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APPENDICES

Appendix A Experimental data

Table A1 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Reactant conversion (%)				Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	H_2	C_2
31.25	1	21.6005	38.1316	58.8239	12.4586	39.17	42.24
62.50	2	21.3141	41.8887	67.2458	13.5631	42.39	37.79
93.75	3	18.3443	40.1798	67.0140	8.6508	47.99	43.21
125.00	4	18.9529	40.7346	72.8272	10.4294	47.29	51.38

Table A2 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Concentration of outlet gas (mol%)								
		H_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
31.25	1	15.19	1.04	52.36	16.07	2.66	2.03	3.03	2.01	0.22
62.50	2	15.49	1.03	53.52	15.95	1.76	2.24	2.66	1.57	0.26
93.75	3	15.54	1.12	51.29	15.96	1.63	2.27	2.76	1.48	0.28
125.00	4	15.71	1.11	52.41	15.84	2.49	2.58	2.81	1.28	0.21

Table A3 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Product selectivity (%)				
		H_2	C_2H_2	C_2H_4	CO	C_4H_{10}
31.25	1	33.04	19.86	15.13	3.56	3.31
62.50	2	32.49	12.58	16.00	3.37	1.19
93.75	3	38.23	13.45	18.45	4.33	4.30
125.00	4	35.69	18.88	19.57	3.92	3.17

Table A4 Effect of stage number of plasma reactors on product molar ratios for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
31.25	1	14.66	5.70	7.49	0.76
62.50	2	15.08	8.78	6.91	1.27
93.75	3	1.39	13.93	9.52	6.83
125.00	4	1.04	14.19	6.30	6.08

Table A5 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
31.25	1	5.10	7.21
62.50	2	3.16	4.52
93.75	3	3.45	3.97
125.00	4	2.75	3.41

Table A6 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas without partial oxidation in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Reactant conversion (%)				Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	H_2	C_2
1.095	1	10.11	19.40	33.36	6.93	13.73	20.41
2.190	2	17.02	30.54	52.34	10.62	27.13	33.09
3.286	3	18.91	40.59	67.80	8.84	49.10	46.23
4.381	4	18.95	40.74	72.83	10.43	47.29	51.38

Table A7 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas without partial oxidation in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Concentration of outlet gas (mol%)								
		H_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
1.095	1	5.27	0.34	64.64	17.75	0.95	1.32	3.89	3.39	0.16
2.190	2	10.40	0.65	57.72	16.77	1.82	1.84	3.25	2.35	0.22
3.286	3	16.36	1.03	51.73	15.90	2.21	2.35	2.77	1.50	0.28
4.381	4	15.71	1.11	52.41	15.84	2.49	2.58	2.81	1.28	0.21

Table A8 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas without partial oxidation in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Product selectivity (%)				
		H_2	C_2H_2	C_2H_4	CO	C_4H_{10}
1.095	1	21.84	12.25	16.99	2.19	4.03
2.190	2	27.16	14.92	15.02	2.64	3.59
3.286	3	38.57	16.49	17.47	3.85	4.13
4.381	4	35.69	17.65	18.30	3.92	2.97

Table A9 Effect of stage number of plasma reactors on product molar ratios for reforming of natural gas without partial oxidation in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Residence time (s)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
1.095	1	15.48	5.53	3.99	1.39
2.190	2	16.12	5.70	5.67	1.01
3.286	3	15.84	7.39	6.98	1.06
4.381	4	14.19	6.30	6.08	1.04

Table A10 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas without partial oxidation in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
1.095	1	2.344	4.993
2.190	2	1.951	3.347
3.286	3	2.497	2.847
4.381	4	2.753	3.409

Table A11 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas with pure O_2 addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Reactant conversion (%)					Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	O_2	H_2	C_2
31.25	1	36.52	57.55	72.85	-0.45	66.07	81.28	47.60
62.50	2	45.66	67.53	82.99	2.81	76.92	102.03	52.47
93.75	3	46.12	68.89	85.63	-0.90	79.01	111.51	56.12
125.00	4	45.33	68.17	85.23	-0.13	77.99	106.83	57.39

Table A12 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas with pure O_2 addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Product selectivity (%)				
		H_2	C_2H_2	C_2H_4	CO	C_4H_{10}
31.25	1	48.70	17.45	11.15	59.33	1.47
62.50	2	52.01	16.94	9.43	55.73	1.19
93.75	3	55.58	18.23	9.88	60.41	1.26
125.00	4	53.76	18.77	10.13	56.94	1.33

