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Development of carbon nanotube/platinum electrocatalytic electrodes for proton exchange membrane fuel cell

Afolabi, Ayo Samuel

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APPENDIX I

PAPERS PUBLISHED AND PRESENTED FROM THIS STUDY

1. Iyuke, S. E., Pienaar, C., Abdulkareem, A. S. and **Afolabi, A. S. (2006)** Optimising carbon nanotubes continuous production in a swirled floating catalyst chemical vapour deposition reactor. Paper presented at the *South African Chemical Engineering Conference, Durban 2006.*

2. Iyuke, S. E, Abdulkareem, A.S. and **Afolabi, A. S. (2007)** Catalytic production of carbon nanotubes in a swirled fluid chemical vapour deposition reactor. *International Journal of Chemical Reactor Engineering* Vol. 5, Note S5, (ISSN 1542 – 6580), pp 1 – 9.

3. P. Mokwena, A. Marshall, **A. S. Afolabi,** A. S. Abdulkareem, and S. E. Iyuke **(2007)** Thermodynamic stability of graphitic diamond films produced using CCVD apparatus. *Journal of the Southern African Institute of Mining and Metallurgy* Vol. 107, No 4, (ISSN 0038 – 223X), pp 211 – 214.

4. Abdulkareem, A. S, **Afolabi, A. S**. Iyuke, S. E. and Pienaar, H. C. vZ **(2007)** Synthesis of carbon nanotubes by swirled floating catalyst chemical vapour deposition method. *Journal of Nanoscience and Nanotechnology, USA* Vol. 7, No 9, pp 3233 – 3238.

6. Afolabi A. S., Abdulkareem A.S. and Iyuke S. E. **(2007)** Synthesis of carbon nanotubes and nanoballs by swirled floating catalyst chemical vapour deposition

method. *Journal of Experimental Nanoscience* Vol. 2, Issue 4, (ISSN 1745 – 8080), pp 269 – 277.

7. A. S. Afolabi, A. S. Abdulkareem, S. E. Iyuke and H.C.Van Zyl Pienaar **(2009)** Continuous production of carbon nanotubes and diamond films by swirled floating catalyst chemical vapour deposition method. *South African Journal of Science* Vol. 105, No 7–8, pp 278 – 281.

8. Mhlanga, S. D., Iyuke, S. E., **Afolabi, A. S.,** Abdulkareem, S. A., Kunjuzwa, N. and Coville, N. J. (2009): Controlled CVD synthesis of carbon spheres in a vertical reactor. *Article accepted for publication in Journal of Experimental Nanoscience.*

9. Afolabi, A. S, Abdulkareem, A. S, Iyuke, S. E, Coville N. J. and Pienaar, H.C.vZ (2009): Preparation and characterization of CNT-platinum nanocatalysts for a proton exchange membrane fuel cell. *Proceedings of Nigerian Materials Congress NIMACON 2008,* November 3 – 8, 2008, Akure, Nigeria

10. Afolabi, A. S, Abdulkareem, A. S, Iyuke, S. E, Mhlanga, S. D and Coville N. J. (2009): Synthesis of bi–metallic catalyzed carbon nanotubes by a CVD method. *Proceedings of Nigerian Materials Congress NIMACON 2008,* November 3 – 8, 2008, Akure, Nigeria

11. Afolabi, A. S, Abdulkareem, A. S, Iyuke, S. E. Coville N. J and Pienaar, H.C.vZ (2009): Preparation and determination of electroactivity of carbon nanotube-platinum catalyst for proton exchange membrane fuel cell. *Postal Presentation at the Nanotechnology Conference, NanoIsrael,* March 30 – April 1, 2009, Jerusalem, Israel.

12. Abdulkareem, A. S, Idibe, C. A, **Afolabi, A. S,** Iyuke, S. E. and Pienaar, H.C.vZ (2009): Development of proton exchange membrane (PEM) from synthetic rubber and carbon nanoballs. *Postal Presentation at the Hybrid Materials 2009, First International Conference on Multifunctional, Hybrid and Nanomaterials, Tours, France*, March 15 – 19, 2009.

13. Abdulkareem A.S, Idibe C.A, **Afolabi A.S,** Piennar .H.C.vZ , Iyuke S.E. and Van Dyk. L (2009): Proton conducting membranes for fuel cell application from polystyrene butadiene rubber: The effect of sulphonating agents on the membrane characteristics. *Article accepted for publication in Energy Sources Part: Recovery, Utilization and Environmental Effects.*

14. Abdulkareem, A. S, **Afolabi A. S**, Idibie C. A, Iyuke S. E. and Pienaar, H. C. vZ (2009): Development of a proton exchange membrane (PEM) for telecom fuel cell applications. *Proceedings of the SATNAC 2009 Conference, August 31st – 2nd September, 2009, Mbabane, Swaziland.*

15. Afolabi, A. S, Abdulkareem, A. S, Mhlanga, S. D, Coville, N. J and Iyuke, S. E (2009): Synthesis and purification of bi–metallic catalyzed CNTs in a horizontal CVD reactor. *Article accepted for publication in Journal of Experimental Nanoscience.*

