^{-3}$ m

Assuming 80% gas in the foam, gives $h(0) \simeq 2.4\,10^{-3}$ m

In the experiment carried out on 08/10/03, the foam thickness was estimated to be 5mm – 1cm, not far from estimated $h(0)$ with $\varepsilon = 90\%$ and $c = 1\%$

Recorded by TJ 13/10/2003

Following Huppert, we get for the height of the foam:

$$h \simeq 1.3 \left(\frac{3\mu q}{\Delta\rho g}\right)^{1/4} \quad (*)$$

μ is the foam thickness:
$\mu = \mu_L (1-\varepsilon)^{-5/2}$, where ε is the volumetric gas fraction in the foam

$\Delta\rho = \bar{\rho} - \rho_f$, where $\bar{\rho}$ is the density of the bubbly flow in the vertical conduit and ρ_f is the density of the foam

$$\Rightarrow \Delta\rho = c\rho_g + (1-c)\rho_L - [\varepsilon\rho_g + (1-\varepsilon)\rho_L]$$

where c is the concentration of the bubbles in the flow.

$$\Leftrightarrow \Delta\rho = (c-\varepsilon)\rho_g + (\varepsilon - c)\rho_L$$

$$\Leftrightarrow \Delta\rho = (\varepsilon - c)(\rho_L - \rho_g)$$

$$\Leftrightarrow \Delta\rho \simeq (\varepsilon - c)\rho_L$$

In equation (*) above, the gas flux per unit width of the tunnel which feeds the foam depends on the concentration also:
$q = L c v_s$ where v_s is the settling (rising) velocity of the bubbles in the liquid.

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Recorded by TJ

Therefore, we've got

$$h = h(0) \simeq 1.3 \quad \left(\frac{3\mu_L L^2 V_s}{\rho g}\right)^{1/4} \left[\frac{c}{(1-\varepsilon)^{5/2}(\varepsilon - c)}\right]^{1/4}$$

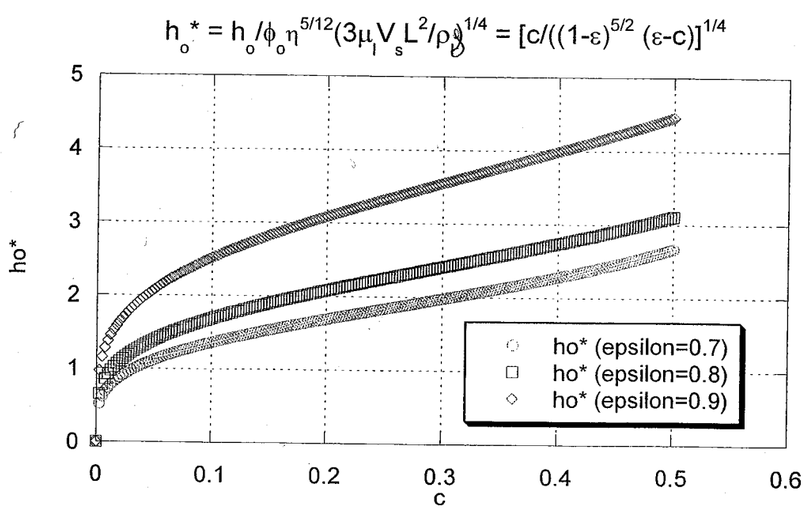
$\eta^{5/12}\phi(0)$

$$\frac{\partial h}{\partial c} \propto \frac{\varepsilon}{c^{3/4}(\varepsilon - c)^{5/4}} > 0$$

$\Rightarrow$ h increases with c.

Using K Graph, we've plot $h_0^* = \dfrac{h(0)}{\eta^{5/12}\phi(0)\left(\frac{3\mu_L L^2 V_s}{\rho g}\right)^{1/4}}$

as a function of c:



During exp on 08/10/03, c has been estimated to be ~ 1%. This gives $h_0^* \simeq 1$ for all values of ε.

11/12/2003

According to the expression of h_0^* (or graph) $c \simeq 10\%$ would create a foam of thickness $h_0^* \simeq 1.5 - 2.5$ depending on the value of ε → The higher the gas content in the foam is, the thicker it would be.

This implies a ~ 2 fold increase in foam thickness if c is increased from 1% to 10%. Note also, that c ~ 0.5% (which is arguably at the lower end of the estimation for the 08/10/03 exp) gives $h_0^* \sim 0.5$ and thus implies a 3 to 5 fold increase in h_0^* if c is increased to 10%

This means that h_0^* could be observed to increase in experiments where c is varied provided that (1) c could be increased enough and (2) h_{foam} could be measured accurately enough.

This raises also the question of ε, the gas content in the foam. It lies presumably in the range 70% - 90%, but such a range leads to a variation in h_{foam} of ~ 100% as $h_{foam}(\varepsilon = 90\%) \sim 2 \times h_{foam}(\varepsilon = 70\%)$ according to the graph on p 69.

→ So what is the value of ε?

Does it depend on the viscosity of the fluid, or its surface tension?

11/12/2003

According to Wallis (1-D two phase flows, 1969), in a conduit where both gas and liquid flow, with respective flow rates Q_g and Q_L, such that a bubbly flow forms then the mean bubble rise velocity is $v_g = v_\infty (1-c)$ where v_∞ is the rise velocity of a single bubble (stoke's velocity)

$$\rightarrow v_\infty = \frac{d^2 \Delta\rho g}{18 \mu_L}$$

This gas velocity v_g is related to the gas flow rate Q_g by $Q_g = c A v_g$ where A is the cross section area of the conduit and c the bubble density (concentration)

Q_g has been calibrated - Hence measuring v_g would give the gas concentration c. However, measuring v_g is tricky as the bubbles need to fill the entire conduit (the entire cross section). By generating bubbles and then switching off the production rate, it could be possible (at least in principle) to measure the rise speed of the interface between the bubbly fluid and the bubble free liquid underneath

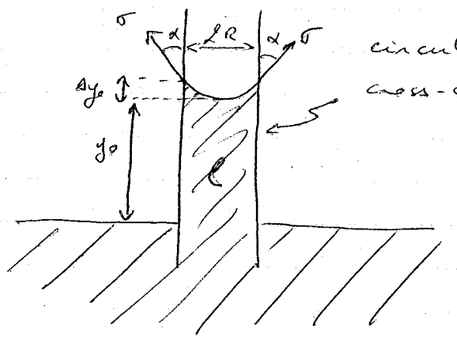
Alternatively, the stoke's velocity v_∞ could be measured, which then would give c as a solution of the following equation: $Q_g = c A v_g = c A v_\infty (1-c)$

11/12/2003

However, v_∞ is very sensitive to the bubble size d which is only crudely estimated. Moreover, the electrolysis used in the experiments produce fine bubbles from the Nickel gauze but also, although less in number, coarser ones from the Platinum wire which is bigger the the neck of the gauze. There is therefore a population of bubbles with different size rather than just one size.