Table A13 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas with pure O_2 addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Concentration of outlet gas (mol%)									
		H_2	O_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
31.25	1	22.54	8.89	15.66	27.11	12.56	2.31	1.47	1.40	0.88	0.10
62.50	2	29.76	6.27	18.29	23.55	12.37	2.75	1.53	1.08	0.56	0.10
93.75	3	30.91	5.55	19.03	22.34	12.31	2.88	1.56	1.00	0.45	0.10
125.00	4	29.99	5.70	18.05	23.07	12.27	2.98	1.61	1.04	0.47	0.11

Table A14 Effect of stage number of plasma reactors on product molar ratios for reforming of natural gas with pure O_2 addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
31.25	1	1.44	9.77	15.29	0.64
62.50	2	1.63	10.82	19.45	0.56
93.75	3	1.62	10.73	19.83	0.54
125.00	4	1.66	10.08	18.66	0.54

Table A15 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas with pure O_2 addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
31.25	1	4.542	3.987
62.50	2	2.844	2.400
93.75	3	2.309	1.786
125.00	4	2.016	1.617

Table A16 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas with pure O_2 addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Reactant conversion (%)					Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	O_2	H_2	C_2
1.095	1	9.78	27.05	38.55	-0.31	35.251	54.15	46.14
2.190	2	33.33	52.23	66.36	-2.15	57.46	71.90	46.69
3.286	3	48.28	70.20	86.68	1.52	81.18	121.35	56.72
4.381	4	45.33	68.17	85.23	-0.13	77.99	106.83	57.39

Table A17 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas with pure O_2 addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Product selectivity (%)				
		H_2	C_2H_2	C_2H_4	CO	C_4H_{10}
1.095	1	71.83	37.08	24.39	83.61	3.96
2.190	2	47.33	19.49	11.69	55.81	1.73
3.286	3	59.15	17.92	9.52	58.50	1.19
4.381	4	53.76	18.77	10.13	56.94	1.33

Table A18 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas with pure O_2 addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Concentration of outlet gas (mol%)									
		H_2	O_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
1.095	1	12.02	17.74	8.44	40.26	13.00	1.88	1.24	2.51	2.08	0.10
2.190	2	20.11	11.22	13.39	28.67	12.75	2.36	1.42	1.58	1.09	0.10
3.286	3	34.21	4.97	19.29	21.49	12.16	2.94	1.56	0.96	0.42	0.10
4.381	4	29.99	5.70	18.06	23.07	12.27	2.98	1.61	1.04	0.47	0.11

Table A19 Effect of stage number of plasma reactors on product molar ratios for reforming of natural gas with pure O_2 addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
1.095	1	1.42	6.40	9.73	0.66
2.190	2	1.50	8.50	14.18	0.60
3.286	3	1.77	11.65	21.92	0.53
4.381	4	1.66	10.07	18.66	0.54

Table A20 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas with pure O_2 addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
1.095	1	4.267	2.328
2.190	2	1.751	1.563
3.286	3	1.769	1.305
4.381	4	2.016	1.617

Table A21 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas with air addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Reactant conversion (%)					Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	O_2	H_2	C_2
31.25	1	54.73	70.91	78.23	15.28	74.01	119.66	80.40
62.50	2	63.85	81.12	88.13	20.38	84.25	140.42	90.47
93.75	3	66.54	83.87	90.84	22.12	86.76	144.69	93.10
125.00	4	62.97	78.92	86.89	21.51	80.89	130.08	88.66

Table A22 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas with air addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Product selectivity (%)				
		H_2	C_2H_2	C_2H_4	CO	C_4H_{10}
31.25	1	58.69	30.79	7.90	62.77	0.74
62.50	2	60.24	31.03	6.90	59.87	0.65
93.75	3	59.97	30.97	6.68	58.93	0.59
125.00	4	56.86	28.79	6.64	57.20	0.73

