Optimisation of Coal-Bed Methane (CBM) Gas Purification Process

Advanced Modeling Forum

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Daeho Ko

GS E&C

Table of Contents

1. Overview

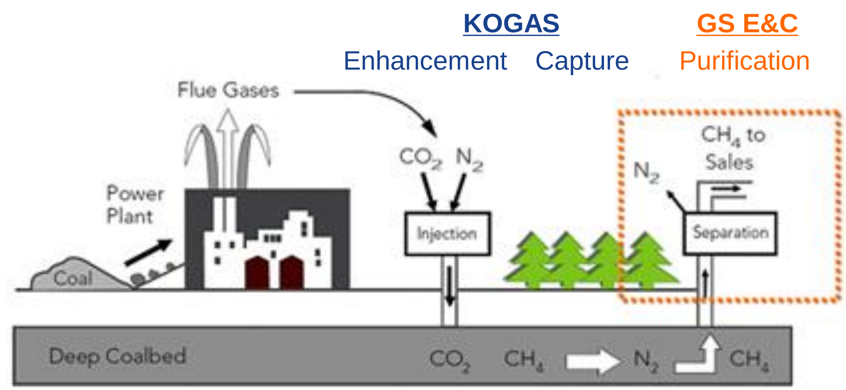
Overview of CBM purification project: Government R&D project in Korea

❑ R&D Project (KEIT of MOTIE in Korea)

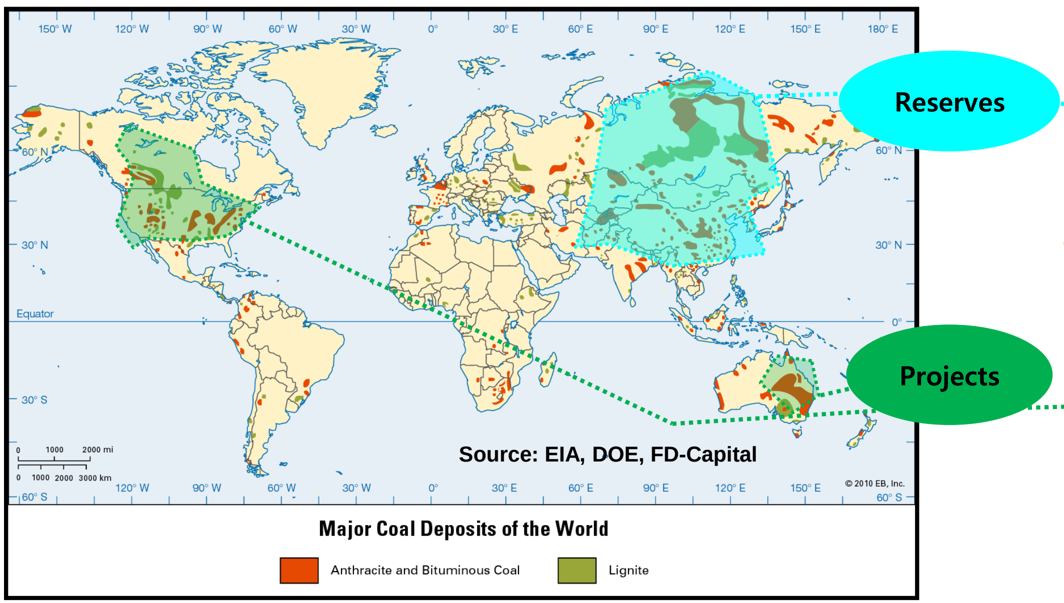
- Development of CoalBed Methane (CBM) Resource Engineering Core Technology

❑ Purposes

- Development of an energy efficient gas separation system to purify Coal Bed Methane (CBM) gas consisting of mainly methane and other impurities such as carbon dioxide, ethane, and so on
- Pilot Plant construction in the corresponding site

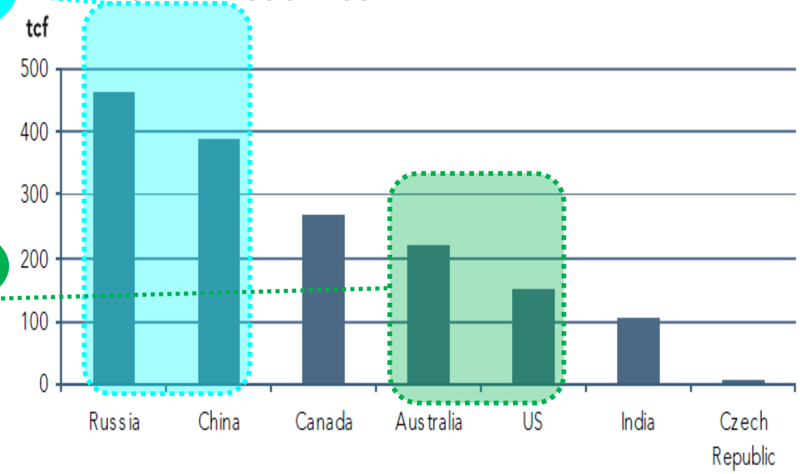


❑ Identified CBM Basin



Source: EIA, DOE, FD-Capital

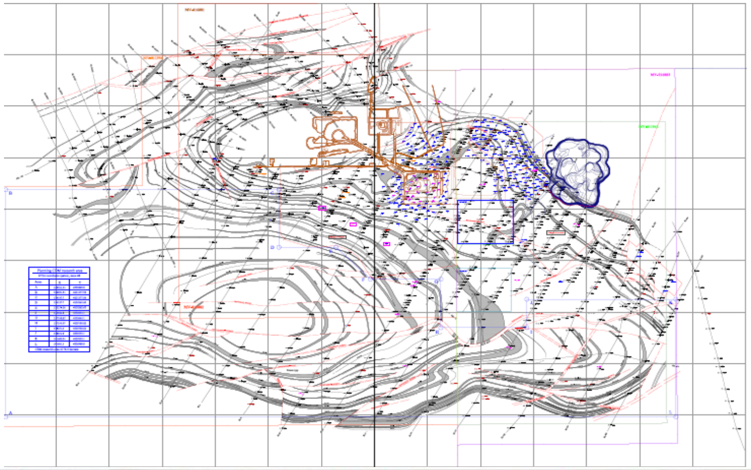
❑ CBM Reserves

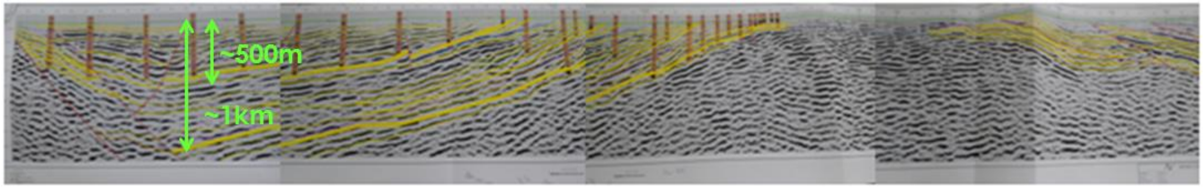


KEIT = Korea Evaluation Institute of Industrial Technology
MOTIE = Ministry of Trade, Industry & Energy

1. Overview

Overview of CBM purification project: CBM Site in Mongolia

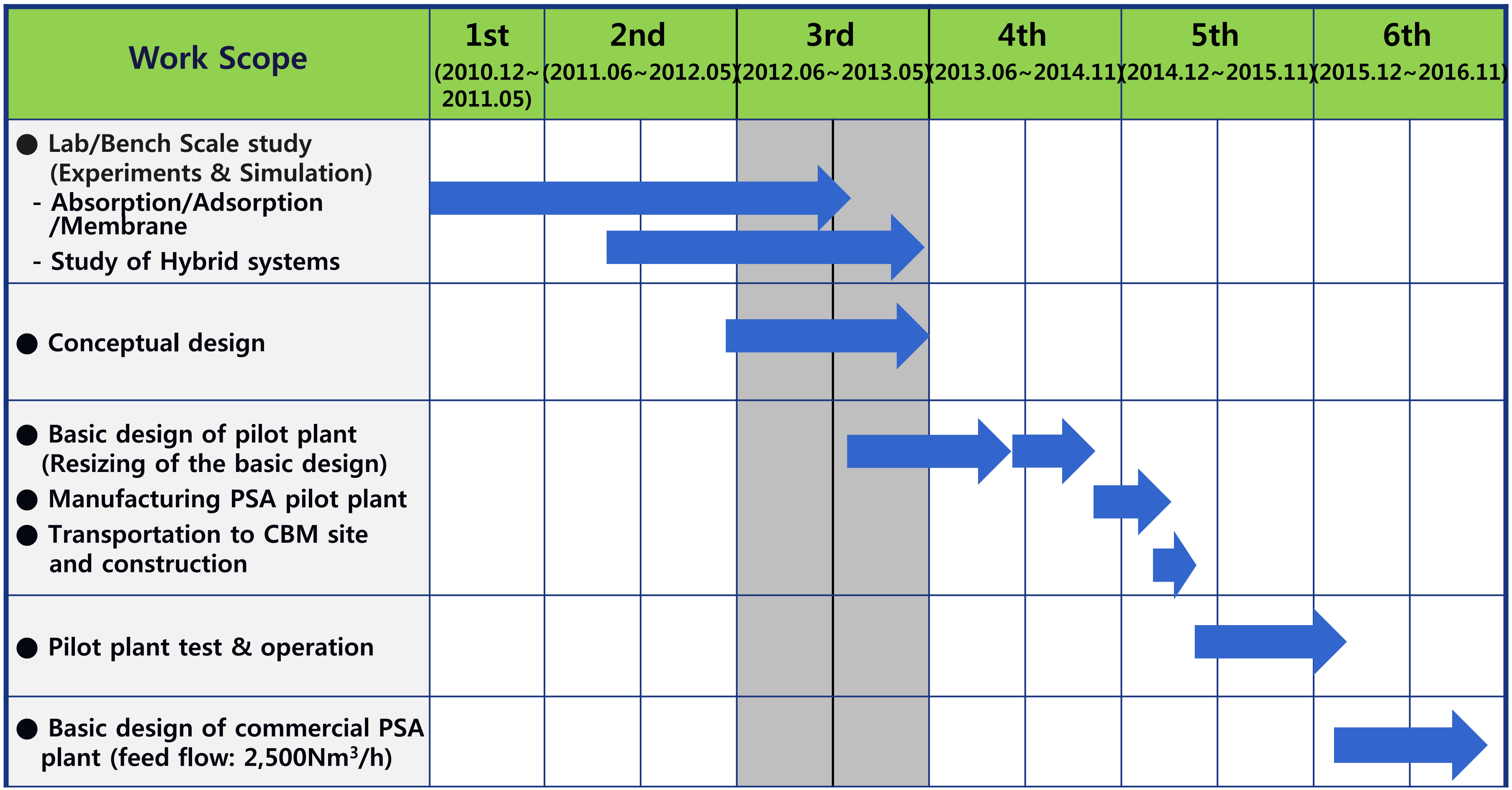




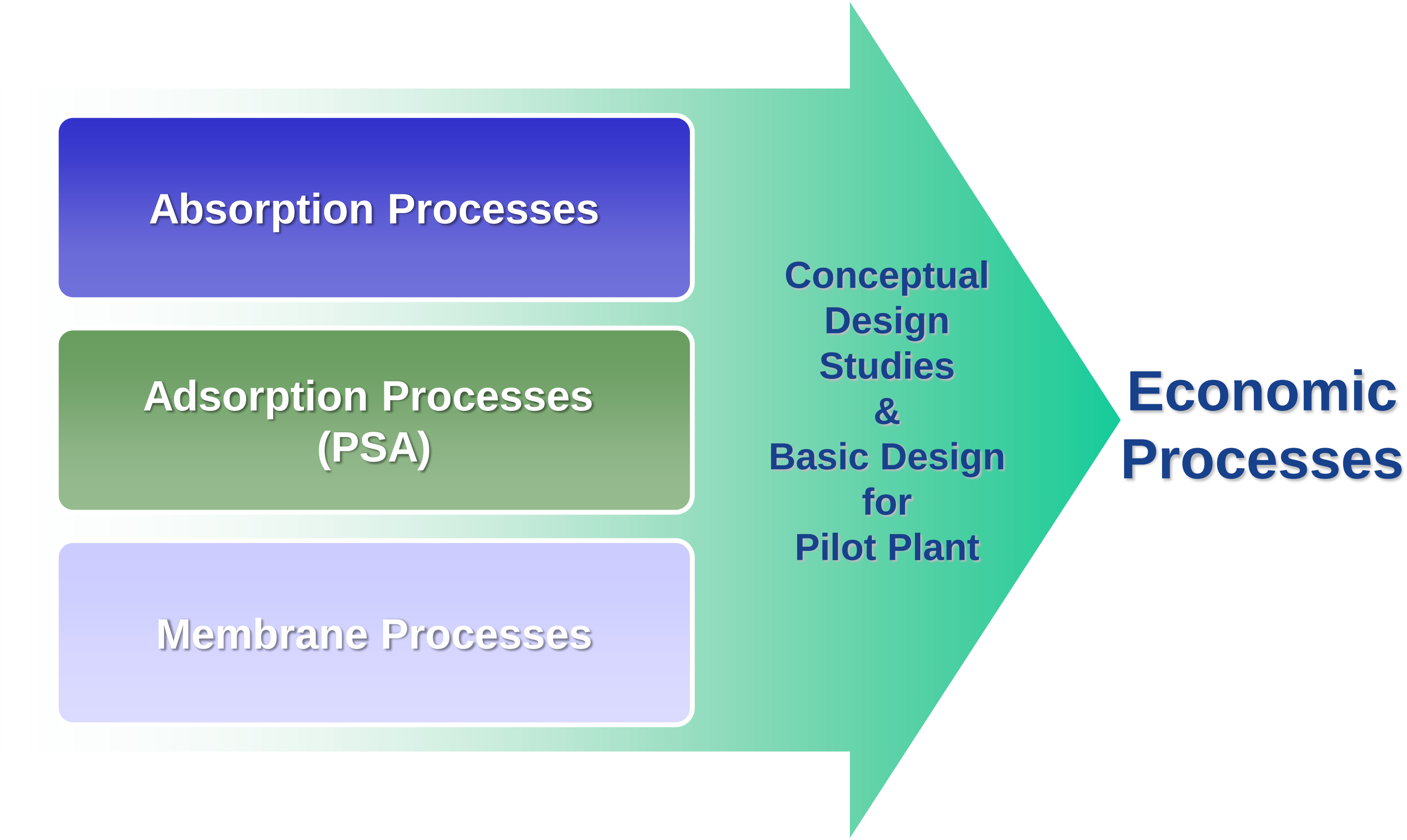
1. Overview

R&D plan (CBM purification technology)

KOGAS has been performing the mining the coal bed methane gas through Mongolian company (ELGEN), and will produce CBM gas on May or June 2015 at Tavan Tolgoi Site in Mongolia.
GS E&C will install PSA pilot plant to purify the CBM gas.



2. Conceptual design study



2. Conceptual design study

Work Done at GE E&C

- Simulation and Experiments of Purification Processes in Bench Scale Unit
- Brief Performance Comparison of Gas Separation/Purification Processes
- Process Design of Pilot Plant to remove sour gas (CO_2) included in CBM
  - ✓ Case Studies of purification processes
  - ✓ Finalization of Concept Design for pilot plant which will be installed in CBM site in Mongolia

2. Conceptual design study

Brief Comparison of Processes

❑ Performance and Scale

Processes	Scale	Performance
Amine absorption	Large	**O**
Adsorption (PSA)	Medium~Large	O
Membrane	Small	△

Since the technologies for scale up and performance improvements of PSA and Membrane have been developed, The improved large size processes of membrane and PSA have been introduced in industries recently.

❑ Size and Cost (Feed flow rate ~ 600Nm3/hr)

Processes	Pilot Plant Size	Pilot Plant Cost	Things to note	Candidate Processes for Pilot Plant Basic Design
Absorption	10m*15m*15m	Higher than $1.9MM	Large Scale & Excellent Performance / expensive absorption cost	X
Adsorption (PSA)	10m*15m*10m	About $0.94MM	Mid-Large Scale & Good performance	O
Membrane	10m*15m*10m	About $0.94MM	Recently started to be commercialized in large scale	O

Considering the cost, size, and ease of transportation to remote CBM site, Membrane and PSA processes are selected for the conceptual design studies.

