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APPENDICES

APPENDIX A Properties of Catalyst

Table A1 Specific surface area and pore structure of $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst

Catalyst	BET surface area (m^2/g)	Total pore volume (cm^3/g)	Average pore diameter (nm)
0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$	175.5	0.288	6.57

The SEM images of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst with various resolutions are shown in Figure A1 to A3. A typical amorphous morphology is observed from with particle sizes ranging from 0.2 μm to 1.2 μm.

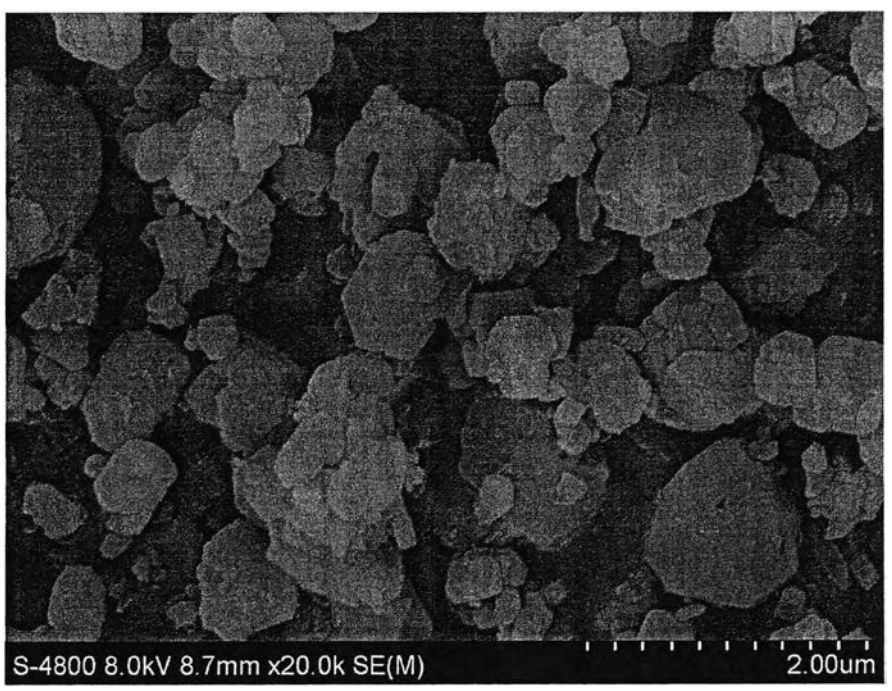

Figure A1 SEM image of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (8.0kV 8.7mm x20.0k).

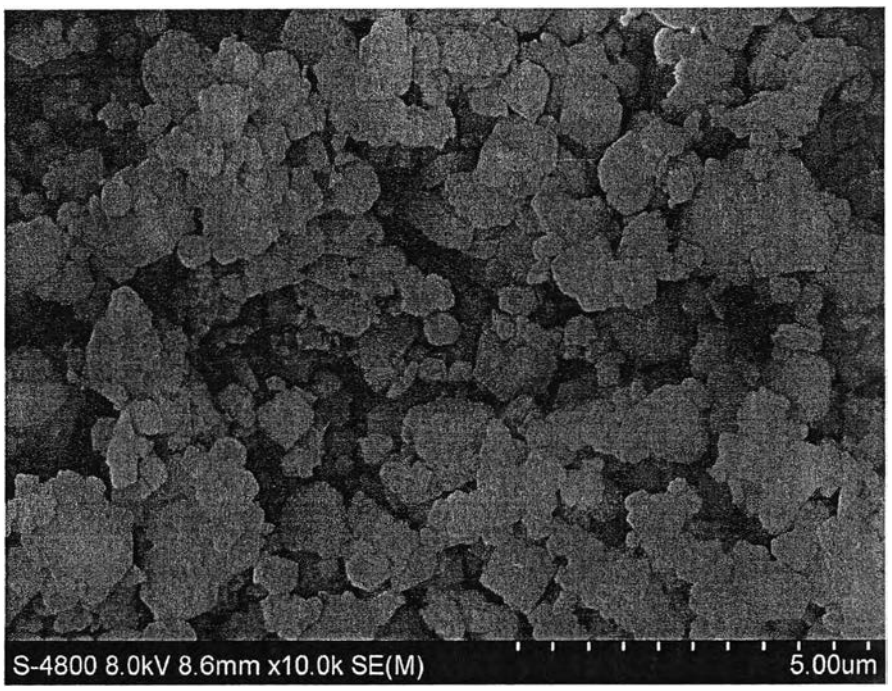

Figure A2 SEM image of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (8.0kV 8.6mm x10.0k).