11/12/2003 TA

How accurate is it to measure surface tension by measuring the rise of liquid in a narrow capillary tube?



circular cross-section

The Science of Soap Films and Soap Bubbles (C. Isenberg, 1978)

Force due to σ:

$$F_\sigma = 2\pi R \cos\alpha\, \sigma$$

$$\Delta y_0 = R\left(\sec\alpha + \frac{2}{3}\tan^3\alpha - \frac{2}{3}\sec^3\alpha\right)$$

Force due to gravity:

$$F_g = \rho g \pi R^2 (y_0 + \Delta y_0)$$

Equilibrium: $F_g = F_\sigma$

$$\Leftrightarrow \quad 2\pi R\, \sigma \cos\alpha = \rho g \pi R^2 (y_0 + \Delta y_0)$$

$$\Leftrightarrow \quad y_0 + \Delta y_0 = \frac{2\sigma}{\rho g R}\cos\alpha$$

Contact angle between water and glass: $\alpha \simeq 14° \Rightarrow \cos\alpha \sim 1$

$$\Rightarrow \quad \Delta y_0 \simeq \frac{R}{3}$$

$$\Rightarrow \quad y_0 = \frac{2\sigma}{\rho g R} - \frac{R}{3}$$

or $$\sigma = \left(y_0 + \frac{R}{3}\right)\frac{\rho g R}{2}$$

Try:

In theory, $\sigma(T = 20°C) \simeq 73\ 10^{-3}$ Pa for water and air

$\Rightarrow$ with a glass tube of internal diameter $2R = 1.8$ mm we expect a rise $y_0 \simeq 16$ mm.

In the lab, we get at most (after several hours) $y_0 = 8$ mm, that is half the expected value. This discrepancy is presumably due to the non-cleanliness of the glass and underlines the unreliable character of this method.

14:15 GS solution 2:

$H_2O = 960$ g (32 wt%)
G.S. = 1920 g (64 wt%)
NaCl = 120 g (4 wt%)

11:00 : Viscosity of GS solution 2 (prepared on 23/10/03) with protocole as before.

Meanwhile, J_∞ is being measured

By creating few bubbles, $c \ll 1$ and therefore we expect that $J_\infty \simeq J_g$ so that we get J_∞.

$\Delta L = 230$ mm.
$I = 0.1$ A
$\Delta t = 31.31$ s
Relationship between Q_g and I: $Q_g \simeq 1.4 10^{-7} I$
$\Rightarrow Q_g \simeq 14 10^{-8}$ m^3 s^{-1}
$A = \pi R^2$ with $R = 2 10^{-2}$ m
$c = \frac{Q_g}{A \Delta L} \Delta t$

$\Rightarrow c \simeq 0.15\%$

Δt enables also to calculate directly J_∞ and calculate d.

$$d = \left(\frac{18 \mu_L J_\infty}{\rho_L g}\right)^{1/2} = \left(\frac{18 \mu_L \Delta L}{\rho_L g \Delta t}\right)^{1/2}$$

μ_L estimated to be $\sim 40-45\ 10^{-3}$ Pa s and $\rho_L \simeq 10^3$ kg/m^3

$\Rightarrow d \simeq 700\ \mu$m : 10 times the expected size!

Moreover, this is much bigger than the observed bubble size ($\ll 1$ mm)

11/11/2003

Other try gives $\Delta t \simeq 54$ s
$\rightarrow$ This is $\sim$ twice as long as 1st try
$\Rightarrow$ very unreliable presumably because of interaction of bubbles (they tend to form/regroupe into plumes) and size range (from both Ni gauge and Pt wire)

Viscosity measurement shows that T° rises from 18.7°C at the beginning ($\dot{\gamma} = 0$) to 19.3°C at the end ($\dot{\gamma} = 1000$ s^{-1}) which could have an effect on μ as the Golden Syrup is very sensitive to temperature

$\Rightarrow$ Viscosity should be measured by keeping T at room temperature by using a circulator.

Easier way of measuring C

A tube (70 cm long) is mounted above the Ni gauge
GS solution 2 is filled up to 60 cm above the gauge and power supply is switched on
$I = 0.1$ A (t_0)
$t \simeq 20$ min $\Rightarrow \Delta H \simeq 5$ mm ± 0.5 mm
$t \simeq 45$ min $\Rightarrow \Delta H \simeq 9$ mm ± 0.5 mm

11/11/2003

$t = 1h\,25$ min — $\Delta H = 10$ mm ± 0.5 mm
$t = 2h$ — $\Delta H = 10$ mm ± 0.5 mm

$$c = \frac{\Delta H}{H + \Delta H} \quad (H = 60\text{ cm})$$

$$\Rightarrow c = 1.6\% \pm 0.1\%$$

Note, however, that the solution level does not drop back to $\Delta H = 0$ when gas production is stopped. This is due to gas produced by the wire that has been trapped beneath the gauze $\Rightarrow$ the residual level ΔH_{end} should be substracted from ΔH to get c.
Alternatively, the Pt wire could be placed above the gauze in order to get rid of this effect.

11/12/2003

Note With GS solution 2 (64 wt% of Golden Syrup) the maximum current intensity is $I = 0.12$ A.
$\Rightarrow$ Need to check whether this comes from the Golden Syrup and if so how a higher intensity I could be achieved

16:00 GS solution 3:
$H_2O = 300$ g (30 wt%)
G.S = 1800 g (60 wt%)
NaCl = 300 g (10 wt%)
} near saturation of NaCl in H_2O

Witnessed & Understood by me, | Date | Invented by TA | Recorded by TA | Date 23/10/2003

GS solution 3 (10 wt% NaCl, 30% H_2O and 60 wt% Golden Syrup; prepared on 23/10/2003) in tube above gauze
$\rightarrow I_{max} = 0.23$ A

$t=0$: $I = 0.2$ A and $H = 60$ cm

$t = 15$ min : $\Delta H = 7$ mm ± 0.5 mm
$t = 30$ min : $\Delta H = 12$ mm ± 0.5 mm
$t = 45$ min : $\Delta H = 14$ mm ± 0.5 mm
$t = 1h$: $\Delta H = 14.5$ mm ± 0.5 mm

ΔH_{end} (no bubble) $= 3.5 - 4$ mm

$$\Rightarrow c = \frac{\Delta H - \Delta H_{end}}{H + \Delta H - \Delta H_{end}} = 1.7\% \pm 0.1\%$$

11/12/2003

GS solution 4:
$H_2O = 960$ g (48 wt%)
G.S = 960 g (48 wt%)
NaCl = 80 g (4 wt%)

Such a solution accepts a maximum current intensity of 0.3 A whereas a 96 wt% H_2O + 4 wt% NaCl solution accepts a maximum of 0.8 A
$\Rightarrow$ Golden Syrup inhibits the electrolysis and hence the gas production rate