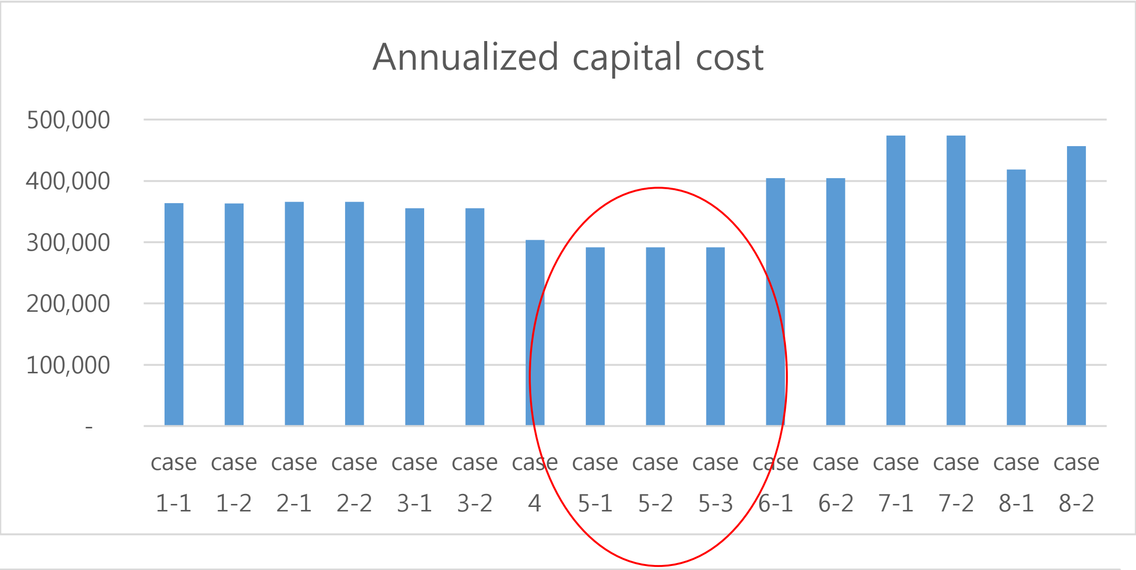
2. Conceptual design study

List of the candidate processes for brief comparison

Scenario Index	Adsorbent	1st PSA adsorption pressure (bara)	1st PSA purge pressure (bara)	1st Membrane permeate pressure (bara)	2nd Membrane permeate pressure (bara)	2nd PSA adsorption pressure (bara)	2nd PSA purge pressure (bara)
	Hybrid Membrane & PSA with Recycle (1)						
CD1.1	Zeolite	1	0.02	1	0.1		
CD1.2	CMS	10	1	1	0.1		
	Hybrid Membrane & PSA with Recycle (2)						
CD2.1	Zeolite	1	0.02	1	0.1		
CD2.2	CMS	10	1	1	0.1		
	Hybrid membrane & PSA without Recycle						
CD3.1	Zeolite	1	0.02	1	0.1		
CD3.2	CMS	10	1	1	0.1		
	Membrane Only with Recycle						
CD4				1	0.1		
	PSA Only						
CD5.1	Zeolite	1	0.02				
CD5.2	CMS	10	1				
CD5.3	CMS	10	0.1				
	Hybrid PSA & Membrane with Recycle (3)						
CD6.1	Zeolite	1	0.02	0.1	0.1		
CD6.2	CMS	10	1	0.1	0.1		
	Hybrid PSA & Membrane with Recycle (4)						
CD7.1	CMS/Zeolite	10	1	0.1		1	0.02
CD7.2	CMS	10	1	0.1		10	1
	Hybrid PSA & Membrane with Recycle (5): Low CH4 composition in feed stream						
CD8.1	CMS			1	0.1	10	1
CD8.2	CMS			1	0.1	10	1

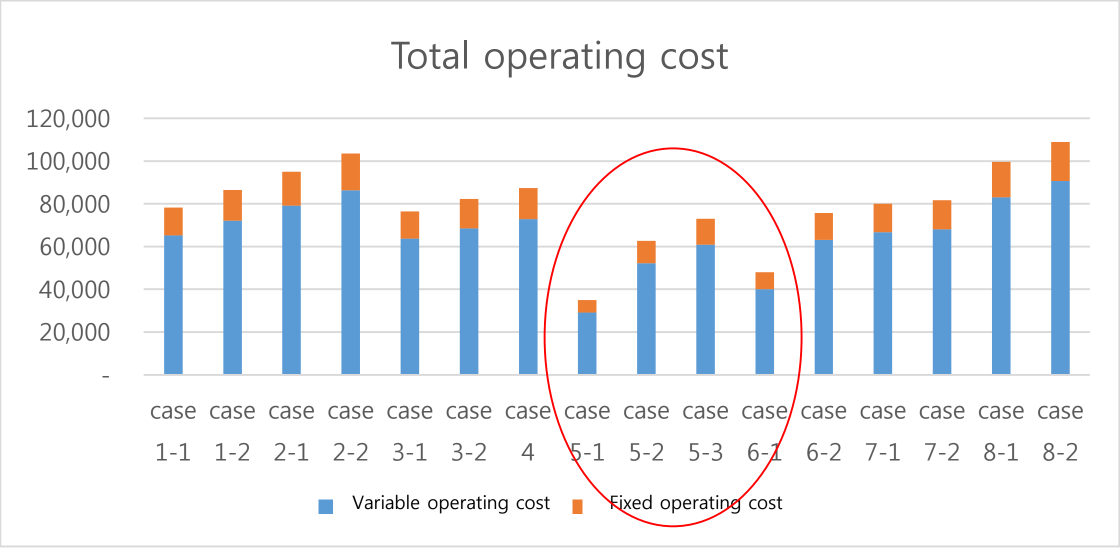
2. Conceptual design study

Economic analysis



Annualized capital cost
 = initial investment cost
 × capital charge factor

Capital charge factor
 = interest rate
 × life time of plant



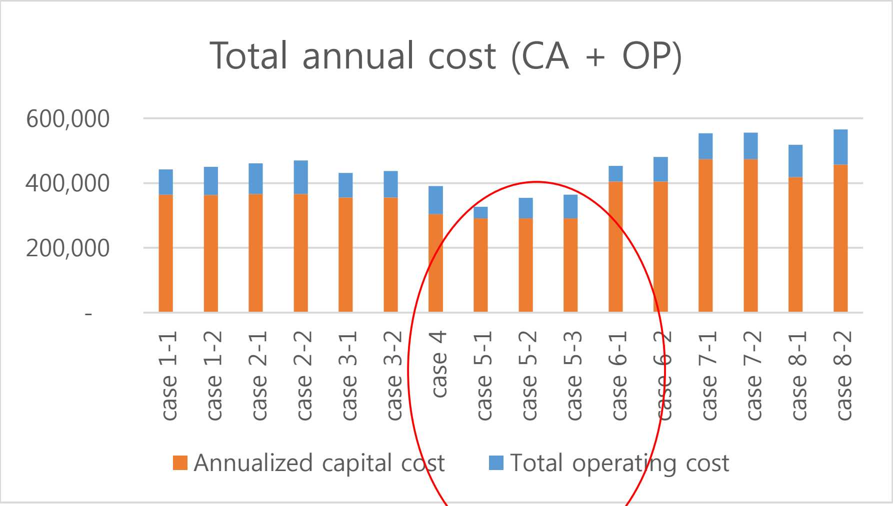
Total operating cost
= fixed operating cost
 + variable operating cost

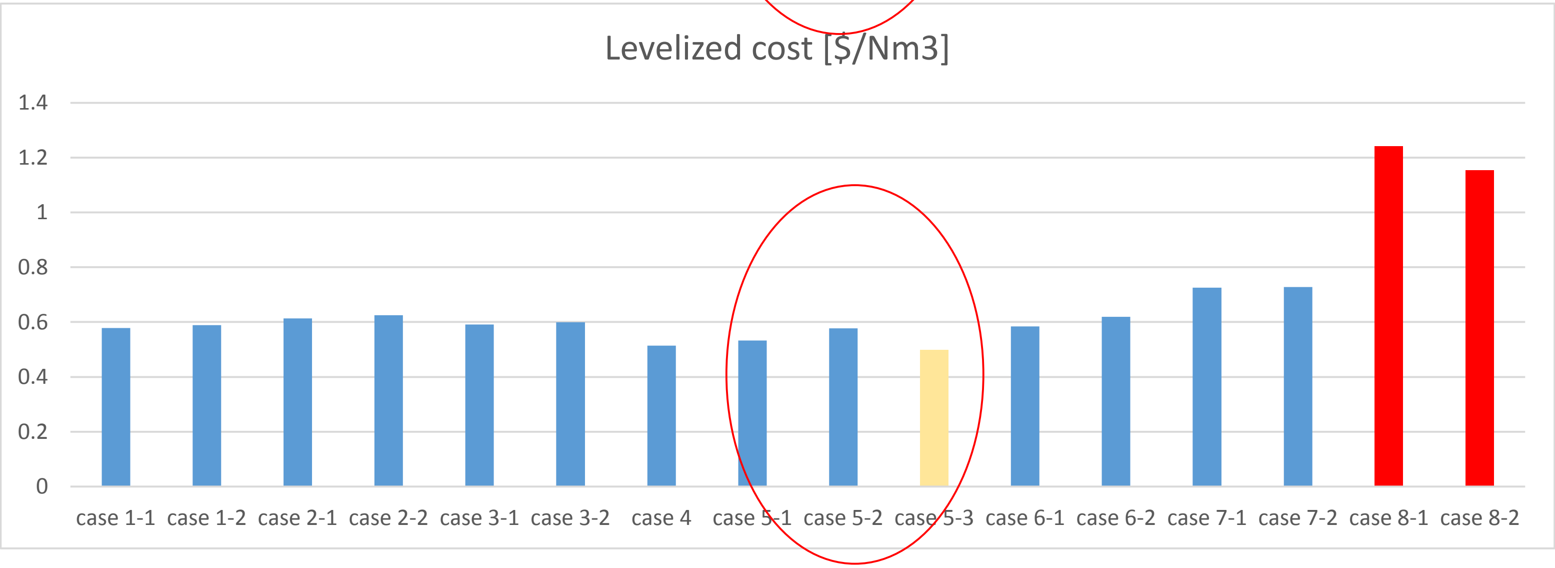
Fixed operating cost
= maintenance & administration fee
 + property tax + depreciation fee
 + …
= 3%~5% of initial investment cost

Variable operating cost
= electricity cost + material cost
 + fuel cost +…
Here, only electricity cost is included.

2. Conceptual design study

Economic analysis

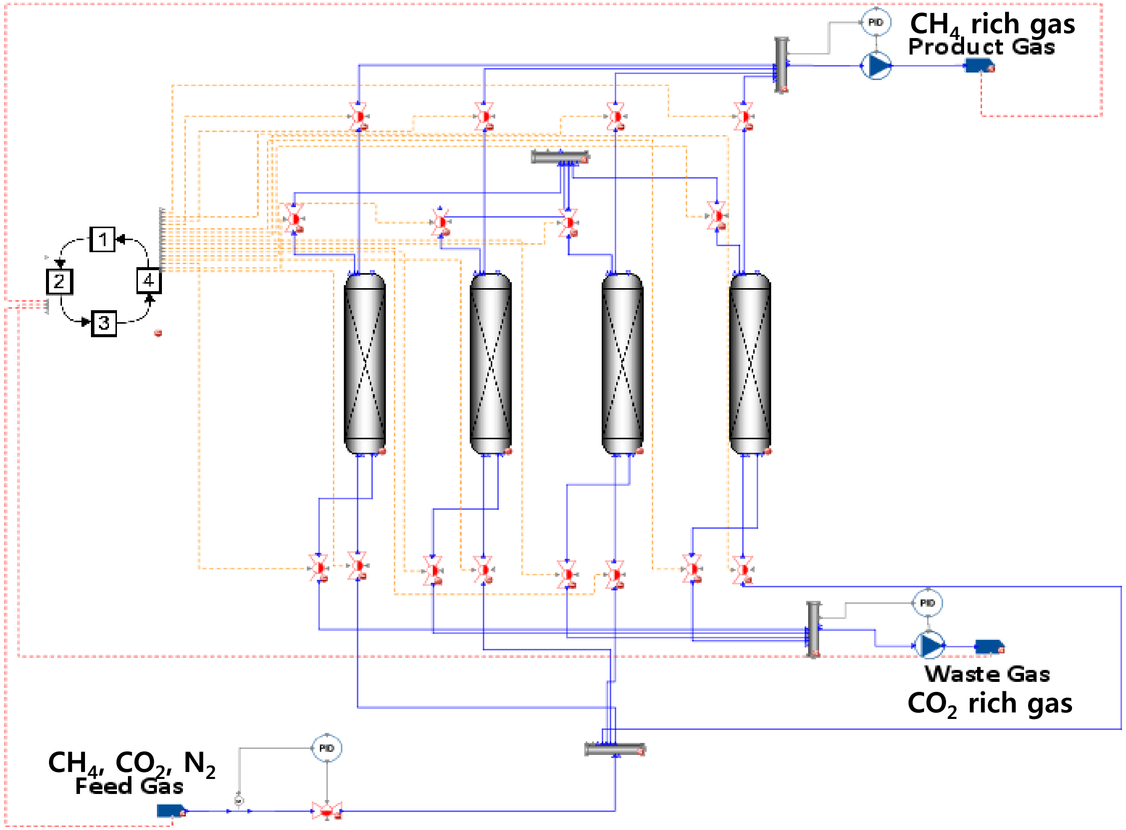




3. Dynamic Modeling of PSA Process

Work Done

1. Isotherm parameter estimation through lab scale experiments
2. PSA simulation model development for CBM purification
3. Basic design of PSA pilot plant
4. Scale up/down design of PSA process
5. Simulation and optimization of PSA through gPROMS modeling



PSA process

CBM feed composition	89.5% CH_4 8.18% CO_2 2.32% N_2
Adsorption/desorption pressure	10 barg / -0.9 barg
Number of adsorption beds	Four
Operating step	Twelve
Adsorbent	CMS 3K

Pressure Swing Adsorption (PSA)

PSA is a technology used to separate some gas species from a mixture of gases under pressure according to the species' molecular characteristics and affinity for an adsorbent material. It operates at near-ambient temperatures and differs significantly from cryogenic distillation techniques of gas separation. Specific adsorptive materials (e.g., zeolites, activated carbon, molecular sieves, etc.) are used as a trap, preferentially adsorbing the target gas species at high pressure. The process then swings to low pressure to desorb the adsorbed material.
(Reference: http://en.wikipedia.org/wiki/Pressure_swing_adsorption)

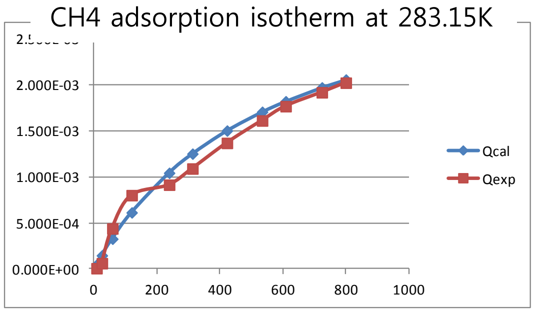
CMS type of adsorbent is selected for PSA systems, because zeolite types are vulnerable to humidity.

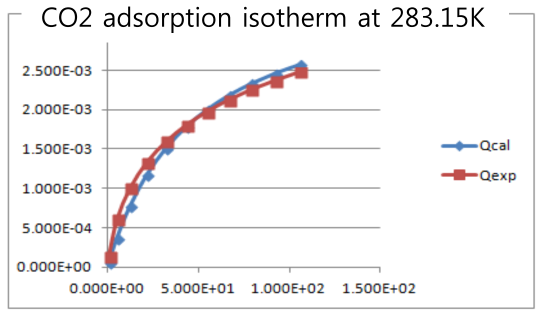
3. Dynamic Modeling of PSA Process

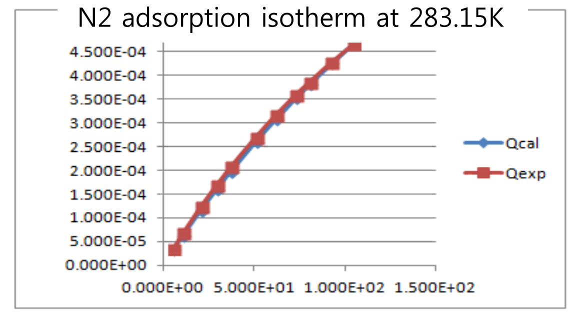
Adsorption equilibrium
(Extended Langmuir isotherm)

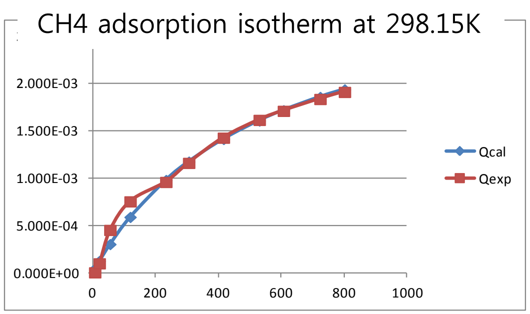
$$q_i^* = \frac{q_{s,i} b_i P_i}{1+\sum_{i=1}^{n} b_i P_i};\ q_{s,i} = q_{sa,i} + \frac{q_{sb,i}}{T};\ b_i = b_{0,i}\exp\left(\frac{D_{E,i}}{T}\right)$$

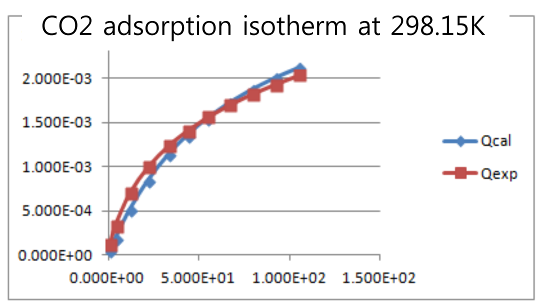
	q_{sa} (mol/g)	q_{sb} (mol-K/g)	b_0 (1/bar)	D_E (K)	△H (cal/mol)
CH_4	-0.0018	1.502	0.413302326	-238	974.54
CO_2	0.0004	0.9374	0.000755814	2250.1	5216.47
N_2	0.0019	-0.00376	0.000335559	1937.8	3847.03