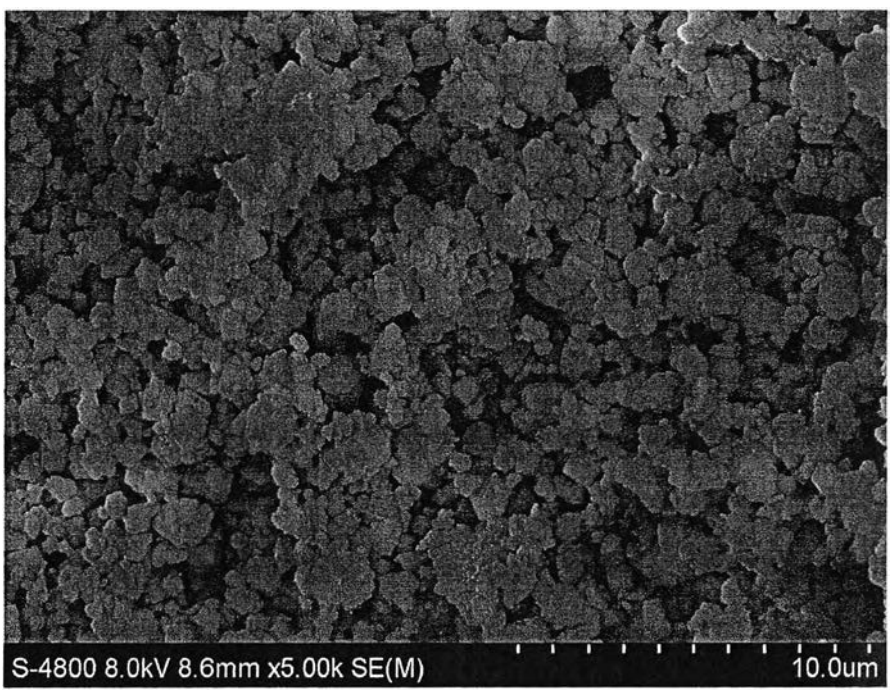

Figure A3 SEM image of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (8.0kV 8.6mm x5.00k).

APPENDIX B Catalytic Activity of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ Catalyst at Various Bio-ethanol Concentrations in the Feed and Reaction Temperatures

Table B1 Product distribution data at various bio-ethanol concentrations in the feed of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (at a fixed temperature of 370 °C)

Selectivity (%)	Ethanol Concentration (%)		
	40 - 50	95	99.5
Carbonmonoxide	0	0	0
Methane	0	0	0.045
Carbondioxide	0	0	0
Ethylene	81.0	83.8	83.8
Ethane	0.182	0.552	0.547
Propylene	0.282	0.265	0.319
Propane	0	0	0
C_4 Products	5.78	4.08	3.97
C_5 Products	11.9	9.60	8.65
C_6 Products	0	0	0
Diethyl Ether	0.842	1.71	2.67
Ethanol Conversion (%)	22.2	82.8	84.2

Table B2 Product distribution data at various bio-ethanol concentrations in the feed of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (at a fixed temperature of 400 °C)

Selectivity (%)	Ethanol Concentration (%)		
	40 - 50	95	99.5
Carbonmonoxide	0	0	0
Methane	0	0.034	0.032
Carbondioxide	0.302	0.291	0.251
Ethylene	93.1	91.4	92.1
Ethane	0.234	0.562	0.549
Propylene	0.627	0.813	0.747
Propane	0	0	0
C_4 Products	4.26	6.66	6.14
C_5 Products	1.49	0.254	0.187
C_6 Products	0	0	0
Diethyl Ether	0	0	0
Ethanol Conversion (%)	69.7	95.9	96.6

Table B3 Product distribution data at various bio-ethanol concentrations in the feed of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (at a fixed temperature of 430 °C)

Selectivity (%)	Ethanol Concentration (%)		
	40 - 50	95	99.5
Carbonmonoxide	0	0	0
Methane	0.060	0.049	0
Carbondioxide	1.24	0.699	0.533
Ethylene	93.7	92.0	93.5
Ethane	0.257	0.473	0.510
Propylene	1.02	0.959	0.795
Propane	0	0	0
C_4 Products	3.43	5.51	4.47
C_5 Products	0.285	0.337	0.213
C_6 Products	0	0	0
Diethyl Ether	0	0	0
Ethanol Conversion (%)	92.5	97.8	97.1

Table B4 Product distribution data at various bio-ethanol concentrations in the feed of 0.5 wt% $MgHPO_4/\gamma\text{-}Al_2O_3$ catalyst (at a fixed temperature of 460 °C)