Table A23 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas with air addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Concentration of outlet gas (mol%)										
		H_2	O_2	N_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
31.25	1	17.81	3.16	45.81	11.20	9.20	5.12	2.60	0.67	0.45	0.33	0.03
62.50	2	21.35	1.95	45.15	12.55	7.40	4.83	3.06	0.68	0.30	0.18	0.03
93.75	3	22.10	1.65	45.22	12.87	6.86	4.70	3.17	0.68	0.25	0.14	0.03
125.00	4	20.32	2.41	45.12	12.12	7.76	4.80	3.05	0.70	0.34	0.21	0.04

Table A24 Effect of stage number of plasma reactors on product molar raios for reforming of natural gas with air addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
31.25	1	1.59	6.84	26.63	0.26
62.50	2	1.70	6.98	31.38	0.22
93.75	3	1.72	6.96	32.29	0.22
125.00	4	1.68	6.66	28.88	0.23

Table A25 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas with air addition in the case of varying feed flow rate (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and residence time, 4.38 s)

Feed flow rate (cm^3/min)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
31.25	1	6.88	5.54
62.50	2	3.63	2.88
93.75	3	3.21	2.57
125.00	4	2.89	2.44

Table A26 Effect of stage number of plasma reactors on reactant conversions and product yields for reforming of natural gas with air addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Reactant conversion (%)					Product yield (%)	
		CH_4	C_2H_6	C_3H_8	CO_2	O_2	H_2	C_2
1.095	1	30.72	40.93	48.95	2.98	41.02	57.17	50.28
2.190	2	48.86	64.63	73.84	8.19	66.43	100.47	73.69
3.286	3	59.16	75.67	84.12	16.39	77.90	124.17	87.03
4.381	4	62.97	78.92	86.89	21.51	80.89	130.08	88.66

Table A27 Effect of stage number of plasma reactors on product selectivities for reforming of natural gas with air addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Product selectivity (%)				
		H_2	C_2H_6	C_2H_4	CO	C_4H_{10}
1.095	1	47.40	28.74	12.68	53.76	1.31
2.190	2	53.63	29.71	9.17	56.91	0.95
3.286	3	56.71	31.33	7.62	58.99	0.77
4.381	4	56.86	30.69	7.08	57.20	0.78

Table A28 Effect of stage number of plasma reactors on concentrations of outlet gases for reforming of natural gas with air addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Concentration of outlet gas (mol%)										
		H_2	O_2	N_2	CO	CH_4	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}
1.095	1	8.76	7.66	47.73	5.68	14.93	6.10	1.49	0.66	0.98	0.83	0.03
2.190	2	15.25	4.26	46.44	9.35	10.77	5.64	2.37	0.73	0.57	0.42	0.04
3.286	3	18.88	2.75	45.63	11.53	8.43	5.03	2.91	0.71	0.39	0.25	0.04
4.381	4	20.32	2.41	45.12	12.12	7.76	4.80	3.05	0.70	0.34	0.21	0.04

Table A29 Effect of stage number of plasma reactors on product molar ratios for reforming of natural gas with air addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Molar ratio			
		H_2/CO	H_2/C_2H_2	H_2/C_2H_4	C_2H_4/C_2H_2
1.095	1	1.54	5.87	13.31	0.44
2.190	2	1.63	6.45	20.89	0.31
3.286	3	1.64	6.49	26.71	0.24
4.381	4	1.68	6.66	28.88	0.23

Table A30 Effect of stage number of plasma reactors on power consumptions for reforming of natural gas with air addition in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min)

Residence time (s)	Number of stage	Power consumption ($\times 10^{18}$ Ws/molecule)	
		per reactant converted	per H_2 produced
1.095	1	2.82	2.67
2.190	2	2.52	2.15
3.286	3	2.36	1.96
4.381	4	2.89	2.44

Appendix B Comparison of Natural Gas Reforming without/with Partial Oxidation Using either Pure Oxygen or Air Addition