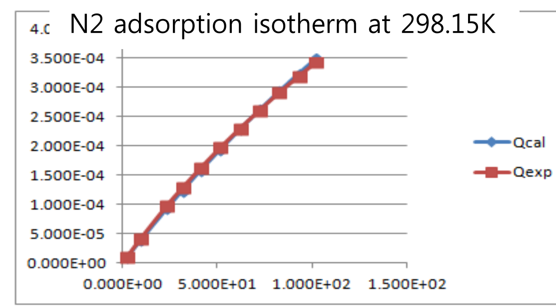


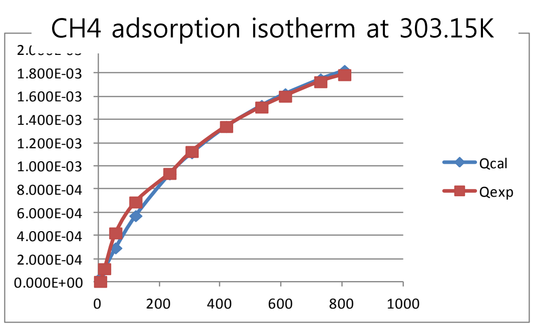


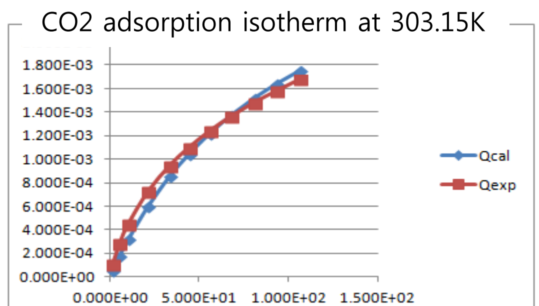


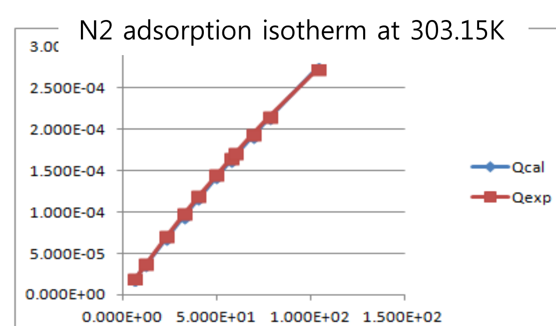








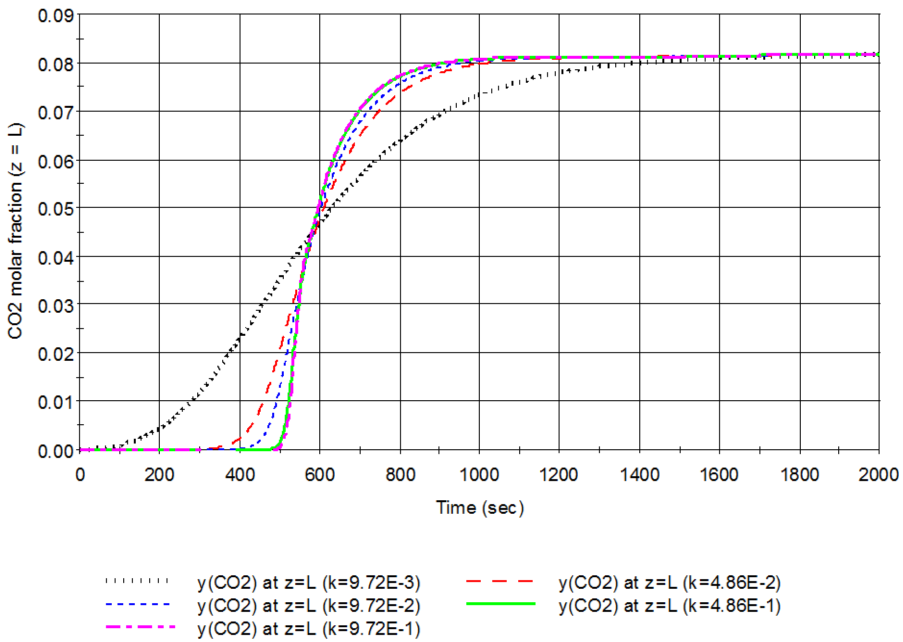




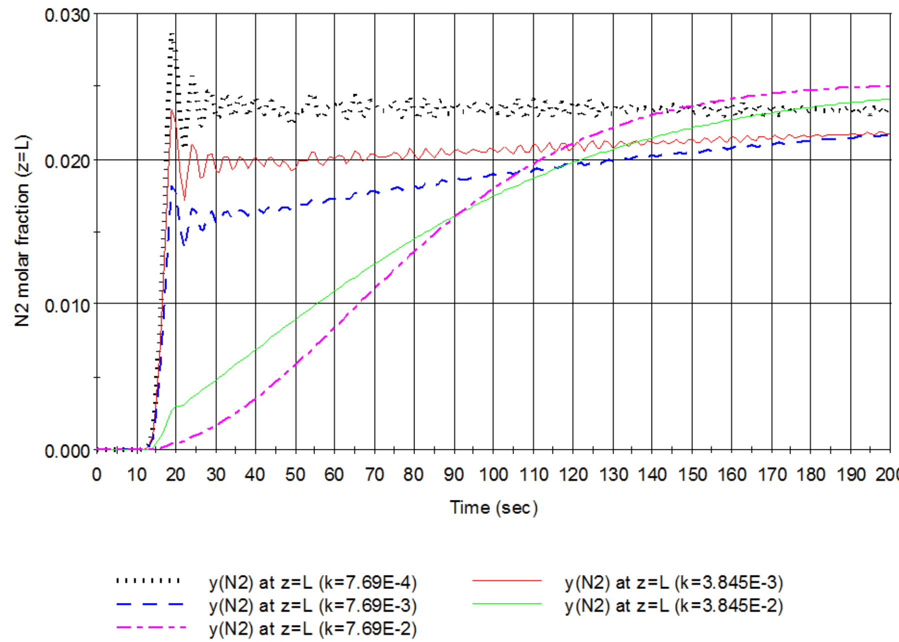
3. Dynamic Modeling of PSA Process

Breakthrough curve behavior

CO2 breakthrough behavior according to k_{co2}



N2 breakthrough behavior according to k_{N2}



Considering the value of CO_2 measured mass transfer coefficient (k_{CO2}=9.72×10^{-2}), the adsorption time can be determined as 140 sec, leading to enough adsorption of CO_2 and high CH4 purity

The N_2 breakthrough begins at around 12.5 sec, independently of the mass transfer coefficient values (measured k_{N2} =7.69×10^{-3}), N_2 comes out with CH_4 in the purified gas stream.

Mass transfer coefficient measured

k_{CH4}=5.35×10^{-3} s^{-1}
k_{CO2}=9.72×10^{-2} s^{-1}
k_{N2} =7.69×10^{-3} s^{-1}

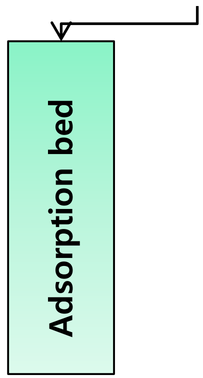
Adsorption rate

$$\frac{\partial q_i}{\partial t} = k_i\left(q_i^* - q_i\right)$$

3. Dynamic Modeling of PSA Process

Modeling of 4 Bed 12 Operating Step PSA through One Bed Simulation instead of the Four Bed simulation

Boundary conditions are calculated
at the each interacting bed
of the corresponding step



Four Bed Twelve Operating Step Sequence & Time

STEP NO.	1	2	3	4	5	6	7	8	9	10	11	12
TIME(sec)	10	120	10	10	120	10	10	120	10	10	120	10
Bed 1	AD	AD	AD	EQ1	RE	EQ2	BD	PU	EQ2	EQ1	PR	PR
Bed 2	BD	PU	EQ2	EQ1	PR	PR	AD	AD	AD	EQ1	RE	EQ2
Bed 3	EQ1	PR	PR	AD	AD	AD	EQ1	RE	EQ2	BD	PU	EQ2
Bed 4	EQ1	RE	EQ2	BD	PU	EQ2	EQ1	PR	PR	AD	AD	AD

- AD : adsorption
- EQ : pressure equalization
- RE : repose
- BD : blow down
- PU : purge
- PR : pressurization

3. Dynamic Modeling of PSA Process

Verification of Simulation Model (4 Bed 12 Operating Step PSA)

100Nm³/h

200 times scale up

0.5Nm³/h

Feed Flow = 100Nm³/h		Variables	Basic Design*	Simulation	RME (%)
Inner Bed Diameter (m)	0.289	CH4 Purity (%)	97.00	96.97	0.0286
Packing Bed Height (m)	1.55	CH4 Recovery (%)	92.00	92.03	0.0329
Adsorption Pressure (bara)	11	Product Flow (Nm³/s)	2.36E-02	2.37E-02	0.4047
BlowDown Pressure (bara)	1	Waste Flow (Nm³/s)	4.20E-03	4.34E-03	3.2081
Purge Pressure (bara)	0.1	Feed Composition: CH4 89.5%, CO2 8.18%, N2 2.32%			

Feed Flow = 0.68Nm3/h		Variables	Experiment C1*	Simulation	RME (%)
Inner Bed Diameter (m)	0.0254	CH4 Purity (%)	96.16	96.00	0.1660
Packing Bed Height (m)	1	CH4 Recovery (%)	93.96	93.78	0.1878
Adsorption Pressure (bara)	11	Product Flow (Nm³/s)	1.65E-04	1.65E-04	0.0828
BlowDown Pressure (bara)	1	Waste Flow (Nm³/s)	2.39E-05	2.35E-05	1.6023
Purge Pressure (bara)	0.259	Feed Composition: CH4 89.5%, CO2 8.18%, N2 2.32%			

Feed Flow = 0.56Nm3/h		Variables	Experiment C2*	Simulation	RME (%)
Inner Bed Diameter (m)	0.0254	CH4 Purity (%)	97.12	96.92	0.2025
Packing Bed Height (m)	1	CH4 Recovery (%)	92.83	92.78	0.0525
Adsorption Pressure (bara)	11	Product Flow (Nm³/s)	1.32E-04	1.33E-04	0.3570
BlowDown Pressure (bara)	1	Waste Flow (Nm³/s)	2.24E-05	2.19E-05	2.1366
Purge Pressure (bara)	0.174	Feed Composition: CH4 89.5%, CO2 8.18%, N2 2.32%			

Feed Flow = 0.44Nm3/h		Variables	Experiment C3*	Simulation	RME (%)
Inner Bed Diameter (m)	0.0254	CH4 Purity (%)	97.48	97.14	0.3516
Packing Bed Height (m)	1	CH4 Recovery (%)	91.19	91.15	0.0475
Adsorption Pressure (bara)	11	Product Flow (Nm³/s)	1.03E-04	1.03E-04	0.5983
BlowDown Pressure (bara)	1.081	Waste Flow (Nm³/s)	2.02E-05	1.93E-05	4.5764
Purge Pressure (bara)	0.176	Feed Composition: CH4 89.5%, CO2 8.18%, N2 2.32%			

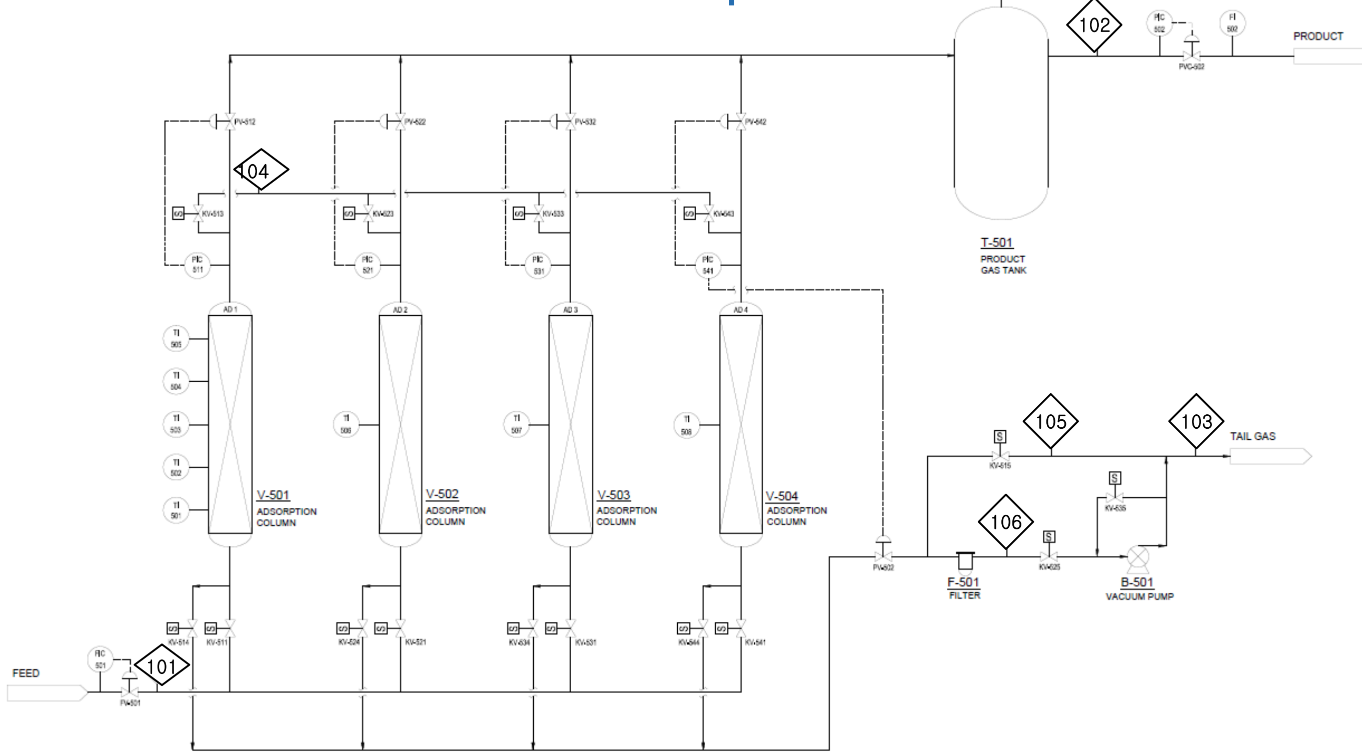
RME < 5%

* Basic design and experiments were performed by GENS Engineering (PSA design company) in Korea

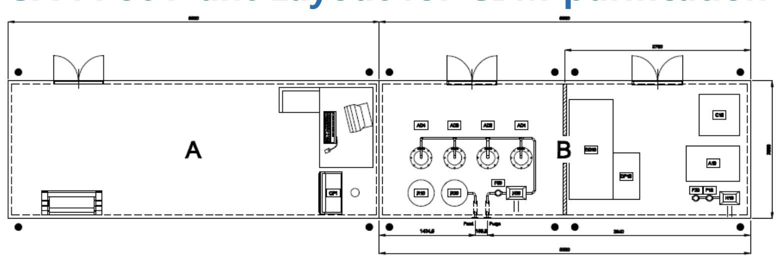
RME =Relative Mean Error = $(\phi_{Exp} - \phi_{Cal})/\phi_{Cal} \times 100\%$

4. Optimization of PSA for Scale up & down Design

PSA Pilot Plant P&ID for CBM purification



PSA Pilot Plant Layout for CBM purification



Length = 11,160mm, Width = 2,050mm, Height = 2,300mm

4. Optimization of PSA for Scale up & down Design

Re-design*: feed flow 100Nm³/h → 10Nm³/h

Material balance for PSA pilot plant (feed flow: 10Nm³/h)

Stream No.		101 Feed stream	102 Product stream	103 Waste stream	104 Pressure equalization stream	105 Blow down stream	106 Purge stream
Phase		Vapor	Vapor	Vapor	Vapor	Vapor	Vapor
Molar Fraction (mole %)	CH_4	0.895	0.97	0.4738			
	CO_2	0.082	0.0072	0.5023			
	N_2	0.023	0.0228	0.0244			
Vol. flow rate (Nm3/h)		10	8.5	1.5	1.45	0.4	1.1
Temperature (°C)		20	20	20	20	20	20
Pressure (kg/cm²G)		10	10	-0.9	10→6.5 6.5→3	0.1	-0.9

Four Bed Twelve Operating Step Sequence & Time

STEP NO.	1	2	3	4	5	6	7	8	9	10	11	12
TIME(sec)	10	120	10	10	120	10	10	120	10	10	120	10
Bed 1	AD	AD	AD	EQ1	RE	EQ2	BD	PU	EQ2	EQ1	PR	PR
Bed 2	BD	PU	EQ2	EQ1	PR	PR	AD	AD	AD	EQ1	RE	EQ2
Bed 3	EQ1	PR	PR	AD	AD	AD	EQ1	RE	EQ2	BD	PU	EQ2
Bed 4	EQ1	RE	EQ2	BD	PU	EQ2	EQ1	PR	PR	AD	AD	AD

- **AD : adsorption**
- **EQ : pressure equalization**
- **RE : repose**
- **BD : blow down**
- **PU : purge**
- **PR : pressurization**

Design Basis	
1. Inner diameter of adsorption bed	0.15m
2. Packing Height of Adsorption bed	1.12m
3. Material of bed	Carbon steel
4. Design Capacity	10Nm³/h (Feed flow)
5. Feed temperature	Ambient temperature
6. Product flow rate	8.5Nm³/h
7. CH_4 Purity	Above 97%
8. CH_4 Recovery	85~90%

* The PSA Optimization method of Ko et. al (2005) is adopted to perform the Re-Sizing of the PSA plant

4. Optimisation of PSA for Scale up & down Design

PSA optimisation* model (feed flow: 10Nm³/h)

$$Min.\ obj = 10^5 \times \varepsilon - Purity_{CH_4} - Recovery_{CH_4}$$

Subject to

		Case 1		Case 2		Case 3	
Variables	Unit	LB	UB	LB	UB	LB	UB
CH_4 Purity	-	0.97	1.00	0.975	1.00	0.975	1.00
CH_4 Recovery	-	0.90	1.00	0.80	1.00	0.75	1.00
L	m	1.0	1.3	1.0	1.3	1.12	1.12
R_{bed}	m	0.0	1.0	0.0	1.0	0.0	1.0
L/u_{feed}	Sec	0.75	2.7	0.75	2.7	0.75	2.7
$T_{i,j,t=0}$	K	290	340	290	340	290	340
$q_{CH4,j,t=0}$	mol/g	0	10	0	10	0	10
$q_{CO2,j,t=0}$	mol/g	0	1	0	1	0	1
$q_{N2,j,t=0}$	mol/g	0	1	0	1	0	1
$y_{i,j,t=0}$	-	0	1	0	1	0	1
$\triangle\phi_j$	K, mol/g, or -	$-\varepsilon$	ε	$-\varepsilon$	ε	$-\varepsilon$	ε
$\Delta\phi_j = \phi_{j,t=0} - \phi_{j,t=t_{cycle}}$, Here, ϕ stands for T, q, and y							

Constraints
to determine cyclic stead state (CSS).