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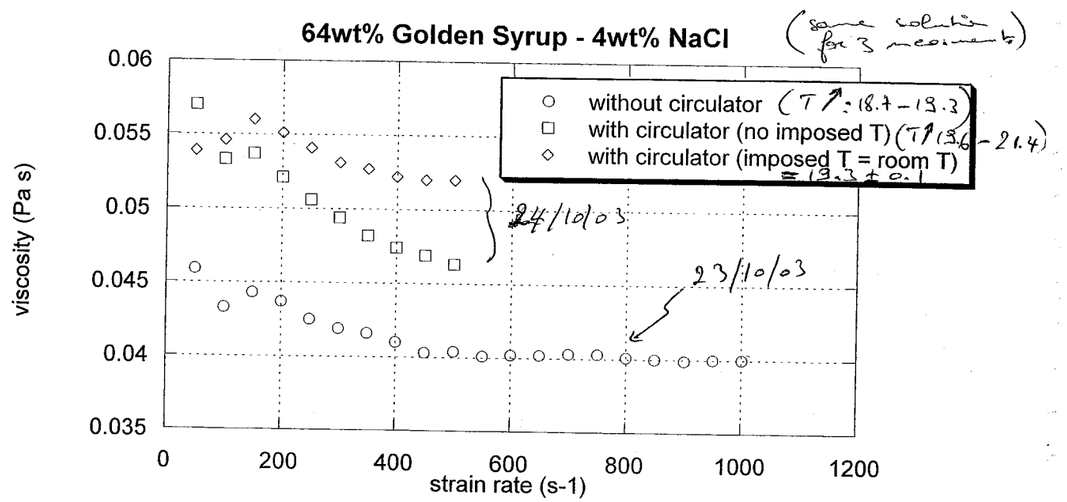
11:30 GS solution 3 — viscosity measurement.

μ is measured with the circulator running and a T° of 5°C ask for. This is way above the room T° so the bath is not heating. And the bath is not cooling as this ability has been disabled so T_{room} should be ensured.

However, T increases between 19.2°C at the begining (on circulator display) to 21.2°C at the end ($\dot{\gamma} = 500\,s^{-1}$), while room T° has been monitored within the bath (initially) at 19.2°C

Second try with both heating and cooling units on and 19.2°C asked for.

As shown on the graph below, the viscosity measurements are not consistent with each other as the viscosity measured on 23/10/03 at ~19°C is lower than the viscosity measured today although this was at lower T than today.



Recorded by TT 24/10/2003

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However, the measurements carried out today are consistent $\mu(19.3°C, \diamond) > \mu(-20°C, \blacksquare)$

The discrepancy/inconsistency between today's and yesterday's measurements is presumably due to chemical evolution of the solution.

⇒ μ must be measured during the experiment to ensure that it represents the viscosity of the solution in the apparatus

and μ should be measured with the circulator on and $T_{room} = T_{bath}$.

11/12/2003 TT

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Recorded by TT | 24/10/2003

Solution: 3000 g in total (prepared on 13/11/03 @ 11:20)
5 wt% NaCl = 150 g
0.5 wt% Natrosol = 15 g
H_2O = 2835 g
1.5 ml of blue food dye (Supercook) is added later on (11:00 on 20/11/03)

Long tube on top of Ni Gauge
Solution poured in up to 60 cm above gauge
Maximum current intensity available is 1.0 A

I = 0.8 A in order not to deplete the solution of its NaCl too quickly.
t=0 (11:35) → Δh=0
t= 4 min → Δh = 26 mm (⇒ c ≈ 4 %)
After 5 min, there is not enough NaCl in solution or the (relatively) high viscosity of the solution does not allow the bubbles between the gauge and the wire to rise fast enough and as a result more and more gas accumulate reducing the ability of the current to flow and hence to produce other bubbles.

→ Other try with new solution:
12:15: 350 cc of solution
10 wt% NaCl = 350 g
0.3 wt% natrosol = 10.5 g
H_2O = 3139.5 g

TN 11/12/2003

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liquid poured in tube up to 60 cm above gauge

I = 0.8 A
Note: I keeps fluctuating between 0.78 and 0.81 A

15:55 t=0 Δh=0 (Δh = increase in height of liquid)
t= 3' Δh = 15 mm
t= 5' Δh = 23 mm
t= 7' Δh = 32 ± 1 mm
t= 8' Δh = 34 mm + 2-3 mm of foam (F) @ liquid surface
t= 9' Δh = 37 mm F= 3 mm
t= 10' Δh = 40 mm F= 4.5 mm
t= 11' Δh = 42 mm F= 6 mm
t= 12' Δh = 44 mm F= 7-8 mm
t= 13' Δh = 47 mm F= 9 mm

About 1 cm of foam accumulates beneath gauge. However, it does not seem to affect I which stays at 0.8 A

t= 14' Δh = 48 mm F= 11 mm
t= 15' Δh = 50 mm F= 13 mm
t= 16' Δh = 51 mm F= 16 mm
t= 17' Δh = 52 mm F= 18 mm
t= 18' Δh = 53.5 mm F= 22 mm
t= 19' Δh = 54 mm F= 25 mm
t= 20' Δh = 55 mm F= 28 mm
t= 21' Δh = 54 mm F= 31 mm
t= 22' Δh = 54 mm F= 35 mm
t= 23' Δh = 53.5 mm F= 37 mm
t= 24' Δh = 53 mm F= 41 mm
t= 25' Δh = 52 mm F= 44 mm

TN 11/12/2003

Witnessed & Understood by me,	Date	Invented by TN	Date
		Recorded by TN	20/11/2003

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Obviously, the concentration keeps increasing and doesn't reach a steady-state.

Meanwhile, the thickness of the foam in surface keeps increasing as well and presumably prevents bubbles to escape freely from the liquid.

How would this compare with a different exit condition, where the area of the liquid surface is much larger for instance?

Obviously the present technique is not working. Needs to find another way of measuring and calibrating c.

TT 11/12/2002

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Witnessed & Understood by me, | Date | Invented by TT | Date 20/11/2003
Recorded by TT

Solution is H_2O + 5 wt% NaCl + 0.5 wt% natrosol
(prepared on 13/4/03, p 81)

Rheometer is RS 100 (stress controlled).
Sensors are plate + cone 35mm / 2°

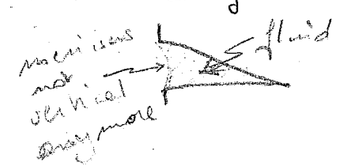
Software is Rheowin Job Manager
Job:
σ: 0 to 20 Pa
with 40 steps and 5 repetitions
1st up (0 → 20 Pa) and then down (20 Pa → 0)

Job saved as Thierry 3
Manual control:
- Zero point (Automatic)
- separate cone from plate
- Put material
- Go to gap
- Wipe out excess fluid
- Close manual control

Start measure at 15:30
It take 30s to ~~make~~ 1 measurement
⇒ 40 minutes for the whole lot (40 steps x 2)
— 20 steps would have been enough

TT 11/12/2003

Note: During 2nd part (20 → 0 Pa) fluid seems to be missing between cone and plate:



Witnessed & Understood by me, | Date | Invented by | Date
Recorded by TT | 20/11/2003

From Page No.