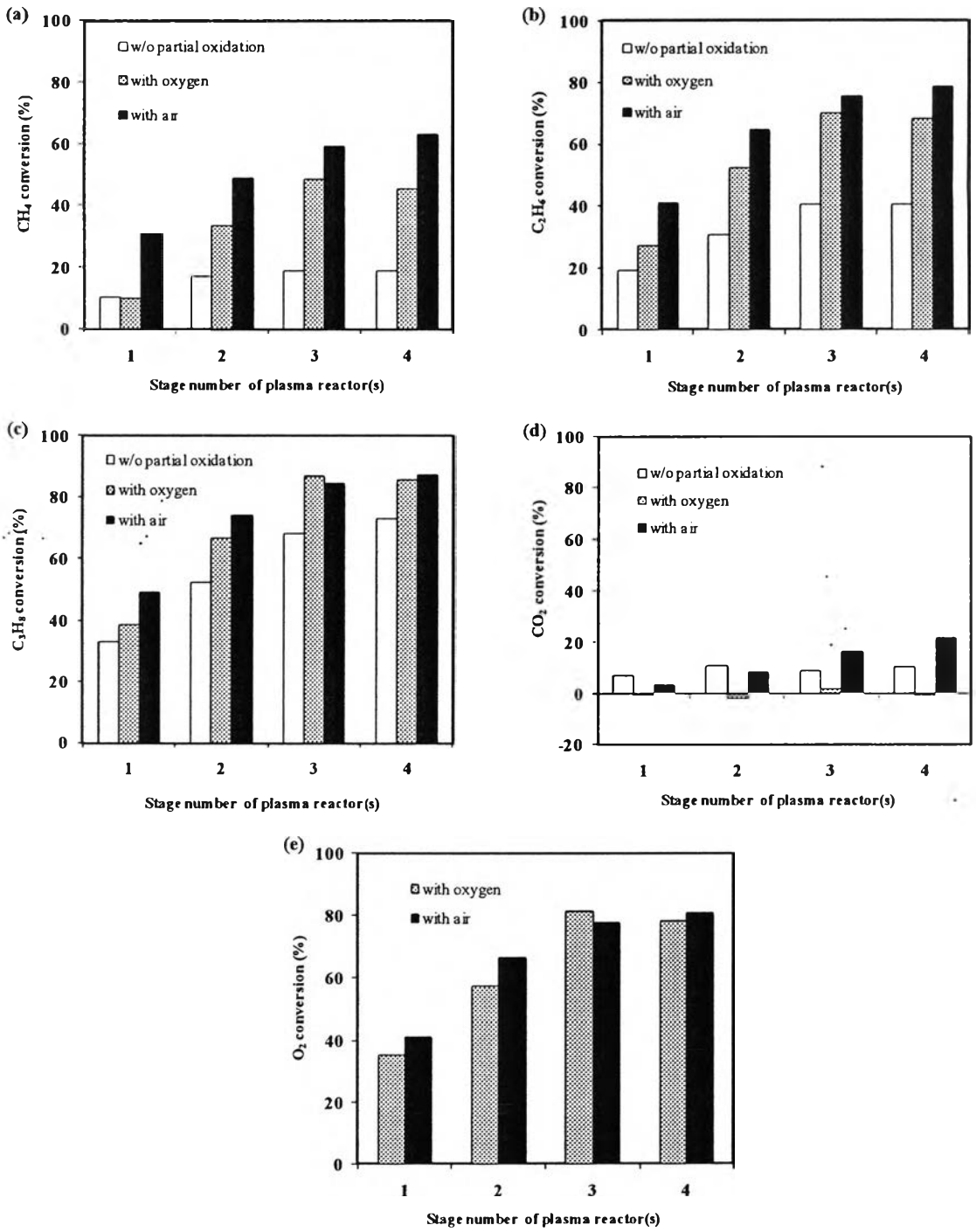

Figure B1 Comparison of conversions of (a) CH_4, (b) C_2H_6, (c) C_3H_8, (d) CO_2, and (e) O_2 for combined reforming and partial oxidation of natural gas in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min).