Step times are fixed as shown in following Table

Step No.	1	2	3	4	5	6	7	8	9	10	11	12
Time(sec)	10	120	10	10	120	10	10	120	10	10	120	10
Step	AD	AD	AD	EQ1	RE	EQ2	BD	PU	EQ2	EQ1	PR	PR

Optimal result

	Case 1	Case 2	Case 3
CH_4 Purity	0.9744	0.97545	0.97603
CH_4 Recovery	0.9104	0.85868	0.78598
L	1.1193	1.00113	1.12
R_{bed}	0.05148	0.06624	0.0755
L/u_{feed}	1.22447	1.81348	2.63549

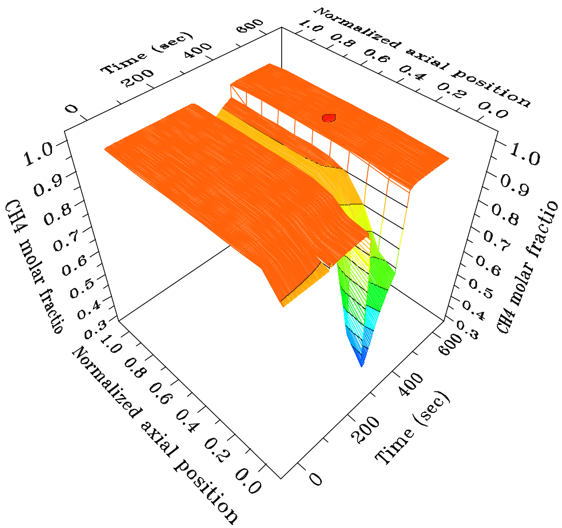
Case 3 is the selected design for pilot plant to obtain the high purity of CH_4.

What is CSS?

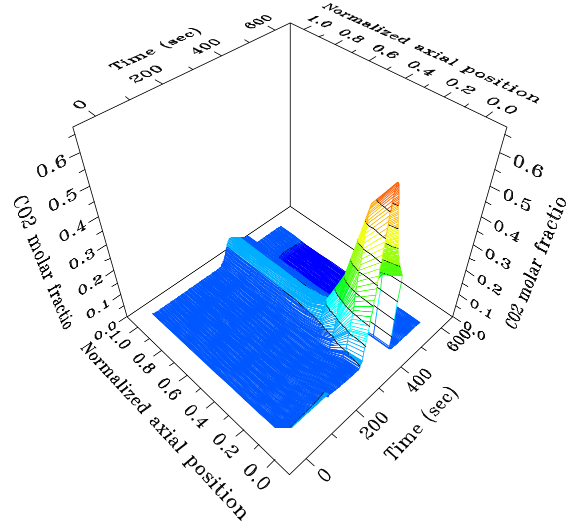
* The PSA Optimization method of Ko et. al (2005) is adopted to perform the Re-design of the PSA plant

4. Optimisation of PSA for Scale up & down Design

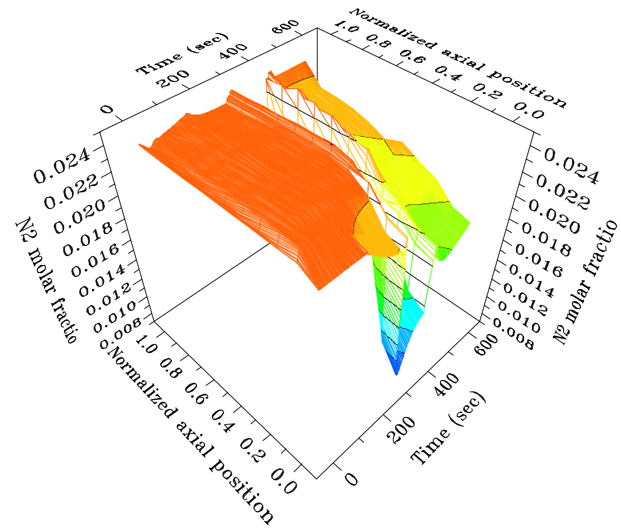
PSA simulation (feed flow: $10Nm^3/h$) of pilot plant



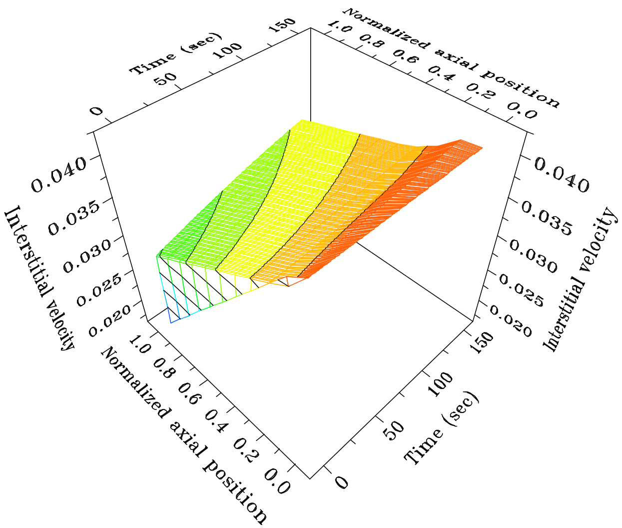
CH4 molar fraction at CSS



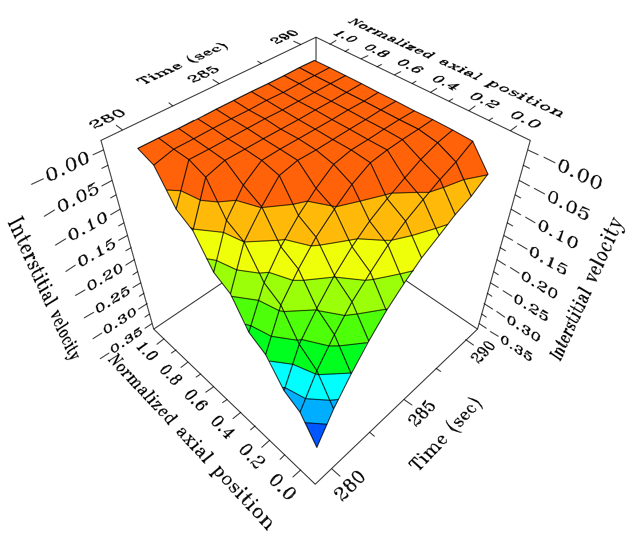
CO2 molar fraction at CSS



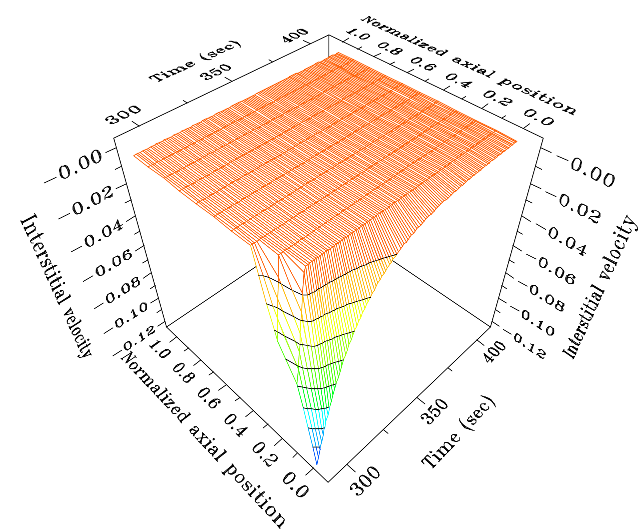
N2 molar fraction at CSS



Velocity of adsorption step at CSS



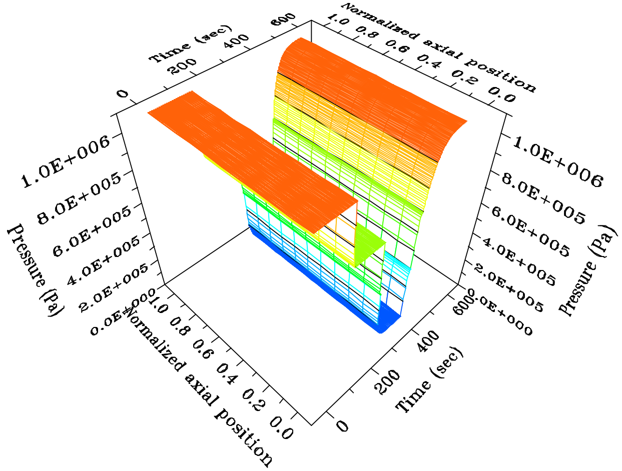
Velocity of blowdown step at CSS



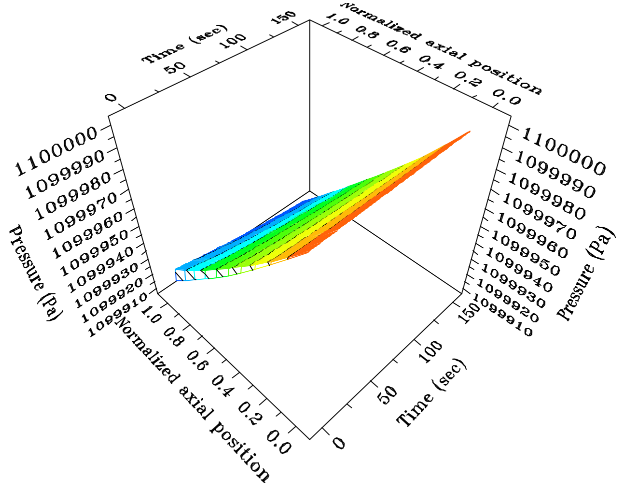
Velocity of purge step at CSS

4. Optimisation of PSA for Scale up & down Design

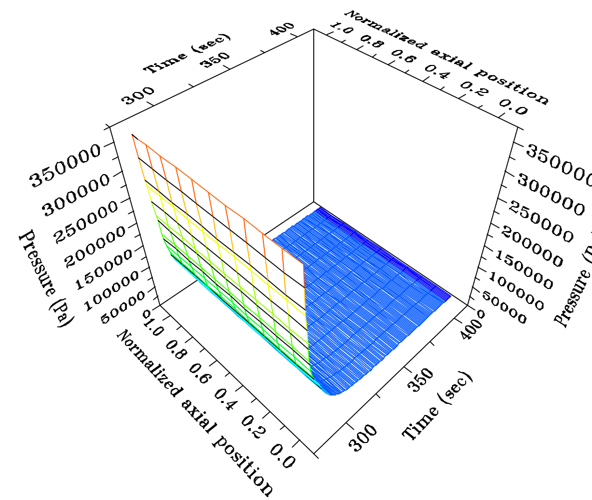
PSA simulation (feed flow: 10Nm^3/h) of pilot plant



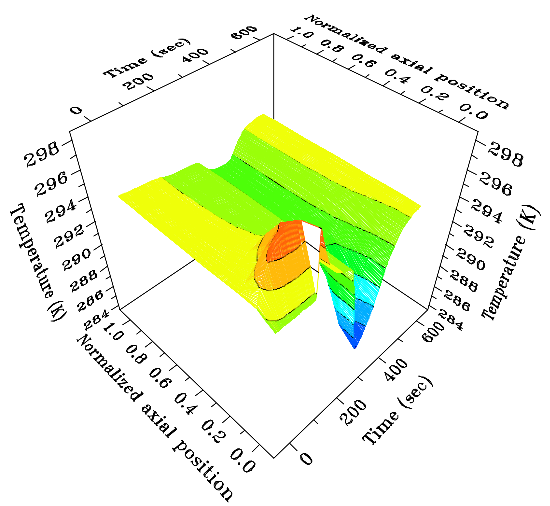
Pressure at CSS



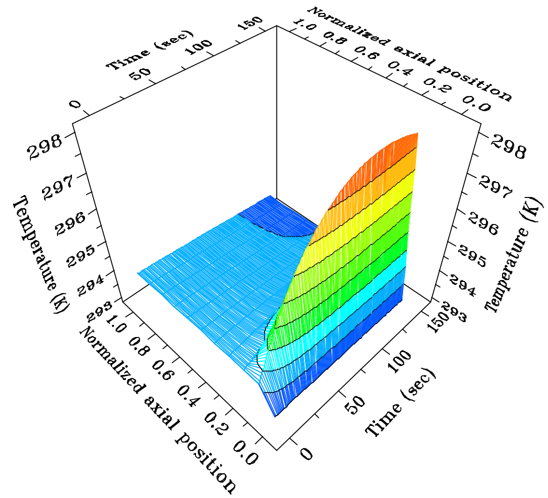
Pressure of adsorption step at CSS



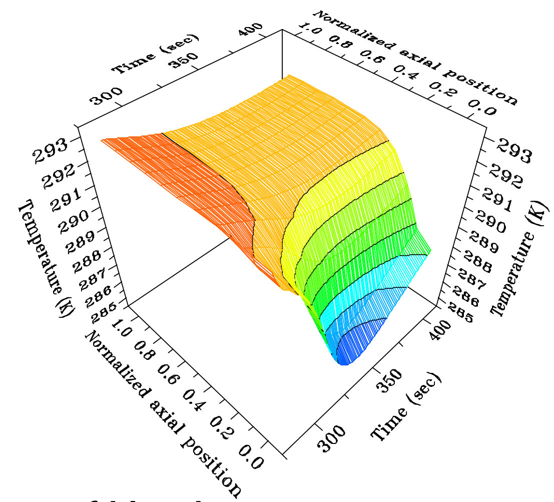
Pressure of blowdown & purge step at CSS



Temperature at CSS



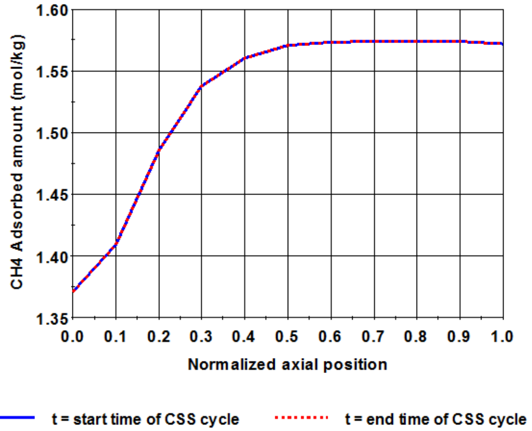
Temperature of adsorption step at CSS



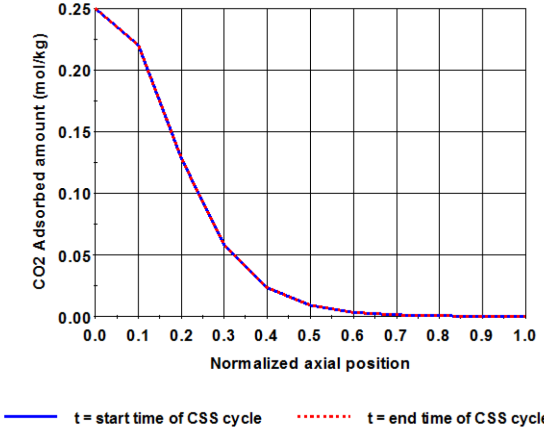
Temperature of blowdown & purge step at CSS

4. Optimisation of PSA for Scale up & down Design

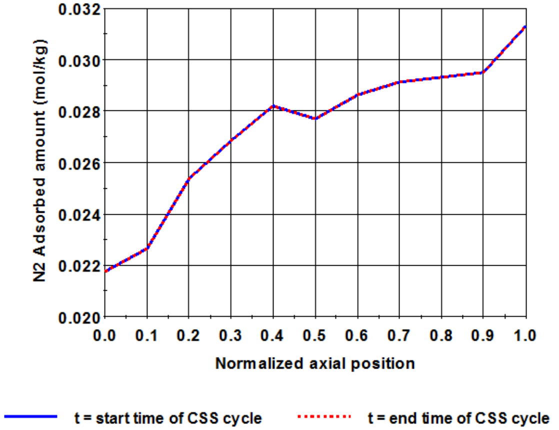
PSA simulation (feed flow: 10Nm³/h) of pilot plant: CSS check