New solution: H_2O + 10 wt% NaCl + 0.3 wt% natrosol
(prepared today)

Job Thierry 3 is modified:
σ: 0 → 2 Pa (solution has lower viscosity)
20 steps with 5 repetitions
and back

Start at 16:55

11/12/2003 IT

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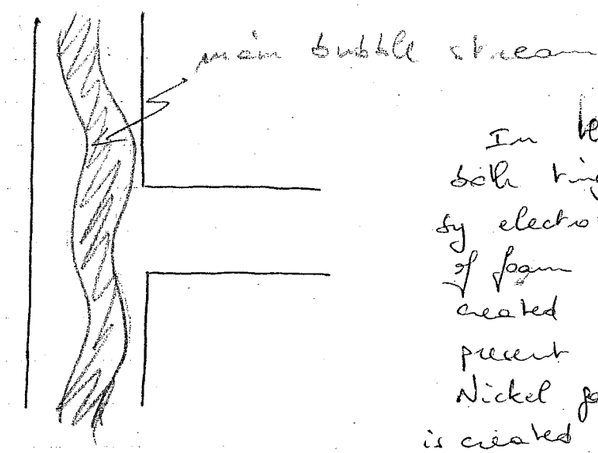
Witnessed & Understood by me,	Date	Invented by IT	Date
		Recorded by IT	20/11/2003

From Page No.

Flow loop filled with 5 wt% NaCl + 0.5 wt% natrosol solution. Solution has been dyed in blue (see yesterday)

14:33 Start of experiment
$I = 0.3$ A
Experiment is recorded with digital video camera.

Flow is not uniform in conduit as bubbles group into a stream that does not fill the entire cross section of the tube. That bubbly stream oscillates:



In the stream are both tiny bubbles, generated by electrolysis, and pockets of foam that have been created by the foam present beneath the Nickel gauze. This foam is created by the bubbles generated at the Platinum wire (hence beneath gauze) that accumulate beneath the gauze.

When bubbles reach the surface of the fluid, they form a uniform bubbly mixture which ultimately fill the entire tube top to bottom.

11/12/2003 IT

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Witnessed & Understood by me,	Date	Invented by IT	Date
		Recorded by IT	21/11/2003

From Page No.

14:51 I is noticed to be at 0.25 A
I back to 0.3 A

14:55 I dropped to 0.17 A!
I back to 0.3 A but appears to be very heratic as it fluctuates between 0.24 A and 0.45 A!

14:58 I up to 0.38 A
I back to 0.3 A.
I keeps fluctuating between 0.3 A and 0.4 A

Note: liquid is loosing its blue dye between the gauge and the wire: totally discoloured from Ni down to ~2 cm below the wire

15:10 After approximately 40 min of experiment, there isn't enough NaCl left in solution for the electrolysis → End of Exp.

New experiment with 10 wt% NaCl + 0.3 wt% methanol solution. Solution is dyed with 2 ml of red food dye (Cochineal, Supercook)

Apparatus rinsed with water but not wiped ⇒ residual water.

11/12/2003

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Witnessed & Understood by me,	Date	Invented by TD	Date
		Recorded by TD	21/11/2003

From Page No.

16:45 Start of exp
I = 0.3 A

Bubbly flow is much more uniform, apart from very beginning of exp when plumes are observed

I very stable: 0.29 - 0.31 A

Dye is disappearing between gauge and wire as in previous experiment, and again down to ~2 cm below wire.

Not much foam beneath gauge this time

Presence of 2 red tongues of fluid below the gauge. They sink down to 2-3 cm above Pt wire. They are clearly coming from the fluid above the gauge → Is it a part of the recycled fluid from the side arm?
This recycled fluid sinks from the side arm back into the conduit but it is very difficult to see were it stops sinking.

Experiment is stopped after ~40'

Note: The record has been accidentally stopped for ~5' (estimate) after 12 min of recording.

11/12/2003

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Witnessed & Understood by me,	Date	Invented by TD	Date
		Recorded by TD	21/11/2003

The electrolysis seems to "eat" the dye of the solution. Not only has the fluid lost its colour between the gauge and the wire, but the solution up the conduit (above gauge) and in the side arm appears much pinker than the original fluid as revealed by the colour of the solution below the wire (this solution has retained its initial colour).

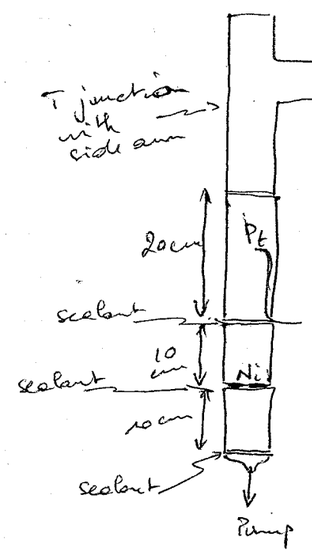
This also shows that the convection in the side arm is effective as the fluid in both the conduit and the side arm has the same pink colour.

24/11/2003

Previous experiments revealed that bubbles produced at the Platinum wire collect beneath the Nickel gauge were they form a foam that grows with time, even more rapidly as the solution is viscous.

To get rid of this problem (the foam tends to interfere with the electrolysis), the apparatus is dismantled et re-built so the Platinum wire is <u>above</u> the Nickel gauge.

New setting:



Sealant between different section is put @ 15:30
It should be left to cure for at least 24h.

24/11/2003

10:25 3138.5 g of H_2O + 350 g of NaCl (10 wt%) + 10.5 g of metasol (0.3 wt%) on magnetic stirrer
stirrer off at 15:00

15:00 T junction removed from apparatus and replaced with 30 cm long tube, as we want to measure c without the interference of the side arm.
Solution prepared this morning poured into apparatus up to the horizontal section at top of loop. → h = 8 mm above base of tube (t=0)

I_{max} = 1.4 A

I = 0.8 A ±0.01 A @ 15.31 (t=0)

Because of configuration (Pt wire above Ni gauge) there is a lot of "blobs" originating from wire along with the finer plumes coming from the gauge.
Total height of fluid above Ni gauge is 75 cm.
Length of upper horizontal tube is 58 cm

t = 1' h = 8.5 mm
t = 2' h = 9 mm
t = 3' h = 9 mm
t = 4' h = 9.5 mm
t = 5' h = 10 mm
t = 7' h = 10 mm
t = 8' h = 10.25 mm

TM 4/12/2003

To Page No.