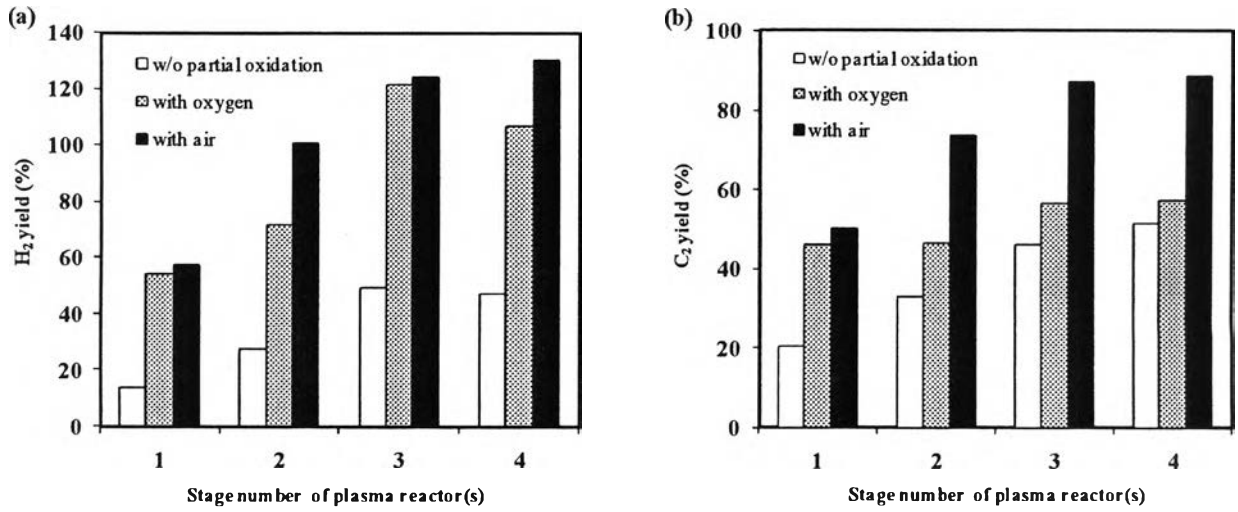

Figure B2 Comparison of yields of (a) H_2 and (b) C_2 for combined reforming and partial oxidation of natural gas in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min).