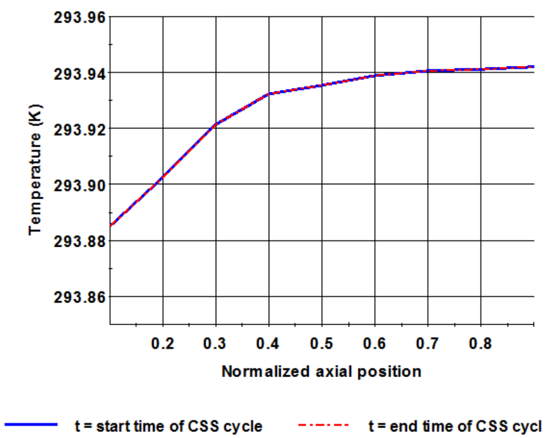
Adsorbed amount of CH_4 at CSS



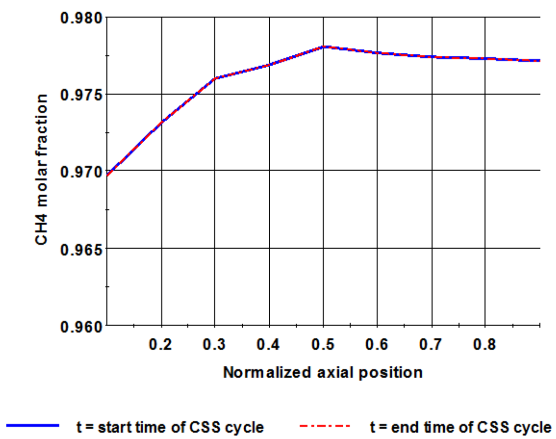
Adsorbed amount of CO_2 at CSS



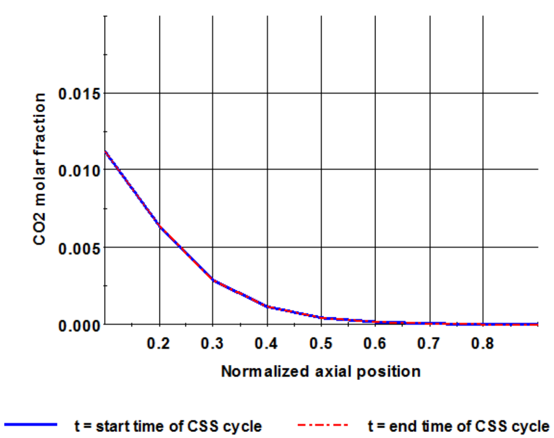
Adsorbed amount of N_2 at CSS



Temperature at CSS



CH_4 molar fraction at CSS

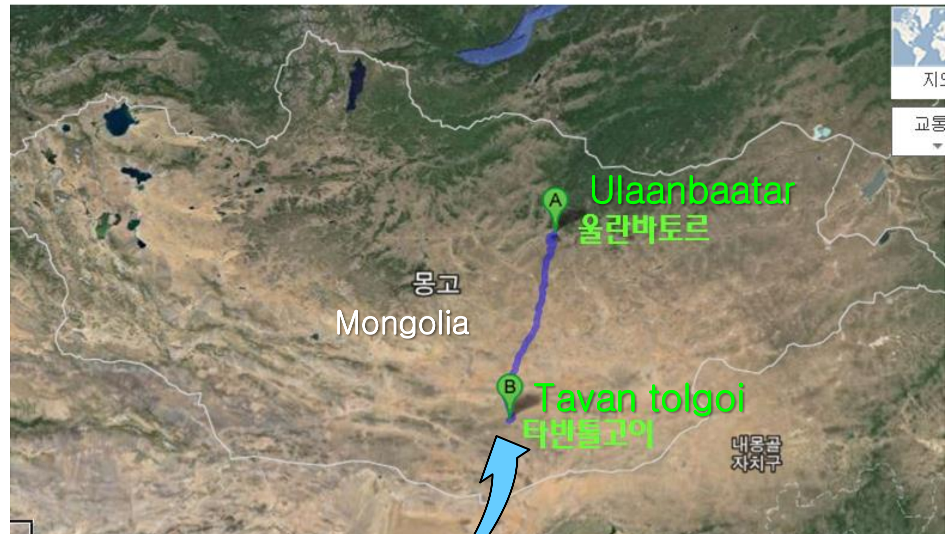


CO_2 molar fraction at CSS

4. Optimization of PSA for Scale up & down Design

Photo of PSA pilot plant ($10Nm^3/h$)

CBM Site in Mongolia



~May 2015

4. Optimisation of PSA for Scale up & down Design

PSA optimisation model

$$Min.\ obj = 10^5 \times \varepsilon$$

Feed flow (Nm^3/h)		200		500		1000		2500		5000	
Variables	**Unit**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
CH_4 *Purity*	-	*0.97*	*1.00*	*0.97*	*1.00*	*0.97*	*1.00*	*0.97*	*1.00*	*0.97*	*1.00*
CH_4 *Recovery*	-	*0.90*	*1.00*	*0.90*	*1.00*	*0.90*	*1.00*	*0.90*	*1.00*	*0.90*	*1.00*
L	*m*	*2.12*	*2.12*	*2.2*	*2.2*	*1.95*	*1.95*	*2.16*	*2.16*	*2.125*	*2.125*
R_{bed}	*m*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*
L/u_{feed}	*sec*	*0.75*	*2.63*	*0.75*	*2.63*	*0.75*	*2.63*	*0.75*	*2.63*	*0.75*	*2.63*
Adsorbent amount per feed flow	$kg/(Nm^3/h)$	*0.7*	*0.72*	*0.7*	*0.72*	*0.7*	*0.72*	*0.7*	*0.72*	*0.7*	*0.72*
$T_{i,j,t=0}$	*K*	*290*	*340*	*290*	*340*	*290*	*340*	*290*	*340*	*290*	*340*
$q_{CH4,j,t=0}$	*mol/g*	*0*	*10*	*0*	*10*	*0*	*10*	*0*	*10*	*0*	*10*
$q_{CO2,j,t=0}$, $q_{N2,j,t=0}$	*mol/g*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*
$y_{i,j,t=0}$	-	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*
$\triangle\phi_j$	*K, mol/g, or -*	$-\varepsilon$	ε	$-\varepsilon$	ε	$-\varepsilon$	ε	$-\varepsilon$	ε	$-\varepsilon$	ε
$\Delta\phi_j = \phi_{j,t=0} - \phi_{j,t=t_{cycle}}$, *Here,* ϕ *stands for T, q, and y*											

4. Optimisation of PSA for Scale up & down Design

Optimal result

Feed flow (Nm^3/h)	Inner Diameter (m)		Adsorbent amount (kg)		CH_4 Purity		CH_4 Recovery	
	PSA Vendor	GS E&C	PSA Vendor	GS E&C	PSA Vendor	GS E&C	PSA Vendor	GS E&C
200	*0.3428*	*0.350247*	*138*	*144*	*0.97*	*0.971106*	*0.90*	*0.909797*
500	*0.5308*	*0.543626*	*344*	*360*	*0.97*	*0.971216*	*0.90*	*0.910607*
1000	*0.8*	*0.8166*	*691*	*720*	*0.97*	*0.971366*	*0.90*	*0.910791*
2500	*1.2*	*1.21405*	*1725*	*1762.8*	*0.97*	*0.971402*	*0.90*	*0.912999*
5000	*1.7*	*1.73253*	*3375*	*3531.8*	*0.97*	*0.971518*	*0.90*	*0.912653*

Conclusion

Work Done

- Conceptual design study for CBM purification processes through
  - comparing various gas separation/purification processes and
  - brief economic analysis of the candidate processes
- Basic design of the selected process (VPSA) through conceptual design study
- Construction and validation of PSA simulation model by using gPROMS
- Scale up/down design (Re-sizing of adsorption bed) of PSA through optimisation by using gPROMS

Work To Do

- PSA pilot plant designed in this study will be transported into CBM site (Tavan tolgoi in Mongolia) and installed by the end of May in 2015.
- Pilot Plant commissioning and operation for the demonstration of CBM purification leading to energy utilization of CBM
- Basic design of commercial size PSA plant (feed flow: 2500Nm^3/h)

Any Question?

Email: daeho.ko@gsconst.co.kr

Appendix

A1. Candidate processes for conceptual design study

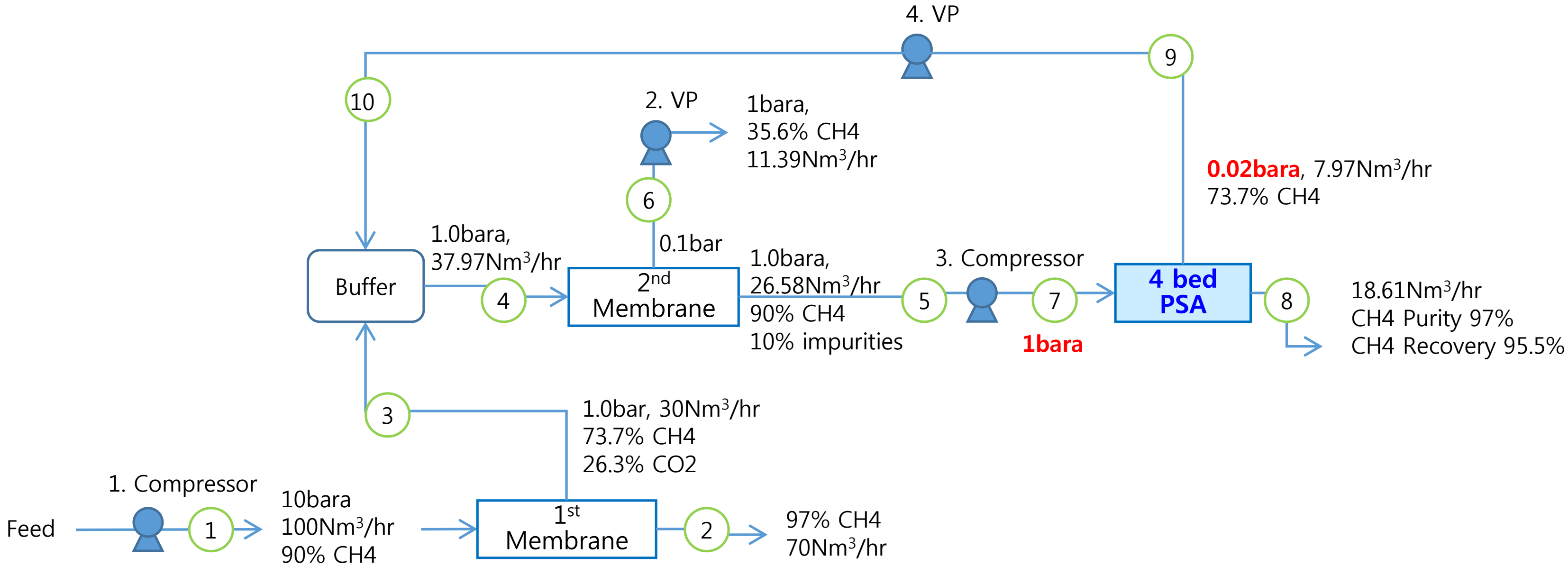
A2. Operation step of four bed PSA process

A3. Definition of cyclic steady state (CSS)

A4. PSA optimisation approach at CSS

A1. Candidate processes for conceptual design study

CD1.1: Hybrid Membrane & PSA(Zeolite) (Feed 100Lube/hr) w/ recycle

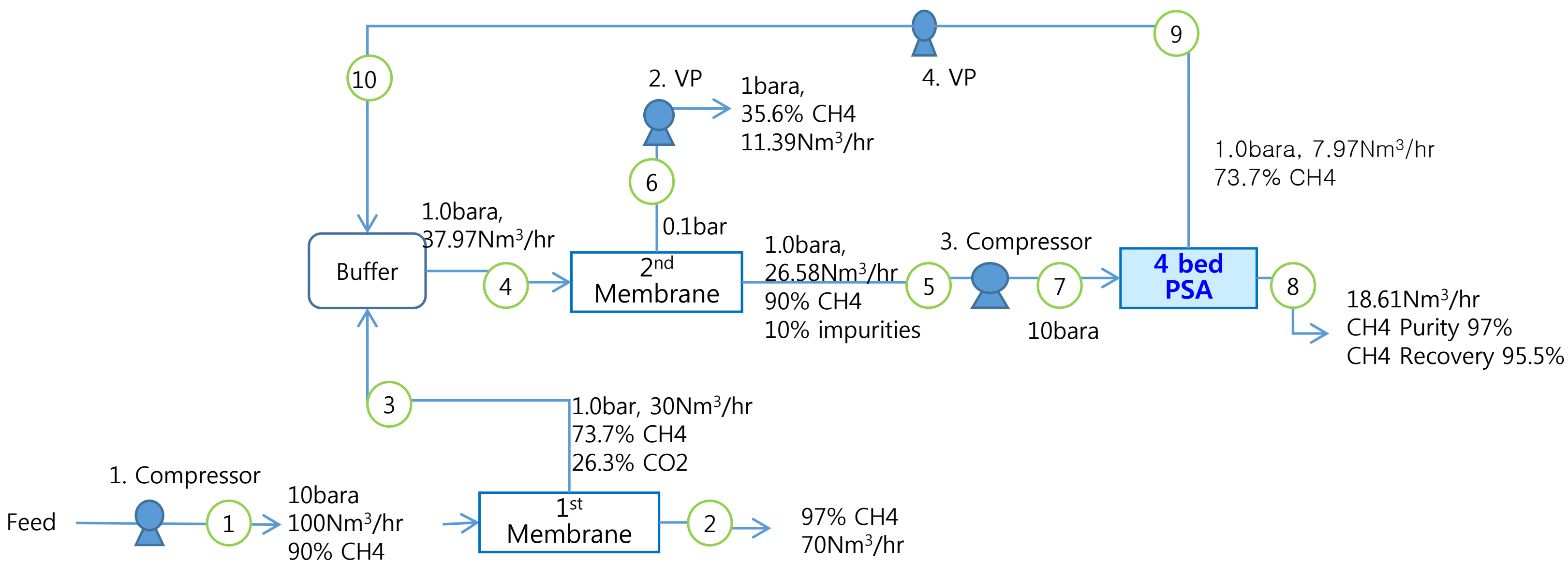


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Mem. 1	**Feed**	1	10	25	100.00	90.00	10.00
Mem. 1	**Retentate**	2	10	25	68.57	97.00	3.00
Mem. 1	**Permeate**	3	1	25	31.43	73.67	26.33
Mem. 2	**Feed***	4	1	25	39.39	73.67	26.33
Mem. 2	**Retentate**	5	1	25	26.56	90.00	10.00
Mem. 2	**Permeate**	6	0.1	25	12.83	35.56	64.44
PSA	**Feed**	7	1	25	26.56	90.00	10.00
PSA	**Product**	8	1	25	18.60	97.00	3.00
PSA	**Purge**	9	0.02	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.49
2	12.83	1.28
3	26.56	0.00
4	7.96	1.64
Total Power [kW]		**12.41**
Total Power per product flow rate [kW/(Nm3/hr)]		**0.14**

A1. Candidate processes for conceptual design study

CD1.2: Hybrid Membrane & PSA(CMS) (Feed 100Lube/hr) w/ recycle

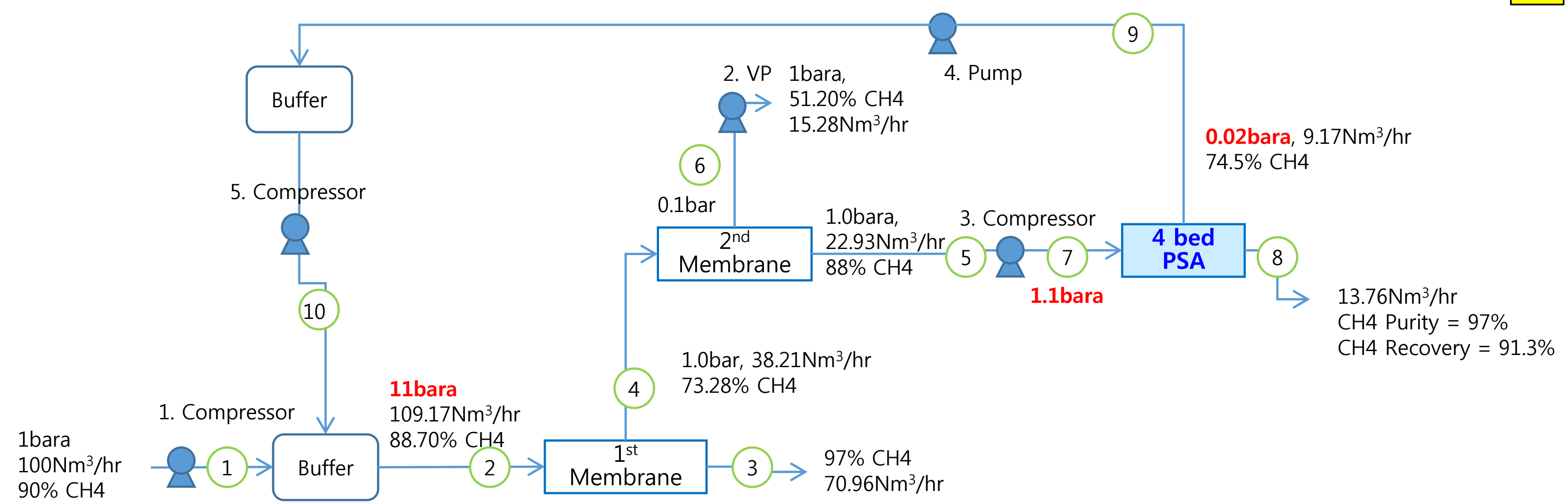


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Mem. 1	Feed	1	10	25	100.00	90.00	10.00
Mem. 1	Retentate	2	10	25	68.57	97.00	3.00
Mem. 1	Permeate	3	1	25	31.43	73.67	26.33
Mem. 2	Feed*	4	1	25	39.39	73.67	26.33
Mem. 2	Retentate	5	1	25	26.56	90.00	10.00
Mem. 2	Permeate	6	0.1	25	12.83	35.56	64.44
PSA	Feed	7	10	25	26.56	90.00	10.00
PSA	Product	8	1	25	18.60	97.00	3.00
PSA	Purge	9	1	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.49
2	12.83	1.28
3	26.56	2.95
4	7.96	0.00
Total Power [kW]		13.72
Total Power per product flow rate [kW/(Nm3/hr)]		0.16