APPENDIX II

PREPARATION OF PLATINUM LOADINGS ON CNTs

1. To prepare 10wt% Pt in 1 g of CNT

Using the concentration of the maximum absorbance (i.e. 0.35 g/cm^3) as the reference,

10 wt% Pt catalyst on 1 g of CNT is $\frac{10}{100}$ X 0.35 = 0.035 g/cm^3

2. To prepare 20wt% Pt in 1 g of CNT

20 wt% Pt catalyst on 1 g of CNT is $\frac{20}{100}$ X 0.35 = 0.07 g/cm^3

3. To prepare 30wt% Pt in 1 g of CNT

30 wt% Pt catalyst on 1 g of CNT is $\frac{30}{100}$ X 0.35 = 0.105 g/cm^3

4. To prepare 40wt% Pt in 1 g of CNT

40 wt% Pt catalyst on 1 g of CNT is $\frac{40}{100}$ X 0.35 = 0.14 g/cm^3

5. To prepare 50wt% Pt in 1 g of CNT

50 wt% Pt catalyst on 1 g of CNT is $\frac{50}{100}$ X 0.35 = 0.175 g/cm^3

APPENDIX III

PEM FUEL CELL RESULTS

Current density and voltage

I density	Voltage 40Wt%	Voltage 30Wt%	Voltage 20Wt%	Voltage 10Wt%
0	718.75	689.79	520.48	307.45
5.72	704.5	647.54	469.24	259.76
12.688	678.9	569.87	398.56	220.45
29.952	645.15	489.99	322.575	191.545
47.84	618.7	433.09	300.78	185.61
87.984	583.05	400.56	291.525	178.914
108.316	534.9	374.43	258.56	160.47
125.32	494.5	355.65	247.25	148.35
160.576	443.9	310.73	219.78	136.023
182.52	403.65	280.55	201.825	119.098
199.68	369	258.3	180.78	115.8
211.848	334.65	234.255	167.325	100.395
221.312	305.9	210.67	150.95	89.78
232.96	256.15	179.305	128.075	76.845
250.64	231.15	161.805	112.567	69.89
256.8	229.85	156.89	114.925	58.955

Current density and power density

I density	P density 40Wt%	P density 30Wt%	P density 20Wt%	P density 10Wt%
0	0	0	0	0
5.72	4029.74	3703.929	2684.053	1485.827
12.688	8613.883	7230.511	5056.929	2797.07
29.952	19323.53	14676.18	9661.766	5737.156
47.84	29598.61	20719.03	14389.32	8879.582
87.984	51299.07	35242.87	25649.54	15741.57
108.316	57938.23	40556.76	28006.18	17381.47
125.32	61970.74	44570.06	30985.37	18591.22
160.576	71279.69	49895.78	35291.39	21842.03
182.52	73674.2	51205.99	36837.1	21737.77
199.68	73681.92	51577.34	36098.15	23122.94
211.848	70894.93	49626.45	35447.47	21268.48
221.312	67699.34	46623.8	33407.05	19869.39
232.96	59672.7	41770.89	29836.35	17901.81
250.64	57935.44	40554.81	28213.79	17517.23
256.8	59025.48	40289.35	29512.74	15139.64

Current density, experimental and simulated voltages for 40wt% Pt–CNT electrode

i	Exp 40%	Sim 40%
5.72	704.5	809.9181
12.688	678.9	709.6151
29.952	645.15	601.4746
47.84	618.7	542.5199
87.984	583.05	465.8099
108.316	534.9	439.6356
125.32	494.5	421.2771
160.576	443.9	390.0669
182.52	403.65	373.9401
199.68	369	362.6272
211.848	334.65	355.1798
221.312	305.9	349.6774
232.96	256.15	343.2196
250.64	231.15	334.0099
256.8	229.85	330.9531

ln Current density and overpotential

	40Wt%	30Wt%	20Wt%	10Wt%
1.743969	14.25	71.21	249.51	458.99
2.540657	39.85	148.88	320.19	498.3
3.399596	73.6	228.76	396.175	527.205
3.867862	100.05	285.66	417.97	533.14
4.477155	135.7	318.19	427.225	539.836
4.685053	183.85	344.32	460.19	558.28
4.83087	224.25	363.1	471.5	570.4
5.078767	274.85	408.02	498.97	582.727
5.20686	315.1	438.2	516.925	599.652
5.296716	349.75	460.45	537.97	602.95
5.355869	384.1	484.495	551.425	618.355
5.399573	412.85	508.08	567.8	628.97
5.450867	462.6	539.445	590.675	641.905
5.524018	487.6	556.945	606.183	648.86
5.548298	488.9	561.86	603.825	659.795

Voltage and time

0	718.75
60	679.67
120	619.7
180	558.64
240	555.89
300	557.67
360	556.87
420	438.48
480	438.49
540	438.48
600	438.48