Selectivity (%)	Ethanol Concentration (%)		
	40 - 50	95	99.5
Carbonmonoxide	0	0	0
Methane	0.052	0.078	0.174
Carbondioxide	1.79	0.920	1.05
Ethylene	94.8	93.3	90.6
Ethane	0.152	0.4381	0.657
Propylene	0.738	1.01	1.34
Propane	0	0	0
C_4 Products	2.08	3.89	5.79
C_5 Products	0.399	0.332	0.372
C_6 Products	0	0	0
Diethyl Ether	0	0	0
Ethanol Conversion (%)	91.7	97.6	98.6

APPENDIX C Economic Basic Assumptions

Table C1 Economic basis assumptions of the economic evaluation for polymer-grade ethylene production via catalytic dehydration of ethanol based on Chematur process

Item	Value	Remark
Plant Capacity		
Capacity (tons/year)	33,000	Based on ethylene product
Working time (hours/year)	8,000	About 333 days/year
Labor and maintenance cost		
Labor and maintenance cost	3.1%	% of investment
Raw material and product		
Ethanol consumption, (ton/ethylene ton)	1.738	1.738 ton of ethanol per 1 ton of ethylene product is required.
99.5% Ethanol (Baht/ton)	22,000	Based on Thaioil ethanol price
Polymer-grade ethylene, (Baht/ton)	46,800	Based on PTT group polymer grade price
Utilities requirement		
Steam, (kg/Ethylene ton)	1,210	Some of steam is available in the process
Electricity, (unit/Ethylene ton)	340	
Fuel, (MMBtu/Ethylene ton)	3.175	Natural gas is used as fuel
Cooling water, (m^3/Ethylene ton)	104	
Process water, (kg/Ethylene ton)	18.4	
Sodium hydroxide, 50%	9.6	
Nitrogen gas, (Nm^3/Ethylene ton)	4.26	
Boiler feed water, (m^3/Ethylene ton)	0.35	
Economic basis		
Depreciation, years	20	Economic life is 20 years
Corporate tax, %	30	All Capex is paid at zero year

Table C2 Economic basis assumptions of the economic evaluation for polymer-grade ethylene production via catalytic dehydration of ethanol based on Petrobras process

Item	Value	Remark
Plant Capacity		
Capacity (tons/year)	200,000	Based on ethylene product
Working time (hours/year)	8,125	About 339 days/year
Labor and maintenance cost		
Labor and maintenance cost	3.1%	% of investment
Raw material and product		
Ethanol consumption, (ton/ethylene ton)	1.7698	1.7698 ton of ethanol per 1 ton of ethylene product is required.
99.5% Ethanol (Baht/ton)	22,000	Based on Thaioil ethanol price
Polymer-grade ethylene, (Baht/ton)	46,800	Based on PTT group polymer grade price
Utilities requirement		
Steam, (kg/Ethylene ton)	-	
Electricity, (unit/Ethylene ton)	340	
Fuel, (MMBtu/Ethylene ton)	3.685	Natural gas is used as fuel
Cooling water, (m^3/Ethylene ton)	50	
Process water, (kg/Ethylene ton)	18.4	
Sodium hydroxide, 50%	9.6	
Nitrogen gas, (Nm^3/Ethylene ton)	4.26	
Economic basis		
Depreciation, years	20	Economic life is 20 years
Corporate tax, %	30	All Capex is paid at zero year

APPENDIX D Total Capital Cost Estimation

The total capital cost estimation of Chematur plant is based on the indexing method using the known capital cost and capacity obtained from Petrobras as shown in Table D1.

Table D1 Estimating CAPEX of Two Commercial Processes

Plant	Capacity	Estimated CAPEX
Petrobras	200,000 tons/year	278 mil USD
Chematur	33,000 tons/year	94 mil USD

Note - CAPEX from Chematur is scaled-down from Petrobras with basis:

$$Price \propto (Size)^{0.6}$$

- CAPEX is inclusion of ISBL and OSBL
- Instrumentation and electrical are included
- Exchange rate = 31 Baht/US$

APPENDIX E Annual Operating Cost Estimation

Table E1 Annual operating cost estimation for polymer-grade ethylene production via catalytic dehydration of ethanol based on Chemature process