Witnessed & Understood by me,	Date	Invented by TM	Date
		Recorded by TM	26/11/2003

From Page No.

t = 10' h = 10.5 mm
t = 12' h = 10.75 mm
t = 15' h = 11 mm
t = 20' h = 11 mm
t = 25' h = 11 mm (in fact, h seems to decrease a bit ≈ 10.75 mm)

Note: A large bubble lies beneath the gauge owing to the coalescence of the bubbles at the Ni gauge (bubble ≈0.5 cm thick but volume is too small to affect level in horizontal tube)

15:58 I = 0.1 A (t=0)

t = 1' h = 10.75 mm
t = 2' h = 10.75 mm
t = 3' h = 10.5 mm
t = 4' h = 10.5 mm
t = 5' h = 10.5 mm
t = 10' h = 10.5 – 10.75 mm

No change in h, which is the same as in I = 0.8 A case.

16:08 I = 1.5 A (higher than I_{max} available earlier on. I_{max} is now 1.66 A)

t = 2' h = 11 mm
t = 3' h = 11 mm
t = 5' h = 11.5 mm

TM 4/12/2003

To Page No.

Witnessed & Understood by me,	Date	Invented by TM	Date
		Recorded by TM	26/4/2003

From Page No.

$t = 10'$ $h = 11.5$ mm
$t = 15'$ $h = 11.5$ mm

Same behaviour and (~) values as for $I = 0.1$ A?!

Clearly, something is going wrong as, at least visually, there is a clear difference in bubble density between $I = 0.1$ A and $I = 1.5$ A cases and this difference is not recorded in level variations (variations in h)

TT 11/12/2003

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Witnessed & Understood by me, | Date | Invented by TT | Date 26/11/2003
Recorded by TT

From Page No.

Another technique would be to measure the mass of a known, or fixed, volume of bubbly mixture.

If m_0 is the mass of a given volume V of pure solution (no bubble), then the concentration is $c = \frac{V_g}{V}$ where V_g is the volume of gas in the same total volume V of the bubbly mixture. This can also be expressed as:

$c = \frac{V - V_L}{V}$ where V_L is the volume of liquid in the mixture

$V_L \simeq \frac{m}{\rho_L}$ where m is the mass of the mixture (the mass of the gas is negligeable). ρ_L = density of pure liquid.

TT 11/12/2003

$$V = \frac{m_0}{\rho_L}$$

$$\Rightarrow \quad c = \left(\frac{m_0}{\rho_L} - \frac{m}{\rho_L}\right) \Big/ \frac{m_0}{\rho_L}$$

$$\Leftrightarrow \quad \boxed{c = 1 - \frac{m}{m_0}}$$

With this technique, the volume V doesn't need to be known. Only the mass of pure liquid m_0 in such a volume and the mass of the mixture m of the same volume have to be precisely measured.

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Witnessed & Understood by me, | Date | Invented by TT | Date 27/11/2003
Recorded by TT

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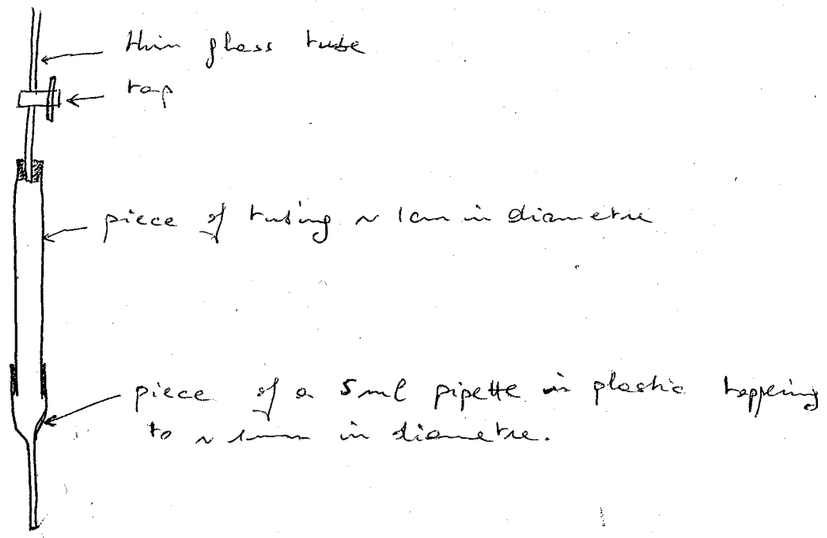
In order to get always the same volume of the mixture straight from inside the apparatus, a special "pipette" has been designed:



A glass tube with a tap is connected to a piece of tubing that is itself connected to the tip of a pipette in plastic. All connection are air-tight. By immersing this new "pipette" to a reference level and opening the tap, a given volume of fluid enters the pipette. By closing the tap, this fluid volume is trapped inside the pipette, the tapering tip preventing the fluid to escape the pipette.

The length of the tubing has to be large enough for the volume of the pipette, and therefore the mass of fluid, to be substantial in order to decrease the uncertainty on the measurement, hence on c. Especially if we want to measure low c (~1%)

Recorded by TJ 27/11/2003

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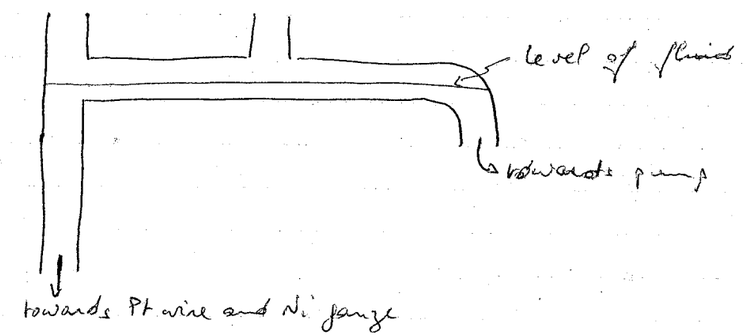
A 35 cm long piece of tubing gives a mass of pure fluid $m_0 \simeq 14g$. Given the precision of the balance to be $\pm 0.001g$ this should be enough, although it should be kept in mind that the main source of error would certainly be in the sampling of the fluid.

To sample the fluid, the apparatus has been slightly modified at its top:



The top left bend has been changed by a T junction, everything else being unchanged. This ensures that the behaviour of the bubbles is as in apparatus for exp and the top left exit allows easy access to the mixture.

Each time a mass of fluid is sampled, the "pipette" is dropped into the apparatus from the top left access down to a reference level ensuring the same volume is sampled each time.

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Witnessed & Understood by me, | Date | Invented by TJ | Date
Recorded by TJ | 27/11/2003

Mass of pure fluid:

$m_0 = 14.072\,g$, $13.882\,g$, $13.967\,g$, $14.008\,g$, $14.005\,g$

These 5 measurements (5 different samplings) gives $\overline{m_0} = 13.97 \pm 0.07\,g$

where the uncertainty is the standard deviation σ of the mean distribution.

$\Rightarrow$ precision of the method estimated at $\frac{\sigma}{\overline{m_0}} \simeq 0.5\%$

15:22 Solution prepared on yesterday = 10% NaCl + 0.3% natrosol

into apparatus.

