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APPENDICES

Appendix A: Calculations

1. Catalysts Preparation

1.1 Amount of Ni loading

Example Prepared 1 g of 5 wt.%Ni/NaY catalyst ;

- Amount of Ni (MW = 58.69 g/mole)

$$\begin{aligned}\text{Ni} &= 1 \cdot (5/100) \text{ g} \\ &= 0.05 \text{ g}\end{aligned}$$

- Amount of Ni(NO₃)₂·6H₂O (MW = 290.81 g/mole)

$$\begin{aligned}\text{Ni(NO}_3)_2 \cdot 6\text{H}_2\text{O} &= 0.05 \cdot (290.81/58.69) \text{ g} \\ &= 0.2478 \text{ g}\end{aligned}$$

- Amount of NaY zeolite

$$\begin{aligned}\text{KL zeolite} &= 1 - 0.05 \text{ g} \\ &= 0.95 \text{ g}\end{aligned}$$

2. Conversion and Selectivity

2.1 CH₄ Conversion

$$\text{CH}_4 \text{ conversion} = \frac{CH_{4,in} - CH_{4,out}}{CH_{4,in}} \times 100$$

Where CH_{4,in} = CH₄ fed to the reactor

CH_{4,out} = CH₄ out of reactor

2.2 H₂ Selectivity

$$\text{H}_2 \text{ selectivity} = \frac{F_t^o * y_{(H_2,out)}}{F_t^o * y_{(H_2,out)} + F_t^o * y_{(CO,out)} + F_t^o * y_{(CO_2,out)}} \times 100$$

Where $y_{(H_2,out)}$ = Mole fraction of H₂ in the effluent stream

$y_{(CO,out)}$ = Mole fraction of CO in the effluent stream

$y_{(CO_2,out)}$ = Mole fraction of CO in the effluent stream

F_t^0 = Total flow of effluent stream

2.3 CO Selectivity

$$\text{H}_2 \text{ selectivity} = \frac{F_t^0 * y_{(CO,out)}}{F_t^0 * y_{(H_2,out)} + F_t^0 * y_{(CO,out)} + F_t^0 * y_{(CO_2,out)}} \times 100$$

Where $y_{(H_2,out)}$ = Mole fraction of H₂ in the effluent stream

$y_{(CO,out)}$ = Mole fraction of CO in the effluent stream

$y_{(CO_2,out)}$ = Mole fraction of CO in the effluent stream

F_t^0 = Total flow of effluent stream

2.4 CO₂ Selectivity

$$\text{H}_2 \text{ selectivity} = \frac{F_t^0 * y_{(CO_2,out)}}{F_t^0 * y_{(H_2,out)} + F_t^0 * y_{(CO,out)} + F_t^0 * y_{(CO_2,out)}} \times 100$$

Where $y_{(H_2,out)}$ = Mole fraction of H₂ in the effluent stream

$y_{(CO,out)}$ = Mole fraction of CO in the effluent stream

$y_{(CO_2,out)}$ = Mole fraction of CO in the effluent stream

F_t^0 = Total flow of effluent stream

2.5 H₂ yield

$$\text{H}_2 \text{ yield} = \frac{X_{CH_4} * S_{H_2}}{100}$$

Where X_{CH_4} = CH₄ conversion

S_{H_2} = H₂ selectivity

2.6 H₂ Production

$$\text{H}_2 \text{ production} = F_{out} \times y_{(H_2,out)} \text{ ml/min}$$

Where F_{out} = Total flow rate of feed stream through the reactor

$y_{(H_2,out)}$ = Mole fraction of H₂ in the effluent stream

Appendix B: Experimental data

Table B1: Effect of Ni content (The impregnated catalysts); CH₄ conversion.

Time-on-stream (min)	Methane Conversion (%)			
	5 % wt	7 % wt	11 % wt	15 % wt
16	73.02	70.99	89.80	81.57
31	73.36	66.33	85.87	80.95
46	77.02	64.27	83.28	87.82
61	74.10	62.35	81.37	88.25
76	73.99	60.97	79.64	85.52
91	72.26	59.81	78.49	78.43
106	68.01	60.29	78.69	75.57
121	62.60	61.75	77.95	70.74
136	57.48	61.26	76.08	60.96
151	53.63	61.58	74.37	55.11
166	47.66	60.99	73.28	58.42
181	43.52	60.62	72.10	58.64
196	37.05	64.04	70.70	58.44
211	37.41	63.27	69.19	65.40
226	33.82	60.62	68.35	65.24
241	30.05	56.75	66.66	64.30

Table B1: Effect of Ni content (The impregnated catalyst); Hydrogen selectivity, CO selectivity, CO₂ selectivity (continue)