APPENDIX IV

ADSORPTION DATA

Stirring time Vs platinum adsorbed on CNT

0	0	0	0	0	0
20	0.012	0.018	0.04	0.042	0.044
40	0.02	0.022	0.046	0.056	0.061
60	0.024	0.036	0.066	0.072	0.079
80	0.026	0.044	0.071	0.089	0.1
100	0.028	0.051	0.088	0.102	0.102
120	0.031	0.059	0.088	0.102	0.102
140	0.031	0.059	0.088	0.102	0.102

Stirring time Vs equilibrium concentration of the Pt precursor

0	0	0	0	0	0
20	0.023	0.052	0.065	0.098	0.131
40	0.015	0.048	0.059	0.084	0.114
60	0.011	0.034	0.039	0.068	0.096
80	0.009	0.026	0.034	0.051	0.075
100	0.007	0.019	0.017	0.038	0.073
120	0.004	0.011	0.017	0.038	0.073
140	0.004	0.011	0.017	0.038	0.073

Temperature Vs platinum adsorbed on CNT

Temp	10wt%	20wt%	30wt%	40wt%	50wt%
25	0.025	0.038	0.086	0.099	0.101
50	0.028	0.049	0.09	0.101	0.102
75	0.03	0.058	0.098	0.102	0.104
100	0.032	0.063	0.102	0.104	0.104

Temperature Vs equilibrium concentration of the Pt precursor

25	0.01	0.032	0.019	0.041	0.074
50	0.007	0.021	0.015	0.039	0.073
75	0.005	0.012	0.007	0.038	0.071
100	0.003	0.007	0.003	0.036	0.071

APPENDIX V

Hitschenhofer's model results for 40wt% Pt–CNT catalyst electrode

i density	Vo	b	i*o*	log i*o*	blogi*o*
5.72	704.5	125.9	0.00572	-2.24260397	-282.344
12.688	678.9	125.9	0.012688	-1.89660683	-238.783
29.952	645.15	125.9	0.029952	-1.52357417	-191.818
47.84	618.7	125.9	0.04784	-1.32020883	-166.214
87.984	583.05	125.9	0.087984	-1.0555963	-132.9
108.316	534.9	125.9	0.108316	-0.96530739	-121.532
125.32	494.5	125.9	0.12532	-0.90197961	-113.559
160.576	443.9	125.9	0.160576	-0.79431936	-100.005
182.52	403.65	125.9	0.18252	-0.73868954	-93.001
199.68	369	125.9	0.19968	-0.69966543	-88.0879
211.848	334.65	125.9	0.211848	-0.67397563	-84.8535
221.312	305.9	125.9	0.221312	-0.65499504	-82.4639
232.96	256.15	125.9	0.23296	-0.63271864	-79.6593
250.64	231.15	125.9	0.25064	-0.60094962	-75.6596
256.8	229.85	125.9	0.2568	-0.59040498	-74.332

R	R*io*	m	expi*o*	mexpi*o*
0.573	0.003278	178.628	1.036337435	185.1188725
0.573	0.00727	162.0875	1.08239169	175.4422156
0.573	0.017162	127.4074	1.205507307	153.5905987
0.573	0.027412	99.27978	1.347864651	133.8157124
0.573	0.050415	56.7204	1.731555539	98.21451871
0.573	0.062065	42.71731	1.96578536	83.97305661
0.573	0.071808	33.69951	2.185832581	73.66149249
0.573	0.09201	20.61128	2.723708144	56.13910861
0.573	0.104584	15.17773	3.123408271	47.40625456
0.573	0.114417	11.94763	3.476420596	41.53499699
0.573	0.121389	10.083	3.750658858	37.8178772
0.573	0.126812	8.836359	3.978826315	35.15833838
0.573	0.133486	7.511563	4.278790602	32.14040537
0.573	0.143617	5.870243	4.777864073	28.04722153
0.573	0.147146	5.387033	4.965092859	26.74711916

P	P_{O2}	P/P_{O2}	log (P/PO_2)	blog(P/P_{O2})
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828
35	15	2.333333	0.367977	46.32828

io	Simulated	Experimental
5.72	755.3934127	704.5
12.688	695.9050368	678.9
29.952	637.0319499	645.15
47.84	604.7428896	618.7
87.984	571.3563631	583.05
108.316	526.068801	534.9
125.32	487.9976553	494.5
160.576	441.3454121	443.9
182.52	402.8118973	403.65
199.68	369.110187	369
211.848	335.2359887	334.65
221.312	306.7504477	305.9
232.96	257.2071084	256.15
250.64	232.2904414	231.15
256.8	230.9594442	229.85

io	m
0.00572	225
0.012688	180
0.029952	124
0.04784	90
0.087984	50
0.108316	39
0.12532	31
0.160576	18
0.18252	14
0.19968	13
0.211848	10
0.221312	9
0.23296	8
0.25064	6
0.2568	6

$m = 193.4e^{-13.9io}$

$R^2 = 0.992$