Items	Quantity/annual	Price (baht/unit)	Cost (Baht/year)
Raw material			
95%ethanol	57,354 tons	22,000/ton	1,261,788,000
Labor and maintenance			
Labor and maintenance cost	3.1% of investment	-	87,420,000
Utiliities			
Steam	39,930 tons	1,692.3/ton	67,573,539
Electricity	11,220,000 units	2.022/unit	22,686,840
Fuel	104,763.78 MMBtu	442.3/MMBtu	46,336,950
Cooling water	3,432,000 m^3	14.4/ m^3	49,420,800
Process water	607,200 kg	0.2829/kg	171,776.88
Sodium hydroxide, 50%	316,800 kg	8.5/kg	2,692,800
Nitrogen gas	140,580 Nm^3	6.1/ Nm^3	857,538
Boiler feed water	11,550 m^3	282.9/m^3	3,267,495
Total			1,525,583,744

Table E2 Annual operating cost of polymer-grade ethylene production via catalytic dehydration of bio-ethanol based on Petrobras process

Items	Quantity/annual	Price (baht/unit)	Cost (Baht/year)
Raw material			
95%ethanol	353,958.85 tons	22,000/ton	7,797,637,320
Labor and maintenance			
Labor and maintenance cost	3.1% of investment	-	267,158,000
Utiliities			
Steam	-	-	-
Electricity	68,000,000 units	2.022/unit	137,496,000
Fuel	737,022 6 MMBtu	442.3/MMBtu	325,985,092
Cooling water	10,000,000 m^3	14.4/ m^3	144,000,000
Process water	3,680,00 kg	0.2829/kg	1,041,072
Sodium hydroxide, 50%	1,920,000 kg	8.5/kg	16,320,000
Nitrogen gas	852,000 Nm^3	6.1/ Nm^3	5,197,200
Boiler feed water	-	-	-
Total			8,694,834,685

APPENDIX F Economic Evaluation Data

Table F1 Chematur plant information

Item	Value	Remark
Total capital cost		
Total investment	2,914	Millions baht
Operating cost		
Raw material cost	1261.78	Millions baht per year
Labor and maintenance cost	90.33	Millions baht per year
Utilities cost	173.76	Millions baht per year
Total	1,525.58	Millions baht per year
Revenue		
Selling ethylene	1,544.4	Millions baht per year
Total margin		
Total margin	18.82	Millions baht per year

Table F2 Petrobras plant information

Item	Value	Remark
Total capital cost		
Total investment	8,618	Millions baht
Operating cost		
Raw material cost	7,799.64	Millions baht per year
Labor and maintenance cost	267.16	Millions baht per year
Utilities cost	630.04	Millions baht per year
Total	8,694.83	Millions baht per year
Revenue		
Selling ethylene	9,360	Millions baht per year
Total margin		
Total margin	665.17	Millions baht per year

Table F3 Summary of economic evaluation of Chematur process

Profitability indicator	Value	
IRR after tax	-	% per year
NPV after tax	-2,445.81	Millions baht
Profitability index (NPV/Fixed cost)	-0.84	-
Simple payback period before tax	1,858.4	Months

Table F4 Summary of economic evaluation of Petrobras process

Profitability indicator	Value	
IRR after tax	3.3%	% per year
NPV after tax	-3,721.55	Million baht
Profitability index (NPV/Fixed cost)	-0.43	-
Simple payback period before tax	155.5	Months

Table F5 Ethanol price sensitivity of Chematur process

Ethanol price (Baht/liter)	IRR (%)	NPV (Mil. Baht)	PI	PB (months)
8.7	16.1	1144.89	0.39	54.5
9.2	15.1	933.07	0.32	57.8
9.7	14.1	721.25	0.25	61.5
10.2	13.0	509.43	0.17	65.8
10.7	12.0	297.61	0.10	70.6
11.2	10.9	85.79	0.03	76.3
11.7	9.8	-126.03	-0.04	83.0
12.2	8.7	-337.85	-0.12	90.9
12.7	7.6	-549.67	-0.19	100.5
13.2	6.4	-761.49	-0.26	112.4
13.7	5.1	-973.31	-0.33	127.4
14.2	3.8	-1185.13	-0.41	147.2
14.7	2.4	-1396.95	-0.48	174.1
15.2	0.8	-1608.77	-0.55	213.1

Table F6 Ethanol price sensitivity of Petrobras process

Ethanol price (Baht/liter)	IRR (%)	NPV (Mil. Baht)	PI	PB (months)
13.7	19.1	5337.4	0.62	46.2
14.2	17.1	4028.38	0.47	51.4
14.7	15	2719.37	0.32	58
15.2	12.9	1410.36	0.16	66.5
15.7	10.7	101.34	0.01	77.8
16.2	8.3	-1207.67	-0.14	93.9
16.7	5.8	-2516.69	-0.29	118.3
17.2	3.3	-3721.55	-0.43	155.5