Time-on-stream (min)	H ₂ selectivity (%)				CO selectivity (%)				CO ₂ selectivity (%)			
	5%	7%	11%	15%	5%	7%	11%	15%	5%	7%	11%	15%
16	90.55	83.32	88.37	87.00	4.74	14.97	5.63	9.67	4.71	1.71	6.01	3.34
31	84.15	82.50	88.82	86.29	4.11	15.51	4.80	10.12	11.73	1.98	6.37	3.59
46	83.41	79.89	88.44	87.84	4.16	16.49	4.81	8.50	12.43	3.63	6.75	3.66
61	80.85	80.70	87.42	90.13	3.77	16.51	5.95	3.09	15.38	2.79	6.63	6.78
76	79.49	80.81	87.37	88.57	4.01	16.78	5.64	3.51	16.50	2.41	6.99	7.92
91	78.45	80.36	86.57	87.43	4.67	16.87	6.39	3.80	16.88	2.76	7.04	8.77
106	78.28	81.42	87.81	86.34	4.33	15.97	5.33	5.45	17.38	2.61	6.86	8.21
121	77.08	81.23	87.68	85.74	3.87	15.33	4.66	5.50	19.05	3.44	7.67	8.76
136	75.97	80.88	87.64	86.29	3.41	16.60	4.23	4.65	20.61	2.52	8.14	9.06
151	75.68	80.23	87.08	83.16	3.91	16.62	4.75	5.97	20.41	3.15	8.18	10.87
166	71.46	80.39	86.64	85.96	4.68	17.33	5.53	5.67	23.86	2.28	7.83	8.37
181	73.67	80.91	86.34	85.89	3.47	16.77	5.72	5.88	22.86	2.32	7.94	8.22
196	66.47	77.90	86.71	85.94	4.46	19.59	5.26	5.60	29.07	2.51	8.03	8.46
211	72.43	76.27	86.19	87.20	3.56	20.61	5.15	8.14	24.02	3.12	8.65	4.66
226	71.90	74.17	85.56	85.08	3.66	22.46	5.51	5.70	24.44	3.37	8.92	9.22
241	71.09	73.74	85.57	84.03	3.35	21.66	5.33	4.27	25.55	4.60	9.11	11.70

Table B1: Effect of Ni content (The impregnated catalysts); H₂ yield (Continue).

Time-on-stream (min)	H ₂ yield (%)			
	5 % wt	7 % wt	11 % wt	15 % wt
16	66.12	59.15	79.36	70.97
31	61.74	54.72	76.27	69.85
46	64.24	51.34	73.65	77.14
61	59.91	50.32	71.13	79.54
76	58.82	49.27	69.58	75.74
91	56.69	48.07	67.95	68.57
106	53.24	49.09	69.10	65.25
121	48.25	50.16	68.34	60.65
136	43.67	49.55	66.67	52.60
151	40.59	49.40	64.76	45.83
166	34.06	49.03	63.49	50.22
181	32.06	49.04	62.25	50.37
196	24.63	49.89	61.31	50.23
211	27.09	48.26	59.64	57.02
226	24.32	44.96	58.48	55.50
241	21.36	41.85	57.03	54.03

Table B2: Steam to carbon ratio; CH₄ conversion.

Time-on-stream (min)	Methane Conversion (%)		
	S/C=1	S/C=1.5	S/C=2
16	89.80	80.66	75.90
31	85.87	80.74	64.99
46	83.28	78.20	58.00
61	81.37	69.89	50.72
76	79.64	65.16	46.85
91	78.49	65.61	45.50
106	78.69	59.51	46.44
121	77.95	59.06	43.21
136	76.08	58.39	40.79
151	74.37	57.78	39.02
166	73.28	51.20	38.50
181	72.10	48.11	41.75
196	70.70	53.14	41.12
211	69.19	47.34	39.24
226	68.35	47.62	37.36
241	66.66	48.72	

Table B2: Steam to carbon ratio; Hydrogen yield (continue).

Time-on-stream (min)	H ₂ yield (%)		
	S/C=1	S/C=1.5	S/C=2
16	88.37	90.98	91.24
31	88.82	90.88	90.53
46	88.44	90.22	90.19
61	87.42	90.26	89.14
76	87.37	89.71	89.25
91	86.57	89.74	89.05
106	87.81	89.46	88.62
121	87.68	89.25	87.83
136	87.64	89.49	88.09
151	87.08	88.95	87.87
166	86.64	89.16	88.61
181	86.34	88.89	88.37
196	86.71	88.49	88.08
211	86.19	88.39	88.02
226	85.56	89.46	88.21
241	85.57	88.53	

Table B3: Catalytic activity of the ion exchanged catalysts; Hydrogen selectivity, CO selectivity, CO₂ selectivity (continue).