A1. Candidate processes for conceptual design study

CD2.1: Hybrid Membrane & PSA (Zeolite) (Feed 100Lube/hr) w/ recycle

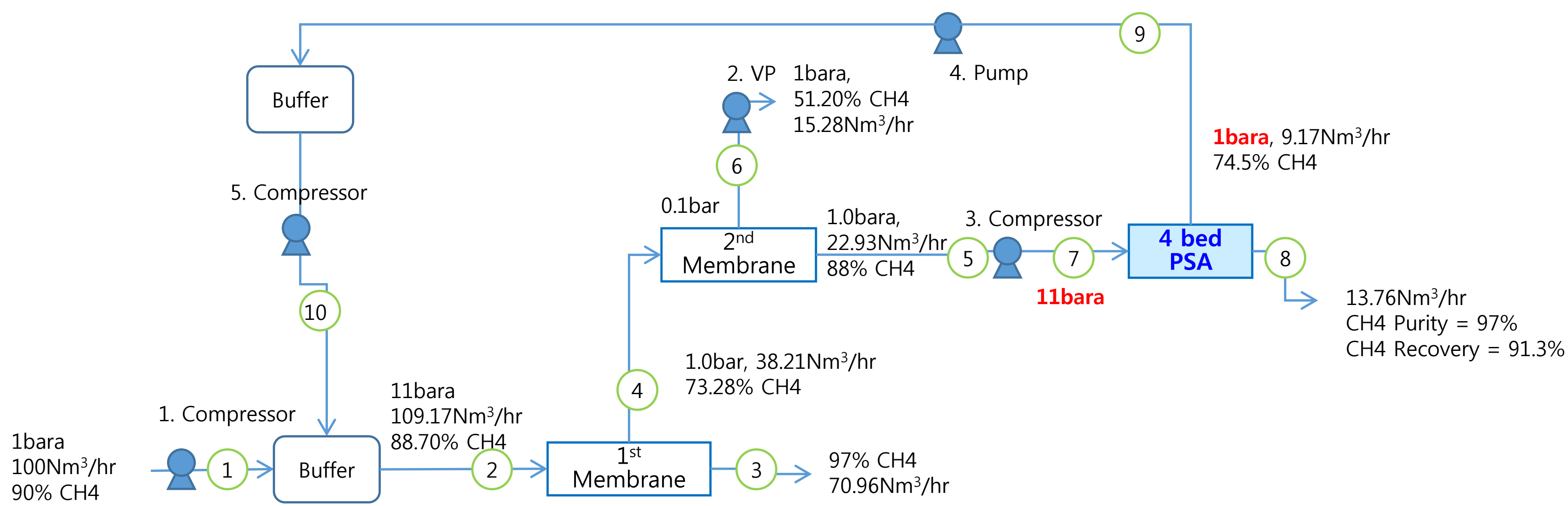


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Feed	**Feed**	**1**	**1**	**25**	**100.00**	**90.00**	**10.00**
Mem. 1	**Feed**	**2**	**11**	**25**	**106.43**	**88.70**	**11.30**
Mem. 1	**Retentate**	**3**	**11**	**25**	**69.34**	**97.00**	**3.00**
Mem. 1	**Permeate**	**4**	**1**	**25**	**37.09**	**73.28**	**26.72**
Mem. 2	**Feed***	**4**	**1**	**25**	**37.09**	**73.28**	**26.72**
Mem. 2	**Retentate**	**5**	**1**	**25**	**22.90**	**88.00**	**12.00**
Mem. 2	**Permeate**	**6**	**0.1**	**25**	**14.19**	**51.20**	**48.80**
PSA	**Feed**	**7**	**1.1**	**25**	**22.90**	**88.00**	**12.00**
PSA	**Product**	**8**	**1**	**25**	**16.47**	**97.00**	**3.00**
PSA	**Purge**	**9**	**0.02**	**25**	**6.43**	**74.50**	**25.50**
	Recycled	**10**	**10**	**25**	**6.43**	**74.50**	**25.50**

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	**kW**
1	**100.00**	**9.92**
2	**14.19**	**1.72**
3	**22.90**	**0.08**
4	**6.43**	**3.34**
5	**6.43**	**0**
Total Power [kW]		**15.06**
Total Power per product flow rate [kW/(Nm3/hr)]		**0.18**

A1. Candidate processes for conceptual design study

CD2.2: Hybrid Membrane & PSA (CMS) (Feed 100Lube/hr) w/ recycle

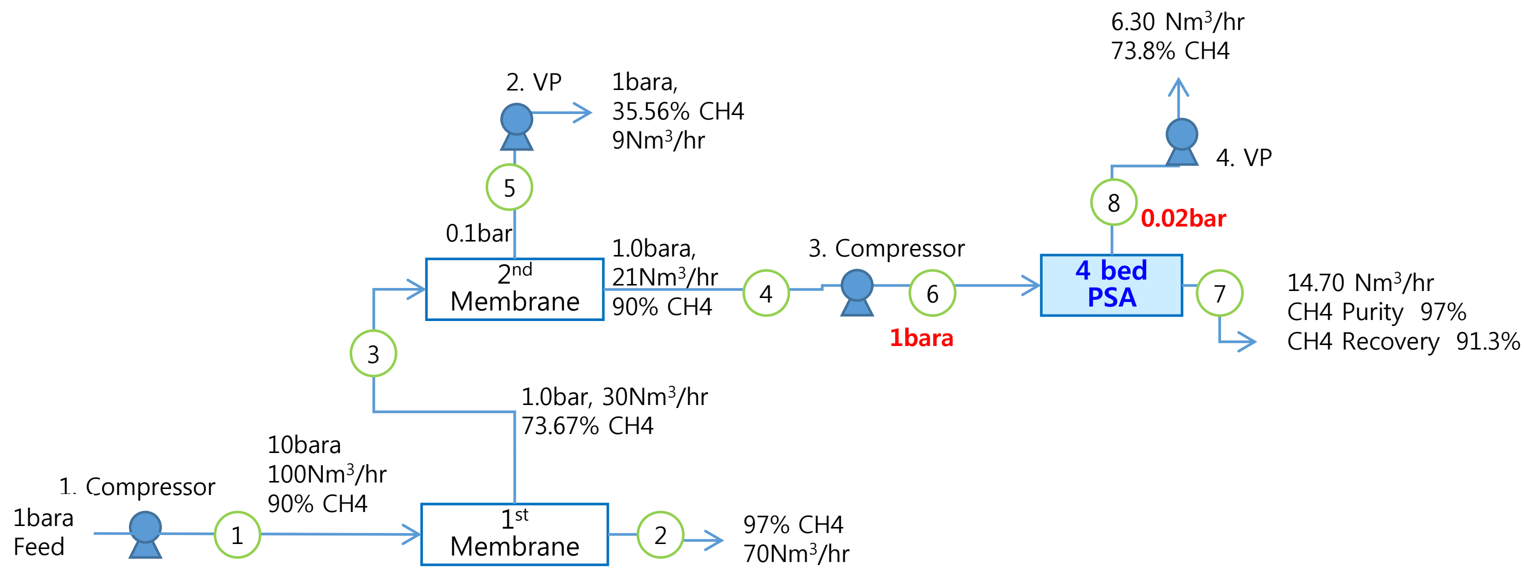


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Feed	Feed	1	1	25	100.00	90.00	10.00
Mem. 1	Feed	2	11	25	106.43	88.70	11.30
Mem. 1	Retentate	3	11	25	69.34	97.00	3.00
Mem. 1	Permeate	4	1	25	37.09	73.28	26.72
Mem. 2	Feed*	4	1	25	37.09	73.28	26.72
Mem. 2	Retentate	5	1	25	22.90	88.00	12.00
Mem. 2	Permeate	6	0.1	25	14.19	51.20	48.80
PSA	Feed	7	11	25	22.90	88.00	12.00
PSA	Product	8	1	25	16.47	97.00	3.00
PSA	Purge	9	1	25	6.43	74.50	25.50
	Recycled	10	11	25	6.43	74.50	25.50

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.92
2	14.19	1.72
3	22.90	2.73
4	6.43	0.94
5	6.43	0
Total Power [kW]		16.41
Total Power per product flow rate [kW/(Nm3/hr)]		0.19

A1. Candidate processes for conceptual design study

CD3.1: Hybrid Membrane & PSA (Zeolite) (Feed 100Lube/hr) w/o recycle

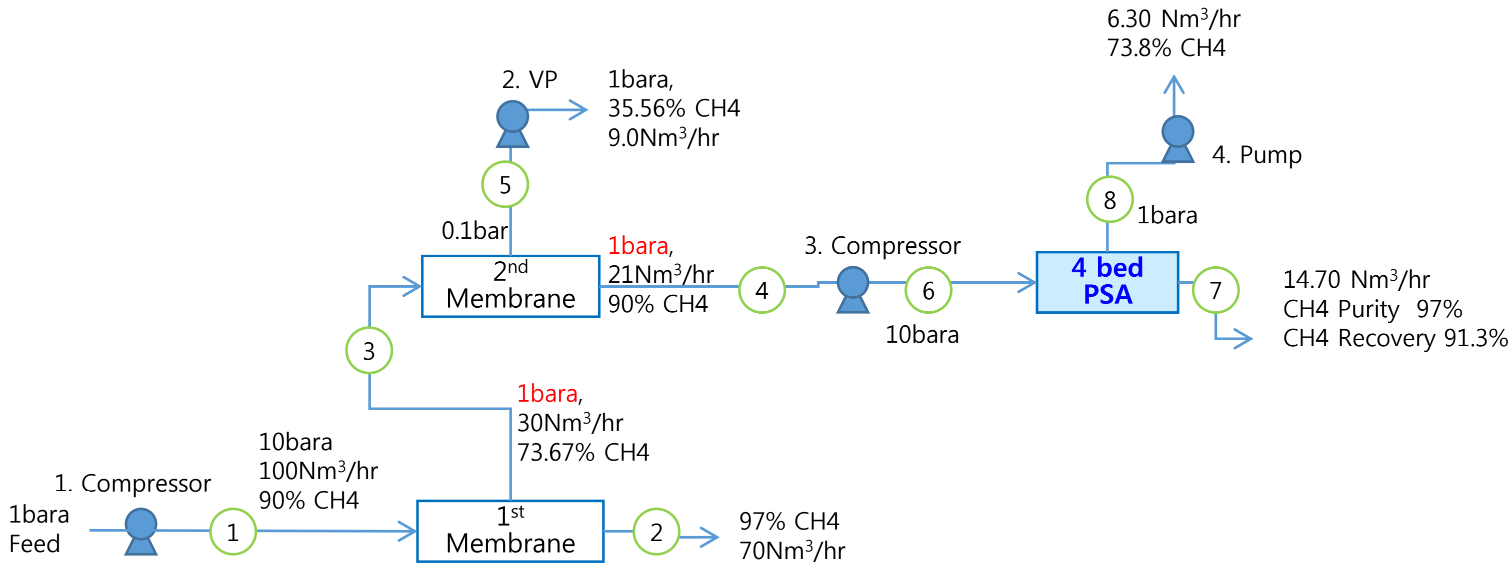


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Mem. 1	Feed	1	10	25	100.00	90.00	10.00
Mem. 1	Retentate	2	10	25	68.57	97.00	3.00
Mem. 1	Permeate	3	1	25	31.43	73.67	26.33
Mem. 2	Feed*	3	1	25	31.43	73.67	26.33
Mem. 2	Retentate	4	1	25	20.99	90.00	10.00
Mem. 2	Permeate	5	0.1	25	10.44	35.56	64.44
PSA	Feed	6	1	25	20.99	90.00	10.00
PSA	Product	7	1	25	14.70	97.00	3.00
PSA	Purge	8	0.02	25	6.29	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.94
2	10.44	1.01
3	20.99	0.00
4	6.29	1.17
Total Power [kW]		12.12
Total Power per product flow rate [kW/(Nm3/hr)]		0.18

A1. Candidate processes for conceptual design study

CD3.2: Hybrid Membrane & PSA (CMS) (Feed 100Lube/hr) w/o recycle

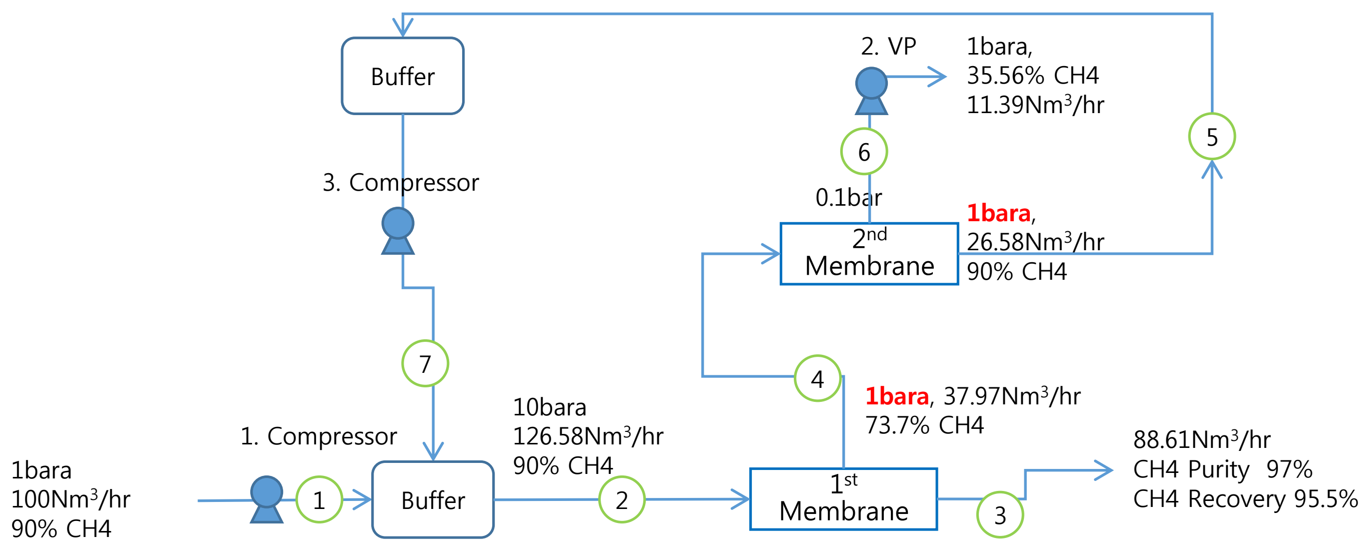


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Mem. 1	Feed	1	10	25	100.00	90.00	10.00
Mem. 1	Retentate	2	10	25	68.57	97.00	3.00
Mem. 1	Permeate	3	1	25	31.43	73.67	26.33
Mem. 2	Feed*	3	1	25	31.43	73.67	26.33
Mem. 2	Retentate	4	1	25	20.99	90.00	10.00
Mem. 2	Permeate	5	0.1	25	10.44	35.56	64.44
PSA	Feed	6	10	25	20.99	90.00	10.00
PSA	Product	7	1	25	14.70	97.00	3.00
PSA	Purge	8	1	25	6.29	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.94
2	10.44	1.01
3	20.99	2.09
4	6.29	0
Total Power [kW]		13.04
Total Power per product flow rate [kW/(Nm3/hr)]		0.19

A1. Candidate processes for conceptual design study

CD4: Membrane System Only (Feed 100Lube/hr)

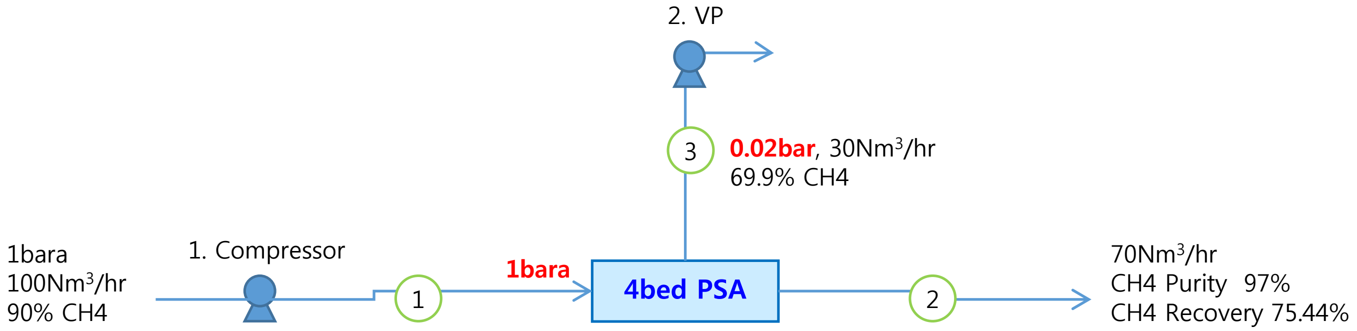


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
Feed	Feed	1	1	25	100.00	90.00	10.00
Mem. 1	Feed	2	10	25	126.56	90.00	10.00
Mem. 1	Retentate	3	10	25	86.79	97.00	3.00
Mem. 1	Permeate	4	1	25	39.77	73.67	26.33
Mem. 2	Feed*	4	1	25	39.77	73.67	26.33
Mem. 2	Retentate	5	1	25	26.56	90.00	10.00
Mem. 2	Permeate	6	0.1	25	13.21	35.56	64.44
	Recycled	7	10	25	26.56	90.00	10.00

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.94
2	13.21	1.28
3	26.56	2.64
Total Power [kW]		13.86
Total Power per product flow rate [kW/(Nm3/hr)]		0.16

A1. Candidate processes for conceptual design study

CD5.1: VSA System Only (Feed 100Lube/hr) (Zeolite)

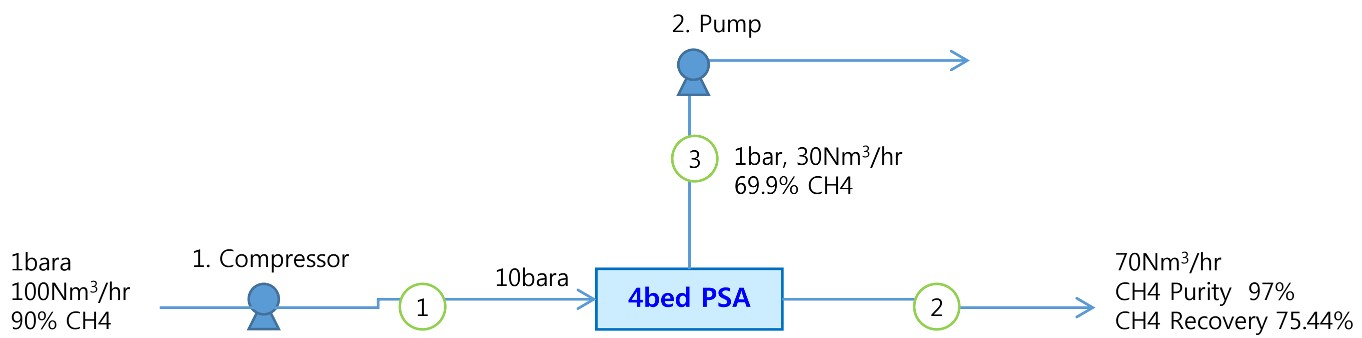


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA	**Feed**	**1**	**1**	**25**	**100.00**	**90.00**	**10.00**
PSA	**Product**	**2**	**1**	**25**	**70.00**	**97.00**	**3.00**
PSA	**Purge**	**3**	**0.02**	**25**	**30.00**	**73.67**	**26.33**