Table F7 Ethylene price sensitivity of Chematur process

% increment of ethylene price	Ethylene price (Baht/ton)	IRR (%)	NPV (Mil. Baht)	PI	PB (months)
0	46800	-	-2445.81	-0.84	-2445.81
2	47736	-5.3	-2267.85	-0.78	-2267.85
4	48672	-3.3	-2089.88	-0.72	-2089.88
6	49608	-1.7	-1911.92	-0.66	-1911.92
8	50544	-0.2	-1733.95	-0.60	-1733.95
10	51480	1.2	-1555.99	-0.53	-1555.99
12	52416	2.5	-1378.02	-0.47	-1378.02
14	53352	3.7	-1200.06	-0.41	-1200.06
16	54288	4.8	-1022.09	-0.35	-1022.09
18	55224	5.9	-844.13	-0.29	-844.13
20	56160	6.9	-666.16	-0.23	-666.16
22	57096	7.9	-488.19	-0.17	-488.19
24	58032	8.9	-310.23	-0.11	-310.23
26	58968	9.8	-132.26	-0.05	-132.26
28	59904	10.7	45.70	0.02	45.70
30	60840	11.6	223.67	0.08	223.67
32	61776	12.5	401.63	0.14	401.63
34	62712	13.4	579.60	0.20	579.60
36	63648	14.2	757.56	0.26	757.56
38	64584	15.1	935.53	0.32	935.53
40	65520	15.9	1113.49	0.38	1113.49
42	66456	16.7	1291.46	0.44	1291.46

Table F8 Ethylene price sensitivity of Petrobras process

% increment of ethylene price	Ethylene price (Baht/ton)	IRR (%)	NPV (Mil. Baht)	PI	PB (months)
0	46800	3.3	-3721.55	-0.43	155.5
1	47268	4.5	-3182.26	-0.37	136.3
2	47736	5.6	-2642.97	-0.31	121.3
3	48204	6.6	-2103.68	-0.24	109.3
4	48672	7.7	-1564.39	-0.18	99.5
5	49140	8.7	-1025.10	-0.12	91.3
6	49608	9.6	-485.81	-0.06	84.3
7	50076	10.6	53.47	0.01	78.3
8	50544	11.5	592.76	0.07	73.1
9	51012	12.4	1132.05	0.13	68.6
10	51480	13.3	1671.34	0.19	64.6
11	51948	14.2	2210.63	0.26	61.0
12	52416	15.1	2749.92	0.32	57.8
13	52884	15.9	3289.21	0.38	55.0

APPENDIX G Comparison of Two Commercial Processes

Table G1 Comparison of two commercial processes in terms of technical and economic issues

Items	Chematur	Petrobras
Technical issues	1. 4 sets of adiabatic reactor are required, leading to high investment and maintenance costs 2 A higher quantity of steam is required, leading to a higher investment in the heat exchangers and a higher consumption of cooling water 3. Utility consumption is higher	1. Only single adiabatic reactor is required, leading to lower investment and maintenance costs 2. The reactor effluents are used as a heating fluid that partially substitutes the steam from external source and reduces the consumption of cooling water, leading to a significantly lower operating cost 3. The heat in the process is utilized, leading to the reduction in the utility consumption
Economic issues	1. The total investment is higher due to the high investment in the heat exchanger equipment and separation of water (investment ; 88,303 baht/ton of ethylene) 2. The operating cost is higher	1. The total investment is lower due to the less number of equipments (Investment ; 43,080 baht/ton of ethylene) 2. The operating cost is lower

Table G1 (cont.) Comparison of two commercial processes in terms of technical and economic issues

Items	Chematur	Petrobras
Economic issues	due to the use of external steam and cooling water (operating cost ; 5,242 baht/ton of ethylene) 3. Low economic viability is observed (No value of IRR, and PI = -0.84) due to a high investment	due to the energy management by using the effluents as a heating fluid (operating cost ; 3,150 baht/ton of ethylene) 3. The economic viability is higher than the Chematur case (IRR = 3.3% and PI = -0.43)

APPENDIX H Analysis of Bio-ethanol Samples

Table H1 Analysis of bio-ethanol samples from Sapthip Company Limited

Sample name	% Alcohol	pH	Acidity (ppm.)
Ethanol from 1st distillation column	40 - 50%	3.5 - 5.5	400 - 1,000
Ethanol from 2nd distillation column	95.0 - 96.0%	4.0 - 9.0	14 - 30
Ethanol from Dehydration unit	99.6 - 99.9%	6.5 – 9.0	14 - 30

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	Company name:	PTT Chemical Public Company Limited

Proceedings:

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