$I = 0.3\,A$ ($\pm 0.01\,A$) ($t=0$)

$t = 5'$ $m = 13.924\,g$ (flow inside vertical tube doesn't seem uniform with c higher when closer to gauge)

$t = 10'$ $m = 13.794\,g$

$t = 15'$ $m = 13.678\,g$

$t = 20'$ $m = 13.708\,g$

$t = 30'$ $m = 13.663\,g$

The uncertainty on these masses are assumed to be $\pm\sigma$ ($\sigma = 0.07\,g$)

$$\Rightarrow c = 1 - \frac{m}{m_0} \pm \delta c$$

and $$\frac{\delta c}{c} = \frac{\sigma}{m} + \frac{\sigma}{m_0}$$

$I = 0.5\,A$ @ 16:44 ($t=0$)

mass of pure liquid: $m_0 = 13.936\,g$, $14.020\,g$, $13.928\,g$

$\Rightarrow \overline{m_0} = 13.98 \pm 0.05\,g$ $\rightarrow$ similar to previous value of $13.97 \pm 0.07\,g$.

$t = 5'$ $m = 13.806\,g$

$t = 10'$ $m = 13.705\,g$

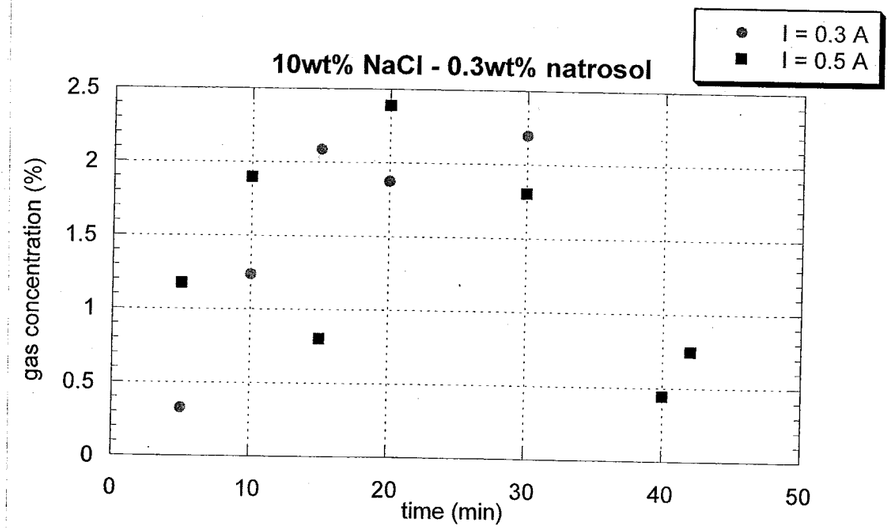
$t = 15'$ $m = 13.858\,g$

$t = 20'$ $m = 13.636\,g$

$t = 30'$ $m = 13.718\,g$

$t = 40'$ $m = 13.908\,g$

$t = 42'$ $m = 13.866\,g$



As shown on this figure (c(%) vs time) for 2 different current intensities, gas concentration

From Page No.

tends to rise for 10'-20' before reaching what seems to be a plateau around $c \simeq 2\%$ - However, it also seems that the concentration decreases after 20'-30' for the case where $I = 0.5$ A.

This might reflect a decrease in NaCl content in solution, although this seems quite unlikely given that the current intensity stayed stable at $I = 0.5$ A and did not show any sign of NaCl shortage.

Note that in cleaning the apparatus, it appeared that the solution contained a lot of oxide particles that might explain the apparent increase in mass of the sample with time if they're sampled with the mixture (variations in mass for $t \geq 20'$ are less than 0.3 g). Changing the solution between 2 sets of measurements would decrease this effect (the 0.5 A set of measurements had been carried out with the same fluid, unchanged from the apparatus, whereas the 0.3 A set did not show the decrease of c with time).

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Witnessed & Understood by me,	Date	Invented by TA	Date 27/11/2003
		Recorded by TA	

From Page No.

New solution : H_2O (3133.5 g) + 10% NaCl (350 g) + 0.3% metrosol (10.5 g)

12:40 700 g of pure liquid (no bubble)

$m_0 = 13.742$ g, 14.355 g, 14.363 g, 14.326 g, 14.366 g, 14.335 g

$\Rightarrow \bar{m}_0 = 14.36 \pm 0.02$ g

Note : The pipette has been left immersed for 10 s before closing the tap to enable the level in the pipette to rise and equilibrate. This has been done for all samples except the first one, which shows a clear discrepancy with the others and has therefore been disregarded from the mean and σ calculation.

$I = 0.5$ A @ 12:51 ($t = 0$)

$t = 5'$	$m = 14.123$ g	bubbles ~ uniformly distributed
$t = 10'$	$m = 13.388$ g	
$t = 15'$	$m = 13.302$ g	
$t = 20'$	$m = 13.314$ g	
$t = 25'$	$m = 13.881$ g	
$t = 30'$	$m = 13.385$ g	
$t = 35'$	$m = 14.058$ g	
$t = 40'$	$m = 14.032$ g	
$t = 50'$	$m = 14.013$ g	
$t = 60'$	$m = 14.144$ g	

Again m rises after ~30' although no particles (oxide) have been observed in samples.

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Witnessed & Understood by me,	Date	Invented by TA	Date 02/12/2003
		Recorded by TA	

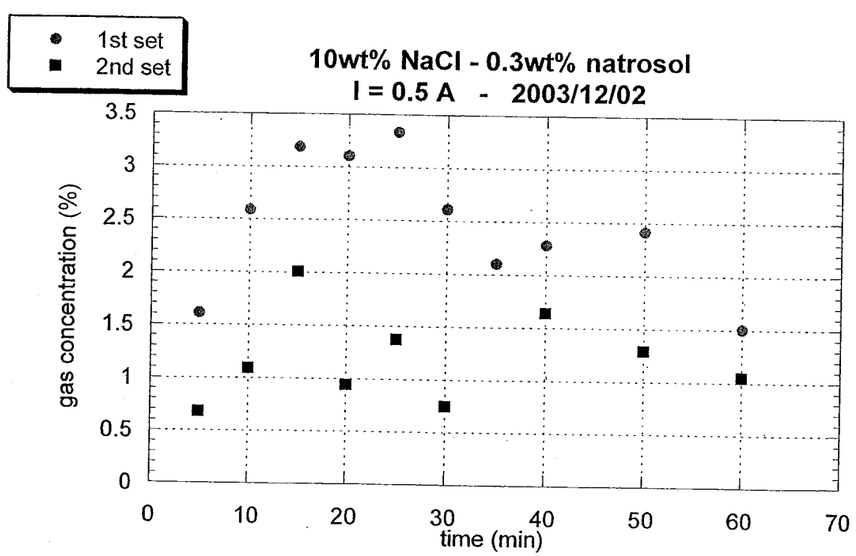
Same solution, new set of measurements

I = 0.5 A @ 16:13 (t=0)

t = 5'	m = 14.302 g
t = 10'	m = 14.243 g
t = 15'	m = 14.111 g
t = 20'	m = 14.264 g
t = 25'	m = 14.202 g
t = 30'	m = 14.232 g
t = 40'	m = 14.164 g
t = 50'	m = 14.214 g
t = 60'	m = 14.248 g

m have higher values than for previous set.
→ mass of pure liquid is measured again when all bubbles have disappeared.