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	0.00
2	30.00	5.55
Total Power [kW]		5.55
Total Power per product flow rate [kW/(Nm3/hr)]		0.08

A1. Candidate processes for conceptual design study

CD5.2: PSA System Only (Feed 100Lube/hr) (CMS)

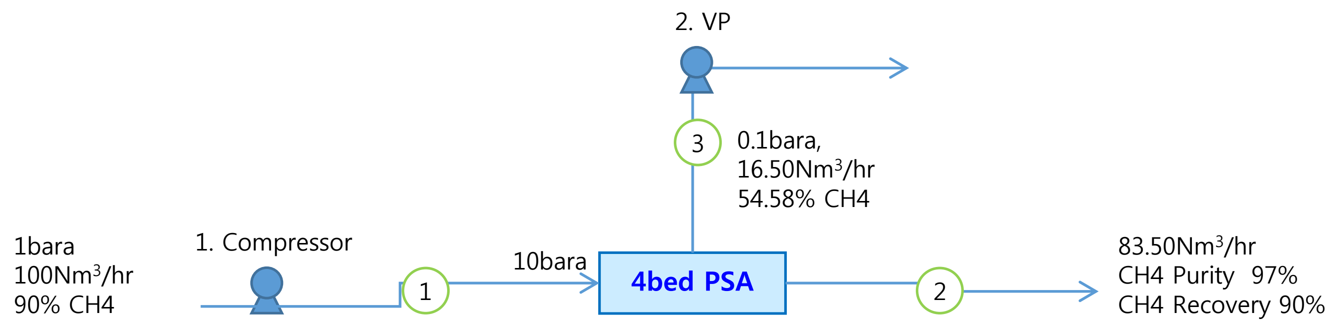


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA	**Feed**	**1**	**10**	**25**	**100.00**	**90.00**	**10.00**
PSA	**Product**	**2**	**1**	**25**	**70.00**	**97.00**	**3.00**
PSA	**Purge**	**3**	**1**	**25**	**30.00**	**73.67**	**26.33**

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.94
2	30.00	0.00
Total Power [kW]		9.94
Total Power per product flow rate [kW/(Nm3/hr)]		0.14

A1. Candidate processes for conceptual design study

CD5.3: VPSA System Only (Feed 100Nm3/hr): CMS, 0.1bar desorption & 10bar adsorption

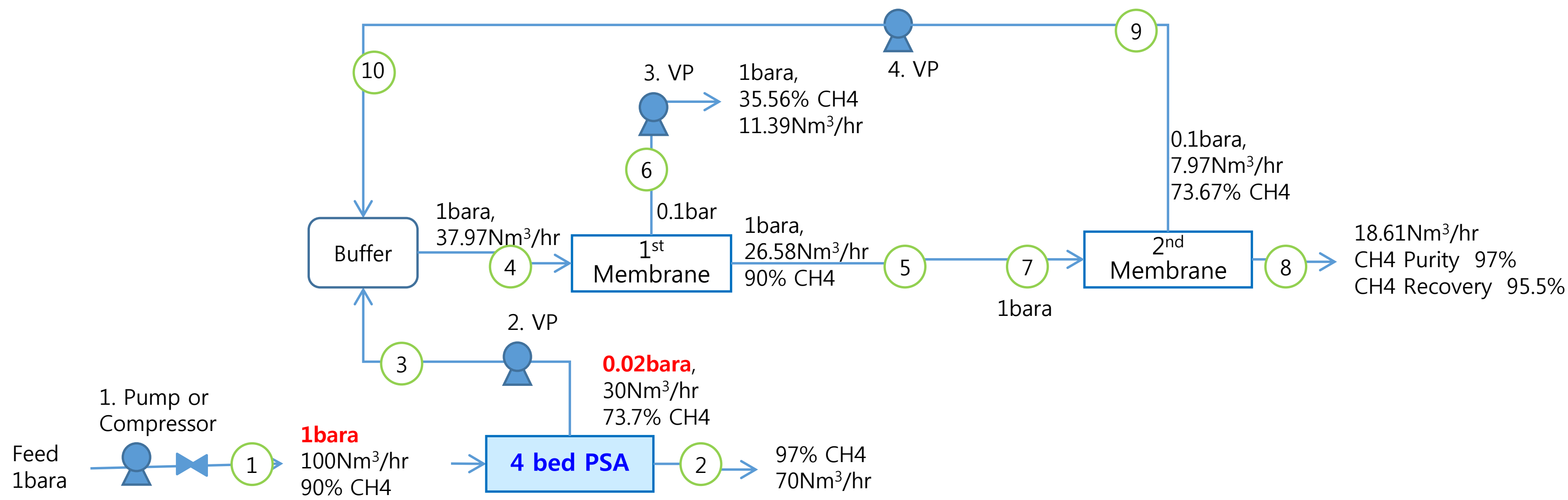


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA	Feed	1	10	25	100.00	90.00	10.00
PSA	Product	2	1	25	83.50	97.00	3.00
PSA	Purge	3	0.1	25	16.50	54.58	45.42

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.94
2	16.50	1.64
Total Power [kW]		11.58
Total Power per product flow rate [kW/(Nm3/hr)]		0.14

A1. Candidate processes for conceptual design study

CD6.1: Hybrid VSA(Zeolite) & Membrane (Feed 100Lube/hr) w/ recycle

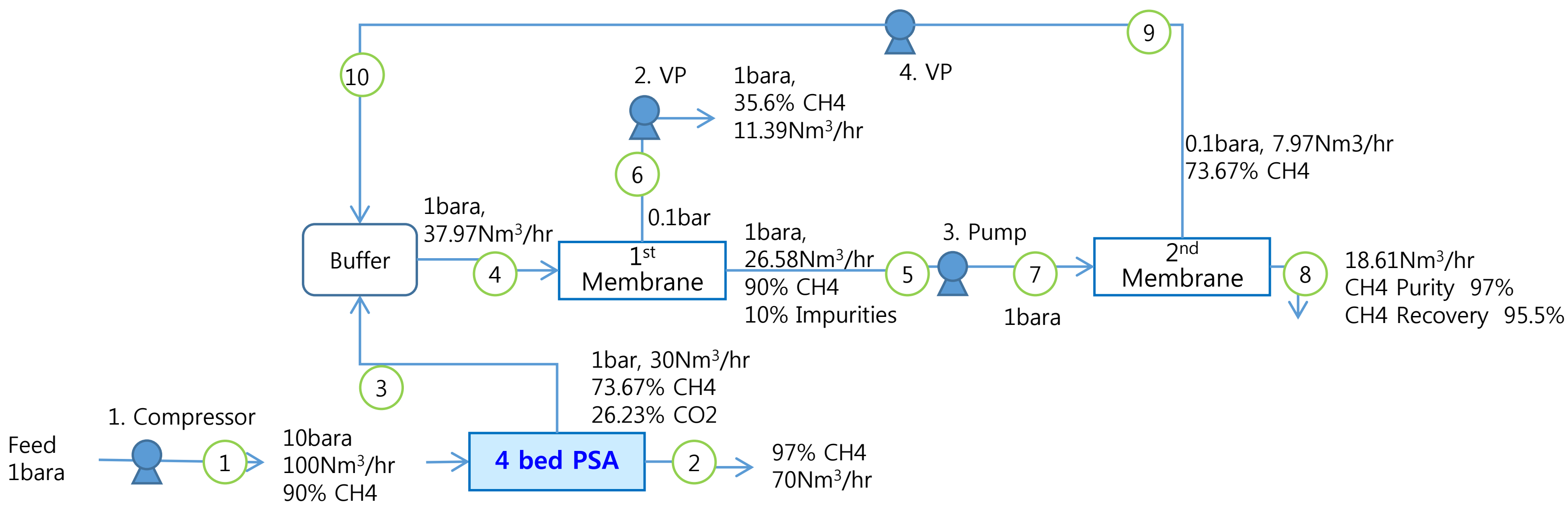


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA	**Feed**	1	1	25	100.00	90.00	10.00
PSA	**Product**	2	1	25	69.92	97.00	3.00
PSA	**Purge**	3	0.02	25	30.08	73.67	26.33
Mem. 1	**Feed***	4	1	25	38.04	73.67	26.33
Mem. 1	**Retentate**	5	1	25	26.56	90.00	10.00
Mem. 1	**Permeate**	6	0.1	25	11.48	35.56	64.44
Mem. 2	**Feed**	7	1	25	26.56	90.00	10.00
Mem. 2	**Retentate**	8	1	25	18.60	97.00	3.00
Mem. 2	**Permeate**	9	0.1	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate (Nm3/hr)	Power (kW)
1	100.00	0
2	30.08	5.55
3	11.48	1.28
4	7.96	0.79
Total Power [kW]		7.62
Total Power per product flow rate [kW/(Nm3/hr)]		0.09

A1. Candidate processes for conceptual design study

CD6.2: Hybrid PSA(CMS) & Membrane (Feed 100Lube/hr) w/ recycle

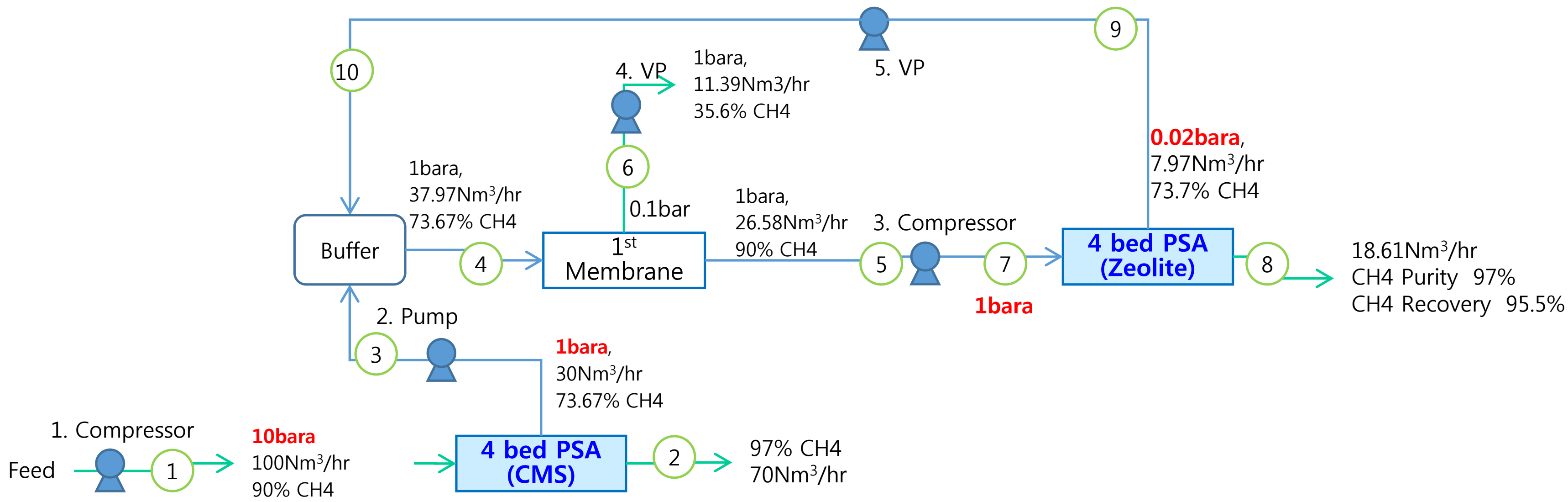


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA	**Feed**	1	10	25	100.00	90.00	10.00
PSA	**Product**	2	1	25	69.92	97.00	3.00
PSA	**Purge**	3	1	25	30.08	73.67	26.33
Mem. 1	**Feed***	4	1	25	38.04	73.67	26.33
Mem. 1	**Retentate**	5	1	25	26.56	90.00	10.00
Mem. 1	**Permeate**	6	0.1	25	11.48	35.56	64.44
Mem. 2	**Feed**	7	1	25	26.56	90.00	10.00
Mem. 2	**Retentate**	8	1	25	18.60	97.00	3.00
Mem. 2	**Permeate**	9	0.1	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate (Nm3/hr)	Power (kW)
1	100.00	9.94
2	11.48	1.28
3	26.56	0
4	7.96	0.79
Total Power [kW]		12.01
Total Power per product flow rate [kW/(Nm3/hr)]		0.14

A1. Candidate processes for conceptual design study

CD7.1. Hybrid VPSA(CMS/Zeolite) & Membrane (Feed 100Lube/hr) w/ recycle

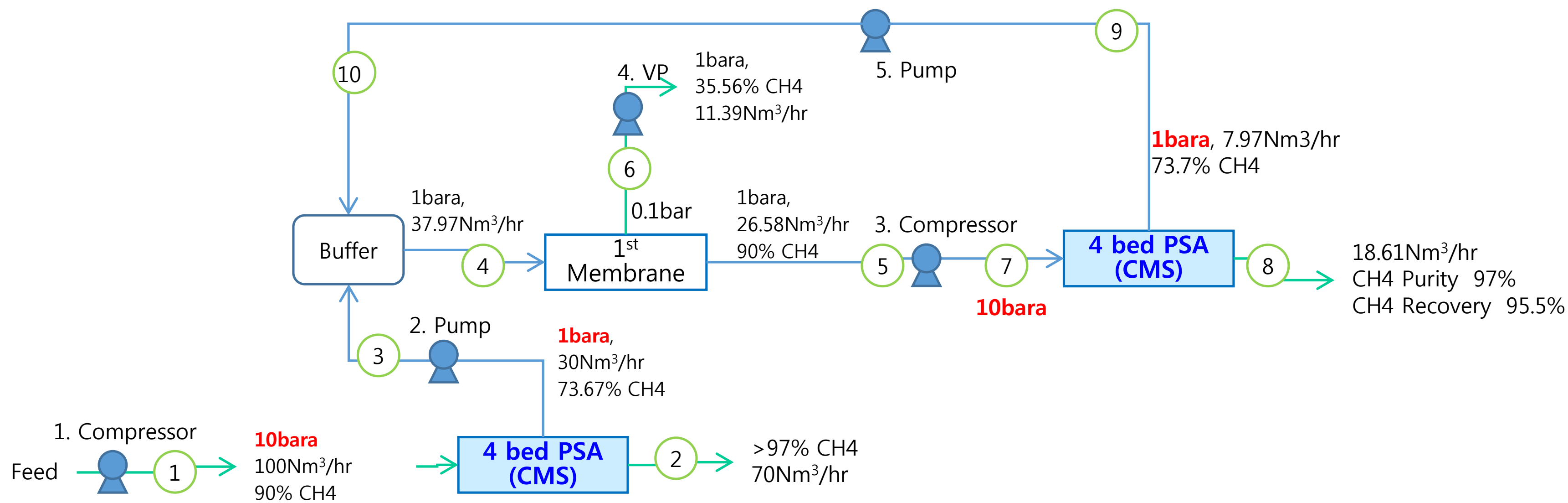


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA 1	Feed	1	10	25	100.00	90.00	10.00
PSA 1	Product	2	1	25	68.57	97.00	3.00
PSA 1	Purge	3	1	25	31.43	73.67	26.33
Mem. 1	Feed*	4	1	25	39.39	73.67	26.33
Mem. 1	Retentate	5	1	25	26.57	90.00	10.00
Mem. 1	Permeate	6	0.1	25	12.82	35.56	64.44
PSA 2	Feed	7	1	25	26.57	90.00	10.00
PSA 2	Product	8	1	25	18.61	97.00	3.00
PSA 2	Purge	9	0.02	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.93
2	31.43	0.00
3	26.57	0.00
4	12.82	1.28
5	7.96	1.48
Total Power [kW]		12.69
Total Power per product flow rate [kW/(Nm3/hr)]		0.15

A1. Candidate processes for conceptual design study

CD7.2. Hybrid PSA(CMS) & Membrane (Feed 100Lube/hr) w/ recycle

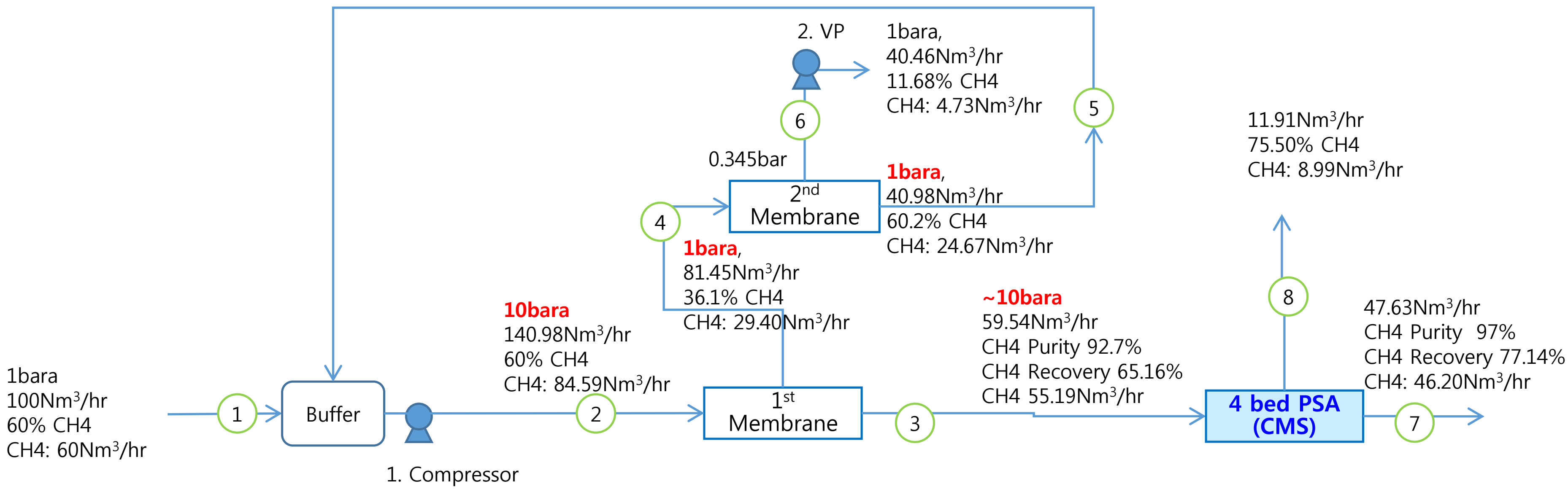


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
PSA 1	**Feed**	1	10	25	100.00	90.00	10.00
PSA 1	**Product**	2	1	25	68.57	97.00	3.00
PSA 1	**Purge**	3	1	25	31.43	73.67	26.33
Mem. 1	**Feed***	4	1	25	39.39	73.67	26.33
Mem. 1	**Retentate**	5	1	25	26.57	90.00	10.00
Mem. 1	**Permeate**	6	0.1	25	12.82	35.56	64.44
PSA 2	**Feed**	7	10	25	26.57	90.00	10.00
PSA 2	**Product**	8	1	25	18.61	97.00	3.00
PSA 2	**Purge**	9	1	25	7.96	73.67	26.33
	Recycled	10	1	25	7.96	73.67	26.33