Time-on-stream (min)	H ₂ selectivity (%)			CO selectivity (%)			CO ₂ selectivity (%)		
	IE-5.4	IE-6.4	IE-7.3	IE-5.4	IE-6.4	IE-7.3	IE-5.4	IE-6.4	IE-7.3
16	91.61	91.57	90.14	4.04	4.14	7.76	4.35	4.29	2.11
31	91.55	91.56	90.18	3.46	3.76	7.35	4.99	4.69	2.47
46	91.20	91.36	90.13	2.53	3.61	7.45	6.27	5.04	2.43
61	90.59	91.20	90.12	3.10	3.59	7.62	6.31	5.21	2.26
76	90.41	91.03	90.01	3.04	3.36	7.72	6.55	5.61	2.27
91	89.71	90.53	89.96	3.21	3.60	7.65	7.08	5.86	2.39
106	89.00	89.13	89.84	3.73	3.63	7.69	7.27	7.24	2.47
121	87.31	87.20	90.16	4.35	4.79	7.64	8.35	8.01	2.20
136	88.48	85.82	89.77	4.15	3.80	7.80	7.37	10.38	2.43
151	87.94	85.44	89.66	4.42	4.10	7.83	7.64	10.46	2.51
166	87.67	85.72	89.73	4.55	5.24	7.86	7.78	9.04	2.41
181	87.56	84.40	90.06	4.62	4.03	7.70	7.81	11.57	2.24
196	87.20	84.14	89.76	4.80	4.41	7.85	8.00	11.45	2.39
211	84.08	84.85	89.61	6.12	5.50	7.89	9.80	9.65	2.50
226	86.71	85.07	89.51	5.24	4.35	8.10	8.05	10.58	2.38
241	85.68	82.27	90.03	6.46	4.87	7.56	7.87	12.87	2.41
256	81.91	81.98	90.03	8.16	4.94	7.56	9.93	13.08	2.41

Table B3: Catalytic activity of the ion exchanged catalysts; H₂ yield (Continue).

Time-on-stream (min)	H ₂ yield (%)		
	IE-5.4	IE-6.4	IE-7.3
16	84.02	84.66	78.57
31	84.39	82.73	77.88
46	82.16	80.28	77.07
61	66.14	78.40	76.81
76	65.11	75.23	76.27
91	55.96	69.73	75.86
106	49.39	52.76	75.49
121	41.49	46.13	75.79
136	40.66	16.30	74.74
151	37.26	12.42	74.36
166	34.19	10.95	74.36
181	30.97	8.09	74.71
196	28.69	7.15	73.91
211	23.30	6.15	73.52
226	24.96	5.37	73.19
241	22.64	5.49	73.59
256	16.27	4.81	73.41

Table B4: Effect of feed component; the concentration of light hydrocarbons.

(a) Natural gas as hydrogen feedstock.

Time on stream (min)	% Concentration			
	H ₂	CO	CH ₄	CO ₂
31	5.02	0.35	26.98	0.17
61	56.25	3.70	4.84	2.97
91	64.47	5.24	2.04	2.32
121	65.08	5.04	2.03	2.33
151	62.72	6.55	2.33	1.55
181	64.05	5.48	2.24	2.16
211	64.22	5.40	2.30	2.11
241	64.29	5.06	2.28	2.42
271	63.83	4.98	2.51	2.41
301	62.58	4.91	2.85	2.44

(b) Methane as hydrogen feedstock.

Time on stream (min)	% Concentration			
	H ₂	CO	CH ₄	CO ₂
31	48.57	2.63	8.53	3.48
61	41.66	2.83	11.25	3.16
91	37.62	2.78	12.99	3.06
121	38.17	2.03	13.32	3.34
151	36.07	1.84	15.48	3.17
181	30.81	2.04	16.85	2.83
211	29.45	1.79	17.69	2.73
241	27.41	1.64	18.60	2.75
271	26.45	1.70	19.11	2.76
301	24.47	1.52	20.13	2.60

(c) Natural gas composition; Comparison between initial natural gas (NG) and composition after reaction for 4 h.

Gas composition	Concentration (%)	
	Initial NG	NG at 4 h
Methane	63.44	33.89
Ethane	16.37	4.95
Propane	12.33	13.26
C4	6.45	23.33
C5	1.41	9.27

Table B5: Bench scale of hydrogen production

(a) Concentration of reformed gas detected from Steam reformer unit.

Time on stream (h)	% Concentration			
	H ₂	CO	CH ₄	CO ₂
1	91.19	1.87	0.29	3.26
3	79.83	1.72	2.39	3.63
4	56.48	2.07	0.99	3.59
5	59.77	1.30	3.55	4.24
6	85.28	1.14	4.23	4.12
7	61.97	1.25	4.83	4.59
8	77.33	1.88	3.27	3.56
9	79.90	2.25	0.33	3.85

(b) Concentration of outlet gas detected from individual reaction zones at 4 h.

Reaction zones	Reformed gas concentration %			
	CH ₄	H ₂	CO	CO ₂
SR	3.672	86.717	2.109	3.995
HT-WGS	3.914	58.662	3.738	14.742
LT-WGS	3.105	60.632	0.195	18.132
PROX	2.784	57.090	0.033	16.967

CURRICULUM VITAE

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1. Chankam, O., Luengnaruemitchai, A., and Jitkarnka, S. (2006, December 3-5) Hydrogen production via steam reforming of methane over Ni-supported NaY zeolite catalyst. 13th Regional Symposium on Chemical Engineering, Nanyang Technological University, Singapore.