18:05 m_0 = 14.501 g, 14.361 g, 14.373 g, 14.428 g, 14.326 g
⇒ $\bar{m}_0$ = 14.40 ± 0.07 g similar to previous measurement.



Recorded by TT 02/12/2003

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As shown on the figure on previous page, the 2 sets of measurements show some discrepancy as the 1st one gives values ~ twice as big as those obtain during the 2nd set.

Does this reflect the variations of the method?

$$\boxed{c = 1 - \frac{m}{m_0}}$$

$$\delta c = \left|\frac{\partial c}{\partial m}\right| \delta m + \left|\frac{\partial c}{\partial m_0}\right| \delta m_0$$

$$\left|\frac{\partial c}{\partial m}\right| = \left|-\frac{1}{m_0}\right| = \frac{m}{m_0} \times \frac{1}{m} = (1-c) \times \frac{1}{m}$$

$$\left|\frac{\partial c}{\partial m_0}\right| = \frac{m}{m_0^2} = (1-c) \times \frac{1}{m_0}$$

$$\Rightarrow \boxed{\delta c = (1-c)\left(\frac{\delta m}{m} + \frac{\delta m_0}{m_0}\right)}$$

this gives uncertainties on c that are $\frac{1-c}{c}$ higher → for c ~ 2%, this gives values ~50 times larger! That is $\delta c \simeq \pm 1\%$ in all cases (0.3 A and 0.5 A) except for the 1st set where $\delta c \simeq \pm 0.25\%$

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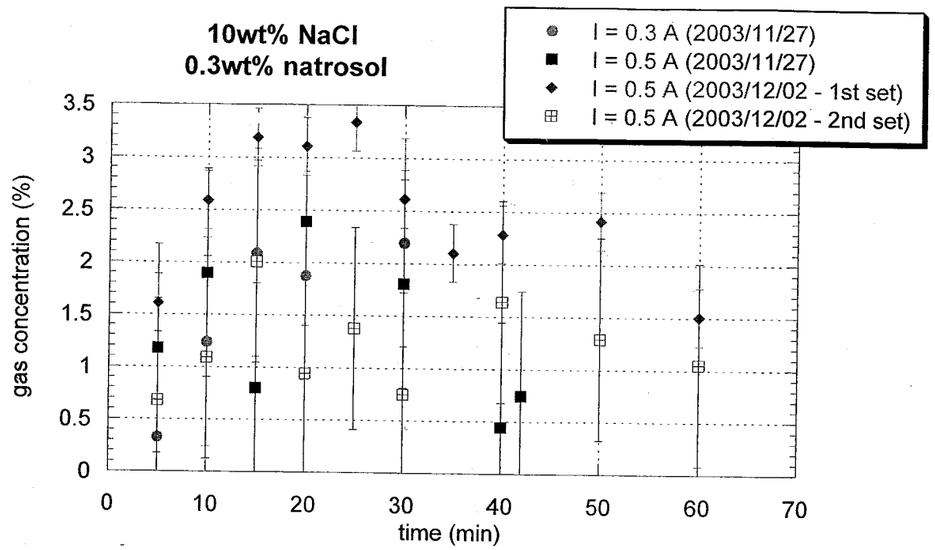
Witnessed & Understood by me,	Date	Invented by TT	Date
		Recorded by TT	02/12/2003



All data points fall within uncertainty bars, and $c \simeq 2\% \pm 1\%$ for $I = 0.3A$ as well as for $I = 0.5A$.

There are 2 questions now:

1- Is there any change in c to be expected when varying the current intensity?
Although we only have 2 different intensities here, one is twice as big as the other one but c stays the same (given the uncertainty on the measurements). Could this reflect the fact that c would depend mainly on the liquid viscosity? For $c \ll 1$, then the rising speed of the bubbles is close the the Stoke's velocity (1 bubble) according to Wallis' book (1-D two phase flow) as few interactions between bubbles. Therefore we would expect

to rise through the fluid column at the same speed irrespective of the gas flow rate, that is the current intensity. This would mean that bubbles spend the same amount of time within the liquid, hence that c would stay constant and be independent of I.

2- Are higher values of c achievable?
This is a more important question as the actual value that we obtained so far are very low indeed. If we are to make a systematic study of the gas segregation and fluid circulation in the side arm, surely we need to be able to get bubble concentration higher by an order of magnitude.

Back to 1-: We expect the bubbles to spend the same amount of time in the liquid, whatever the gas flow rate is BUT for higher flow rate, more bubbles are produced during the time needed for 1 bubble to rise from the gauge up to the surface
$\Rightarrow$ we expect c to rise with the gas flow rate.

Similarly, for a given Q_g, the rising speed of the bubbles decreases when the viscosity of the fluid increases, i.e. the time spent in fluid increases with the viscosity
$\Rightarrow$ we expect c to increase with the fluid viscosity.

Solution : 10 wt% NaCl + 0.3 wt% Natrosol + H_2O
(350 g) (10.5 g) (3133.5 g)

Jars of pure solution (no bubble):
m_0 = 14.376 g , 14.382 g , 14.403 g , 14.352 g , 14.424 g
⇒ $\bar{m}_0$ = 14.40 ± 0.02 g.

11:20 I = 1.20 ± 0.02 A (t=0)

Bubbly flow is fairly uniform and homogeneous rather quickly.

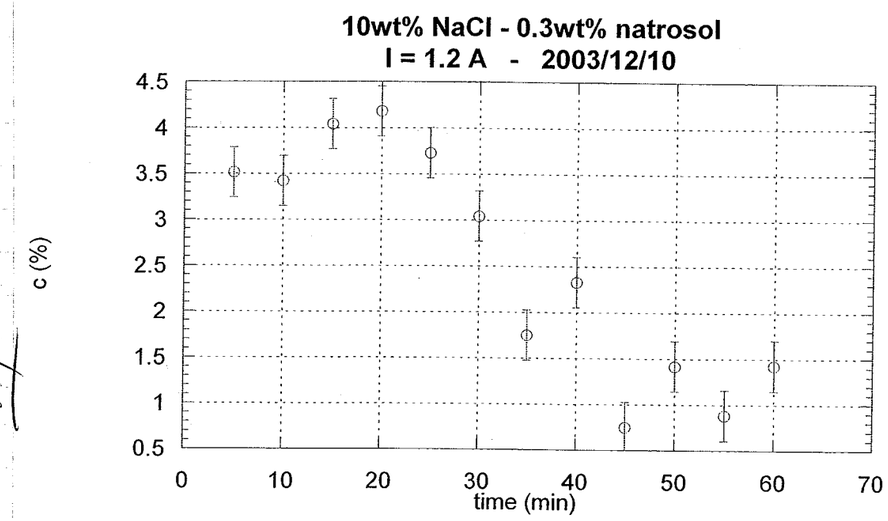
t = 5'	m = 13.834 g	flow is greyish (particles)
t = 10'	m = 13.307 g	note: particles in sample
t = 15'	m = 13.818 g	note: I keeps rising slightly and needs adjustment
t = 20'	m = 13.788 g	
t = 25'	m = 13.863 g	⇒ I = 1.21 ± 0.02 A is closer to reality
t = 30'	m = 13.362 g	

note: Foam thickness at liquid surface is decreasing.