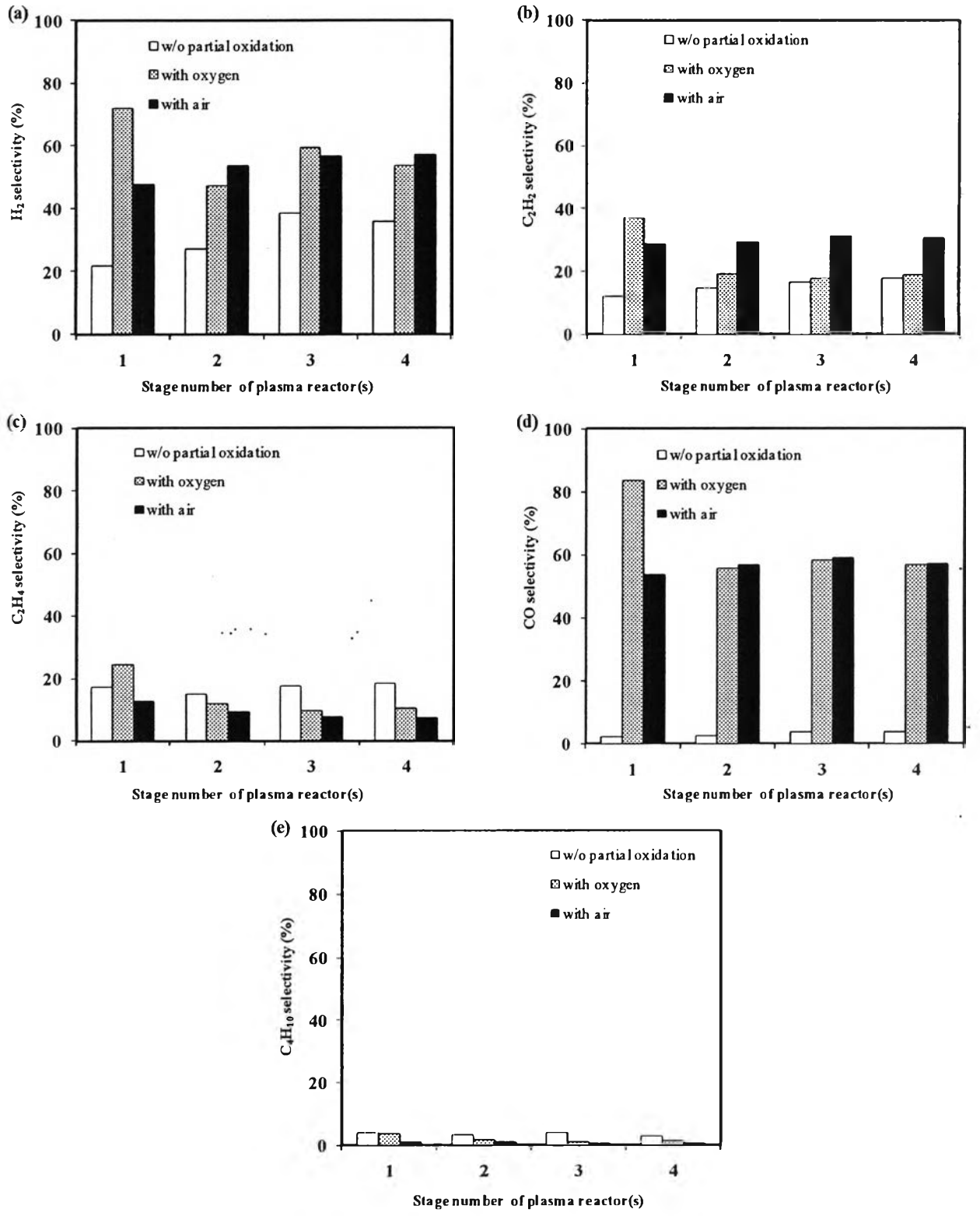

Figure B3 Comparison of selectivities for (a) H_2, (b) C_2H_2, (c) C_2H_4, (d) CO, and (e) C_4H_{10} for combined reforming and partial oxidation of natural gas in the case of varying residence time (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min).

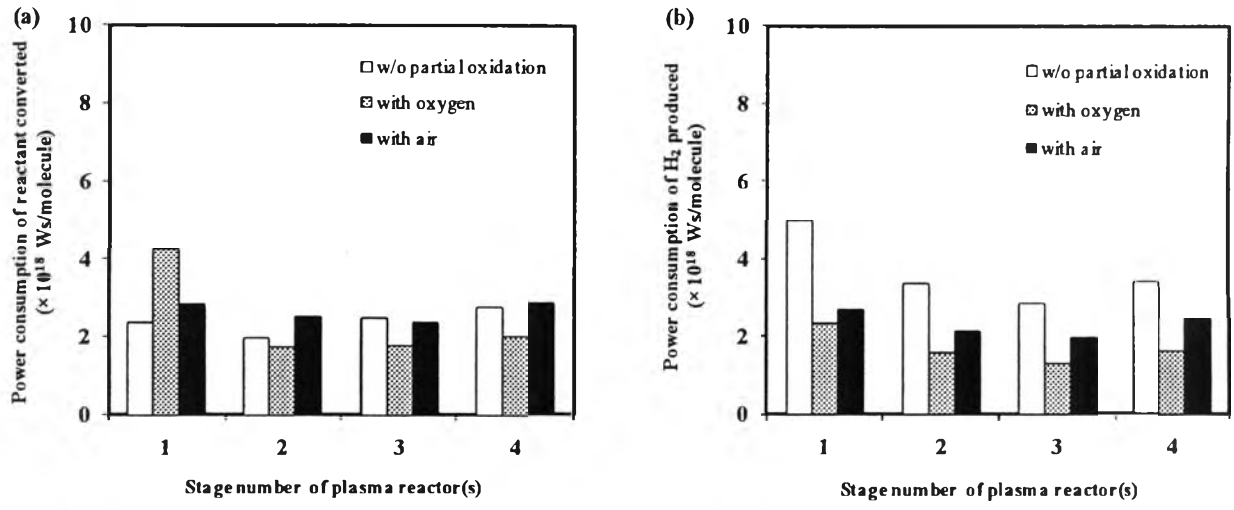

Figure B4 Comparison of power consumptions for combined reforming and partial oxidation of natural gas in the case of varying residence time: (a) power consumption per reactant molecule converted, (b) power consumption per hydrogen molecule produced (applied voltage, 17.5 kV; frequency, 300 Hz; electrode gap distance, 6 mm; and feed flow rate, 125 cm^3/min).

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Presentations and Proceedings:

1. Jittiang, W., Sreethawong, T., and Chavadej, S. (2007, November 21-24) Reforming of Natural Gas in Low-Temperature AC Gliding Arc Discharge: Effect of Number of Stages. Paper presented at The 5th Eco-Energy and Materials Science and Engineering Symposium, Pattaya, Thailand.
2. Jiittiang, W., Sreethawong, T., and Chavadej, S. (2008, April 23) Combined Reforming and Partial Oxidation of CO_2-containing Natural Gas using Low-Temperature Gliding Arc Discharge: Effect of Stage Number of Plasma Reactors. Proceedings of The 14th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.