t = 35'	m = 14.148 g	?? why such an increase?
t = 40'	m = 14.065 g	note: particle in samples
t = 45'	m = 14.232 g	→ few tiny particles
t = 50'	m = 14.196 g	→ " " "
t = 55'	m = 14.273 g	→ particles
t = 60'	m = 14.195 g	→ few particles

TT 10/12/2003

This measurements give the following concentration evolution graph:



TT 10/12/2003

2 things are remarquable:

1. C ≃ 4.0 ± 0.5% during the 25 first minutes of the experiment. This is higher a value when compared to previous exp

2. C drops markedly after ~30 min to reach a value of ~ 1 - 1.5% and seems to stay at such a value.

Note that this value is comparable to that of previous experiment.

Why such a variation?

Does it reflect some physical process or is it induced by the way c is measured.

↳ for instance, if the surface level rise as bubbles are "pumped" into fluid, the amount of fluid sampled would rise because the pipette is always immersed at the same location.

Could this rise in fluid level increase the measured mass in such a way that it would create a decrease in c?

→ This can be avoided by sampling the same volume using a syringe connected to a small plastic capillary that would be immersed in the apparatus.

This technique is going to be used now on instead of the pipette one.

10/12/2003

Density of solution:

Before experiment: $m = 28.633\,g$

After experiment: $m = 28.637\,g$

→ particles do not seem to affect mass of sample.

V (density bottle) $= 26.714\,cm^3$

$\Rightarrow \rho = 1072.0\,kg/m^3$

Another possibility, to explain the brutal decrease in bubble concentration, could be a change in viscosity: if viscosity decreases then the rising speed of bubbles would increase and c would decrease.

The viscosity of the fluid is measured using the sample used to measure density.

Rheometer is RS 100 with plate and cone 35 mm/2°

software is Rheowin Job Manager.

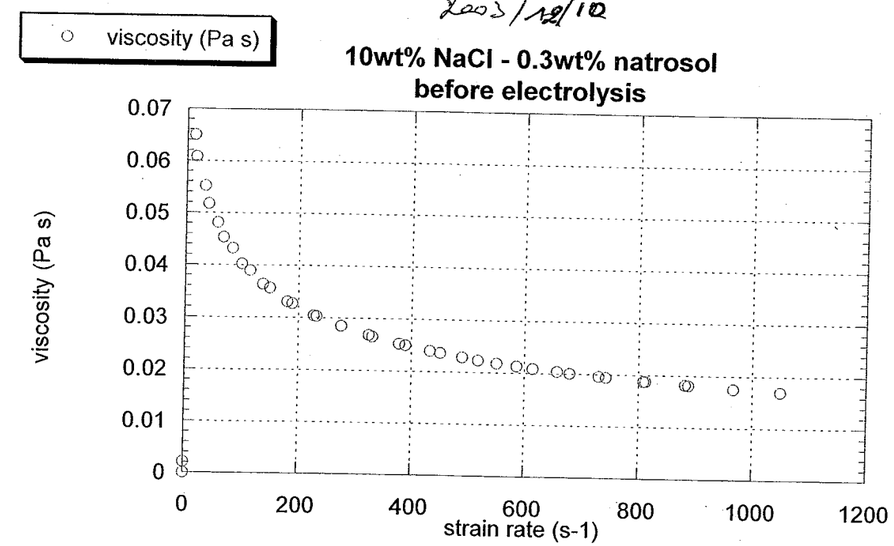
Job for sample before exp:

σ: 0 to 20 Pa with 20 steps & 5 rep. (and back)

Job for sample after exp:

σ: 0 to 2 Pa with 20 steps & 5 reps. (and back)

2003/12/10



Project No. 06002-01-051
Book No. 561 TITLE

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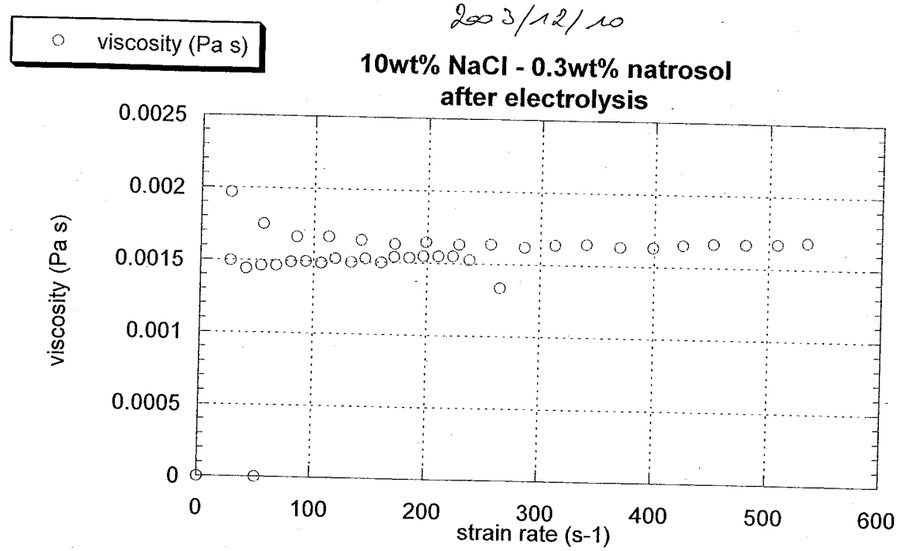
2003/12/10



Before exp: solution is shear thinning, as expected for a Natrosol solution: $\mu \approx 20-70$ mPa s

After exp: solution shows a Newtonian behaviour and a much smaller viscosity: $\mu \approx 1.5$ mPa s.

Note that this viscosity is very much like that of water.

⇒ It seems that somehow, the Natrosol polymer is consumed by the electrolysis and the solution becomes more watery as the exp. proceeds.
⇒ μ decreases during exp.
⇒ C decreases as well.

11/12/2003

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Witnessed & Understood by me,	Date	Invented by IJ	Date
		Recorded by IJ	10/12/2003

I have reviewed scientific notebook 561 and find it in compliance with QAP-001. There is sufficient information regarding procedure used for conducting the research and acquiring and analyzing the data so that another qualified scientist could repeat the activity or activities recorded in this scientific notebook The record of work on this task will be continued in #619 This scientific notebook (516) can be archived.

H. Lawrence McKague 10/27/04

H. Lawrence McKague
GLGP Element Manager