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
	Nm3/hr	kW
1	100.00	9.93
2	31.43	0.00
3	26.57	2.64
4	12.82	1.28
5	7.96	0
Total Power [kW]		13.85
Total Power per product flow rate [kW/(Nm3/hr)]		0.16

A1. Candidate processes for conceptual design study

CD8.1: Hybrid PSA & Membrane with Recycle (Feed 100Lube/hr)
(when low CH4 composition in feed gas)

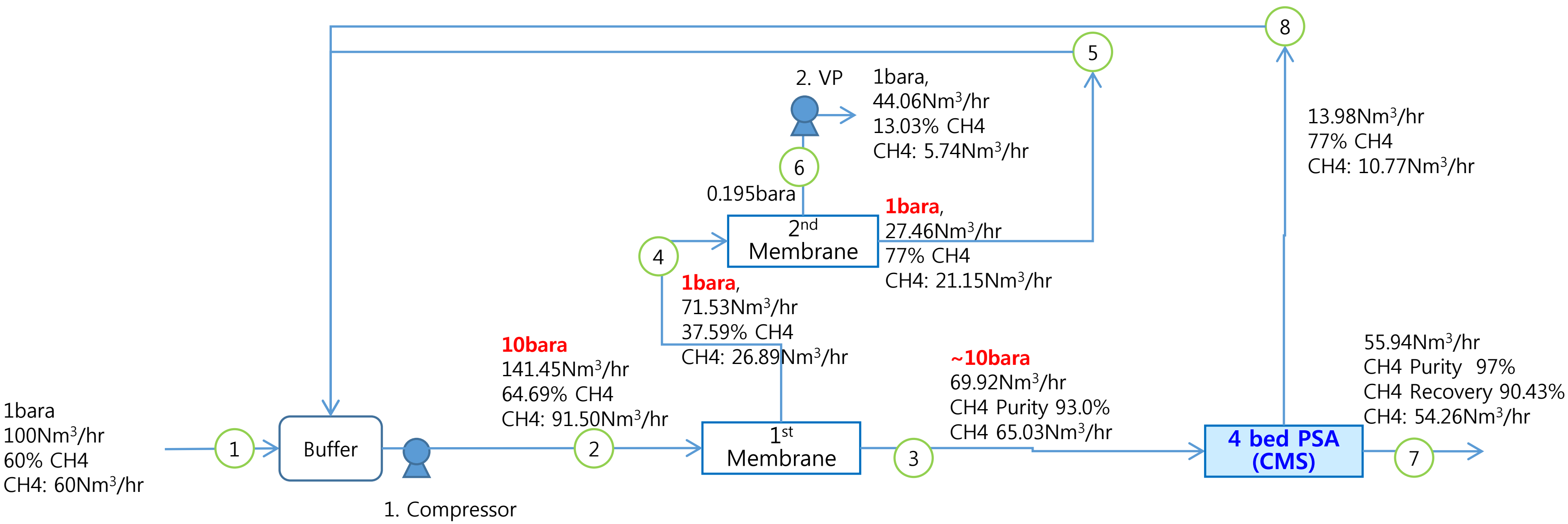


	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
	Feed	1	1	25	100.00	60.00	40.00
Mem. 1	Feed w/Recycle	2	10	25	140.92	60.00	40.00
Mem. 1	Retentate	3	10	25	58.38	92.70	7.30
Mem. 1	Permeate	4	1	25	82.54	36.10	63.90
Mem. 2	Feed	4	1	25	85.54	36.10	63.90
Mem. 2	Retentate	5	1	25	40.95	60.20	39.80
Mem. 2	Permeate	6	0.345	25	44.59	11.68	88.32
PSA	Feed	3	10	25	58.38	92.70	7.30
PSA	Product	7	1	25	47.63	97.00	3.00
PSA	Purge	8	1	25	10.75	75.50	24.50

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
1	140.92	13.97
2	44.59	1.84
Total Power [kW]		15.81
Total Power per product flow rate [kW/(Nm3/hr)]		0.33

A1. Candidate processes for conceptual design study

CD8.2: Hybrid PSA & Membrane with Recycle (Feed 100Lube/hr)
(when low CH4 composition in feed gas)



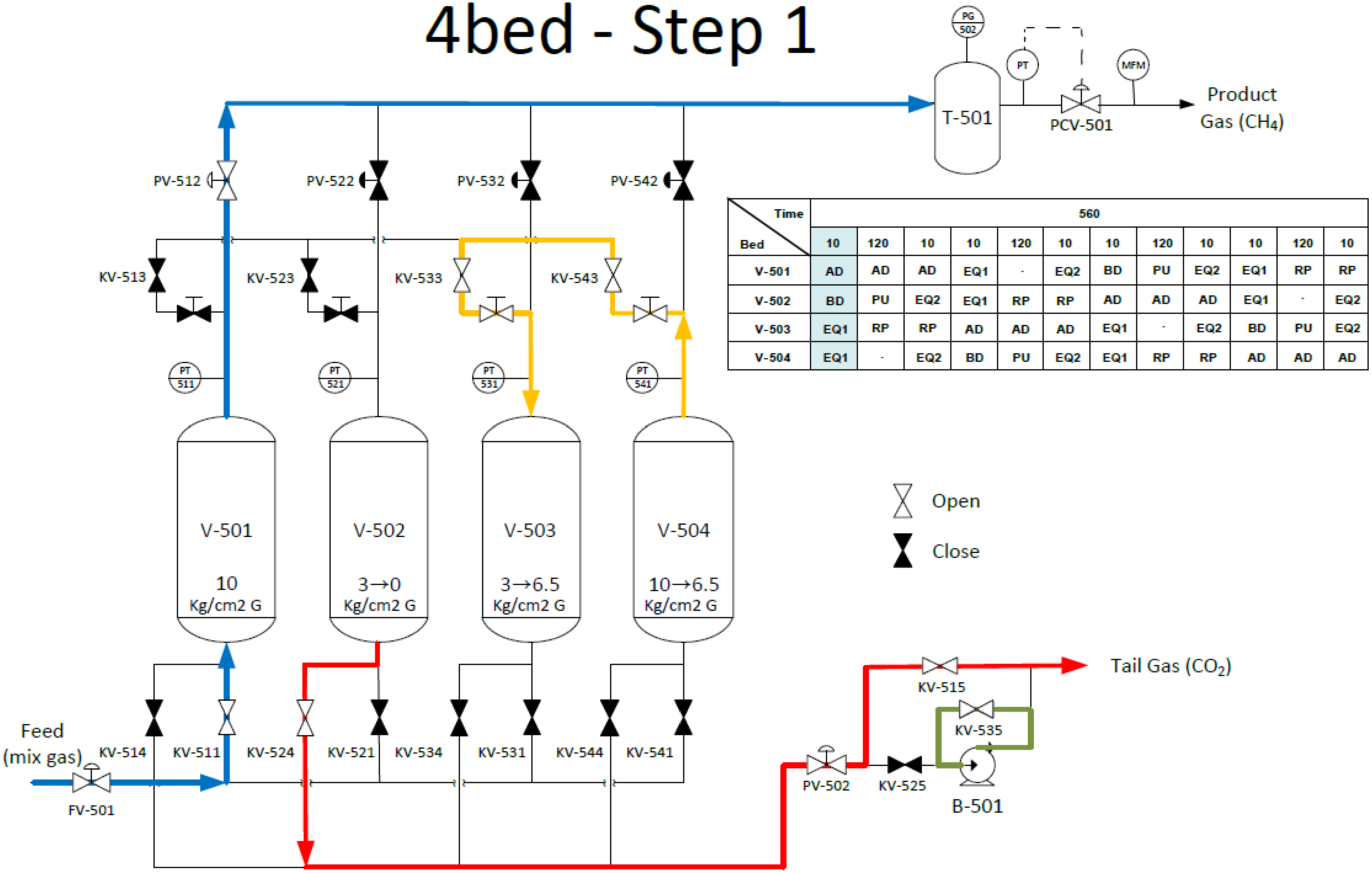
	Stream	Stream #	Pressure (bara)	Temperature (°C)	Flow rate (Nm3/h)	CH4 Conc. (mol.%)	CO2 Conc. (mol.%)
	Feed	1	1	25	100.00	60.00	40.00
Mem. 1	Feed w/Recycle	2	10	25	137.24	64.98	35.02
Mem. 1	Retentate	3	10	25	68.53	93.00	7.00
Mem. 1	Permeate	4	1	25	68.71	37.59	62.41
Mem. 2	Feed	4	1	25	68.71	37.59	62.41
Mem. 2	Retentate	5	1	25	27.17	77.00	23.00
Mem. 2	Permeate	6	0.195	25	41.54	13.03	86.97
PSA	Feed	3	10	25	68.53	93.00	7.00
PSA	Product	7	1	25	58.46	97.00	3.00
PSA	Purge	8	1	25	10.07	77.00	23.00

Power Unit	Flow Rate [Nm3/hr]	Power [kW]
1	137.24	13.99
2	41.54	3.27
Total Power [kW]		17.26
Total Power per product flow rate [kW/(Nm3/hr)]		0.3

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 1

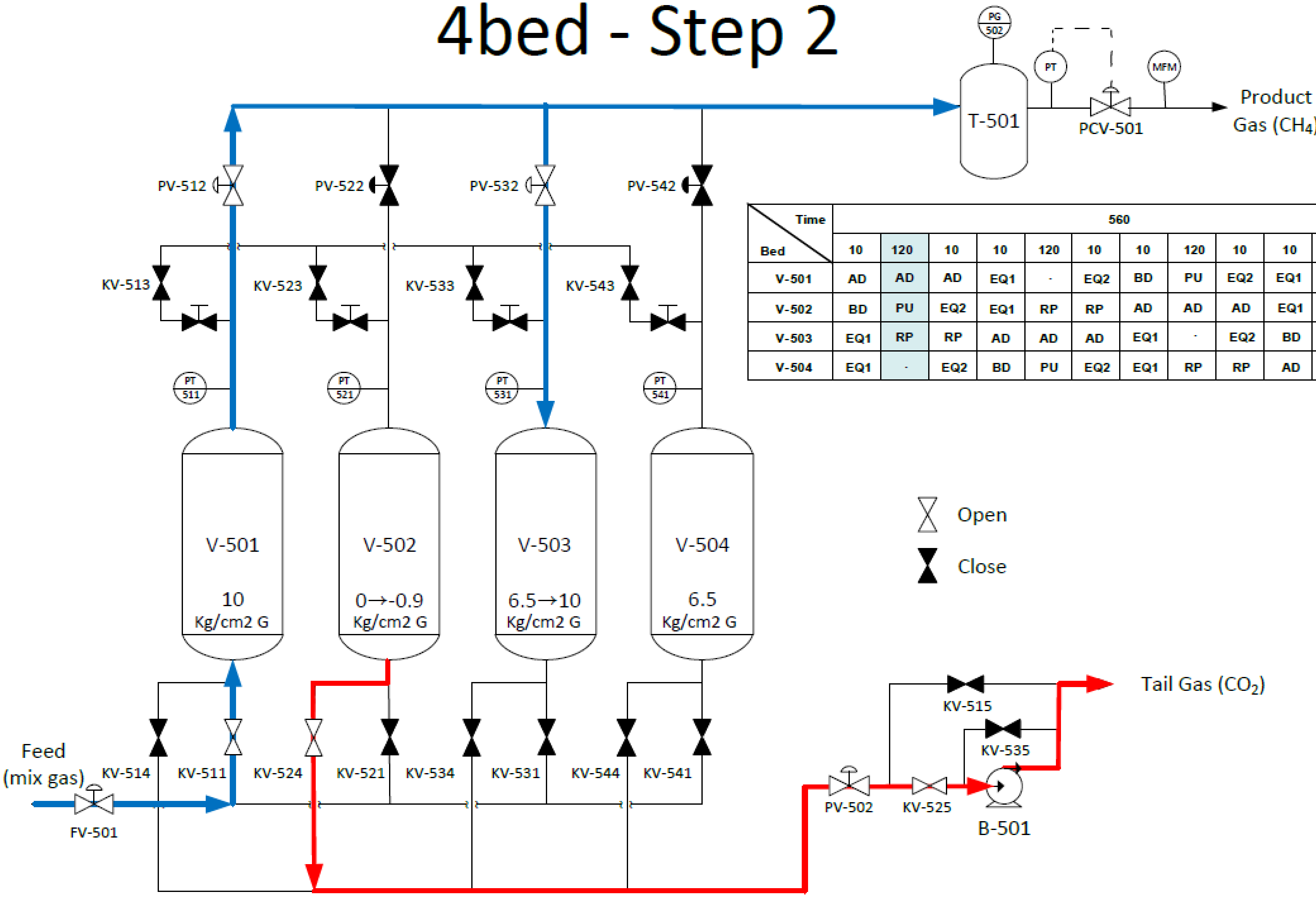


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 2

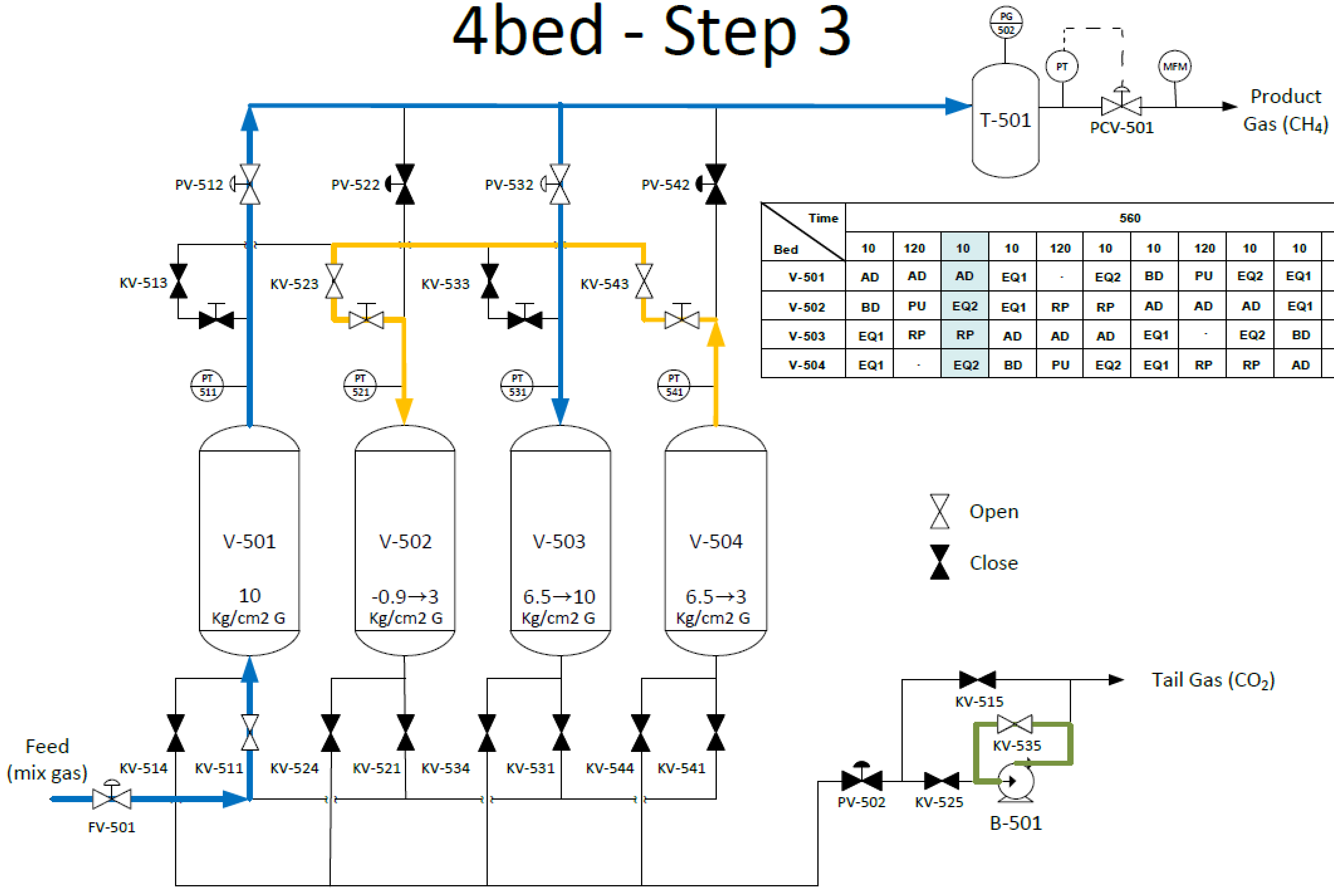


Time / Bed	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 3

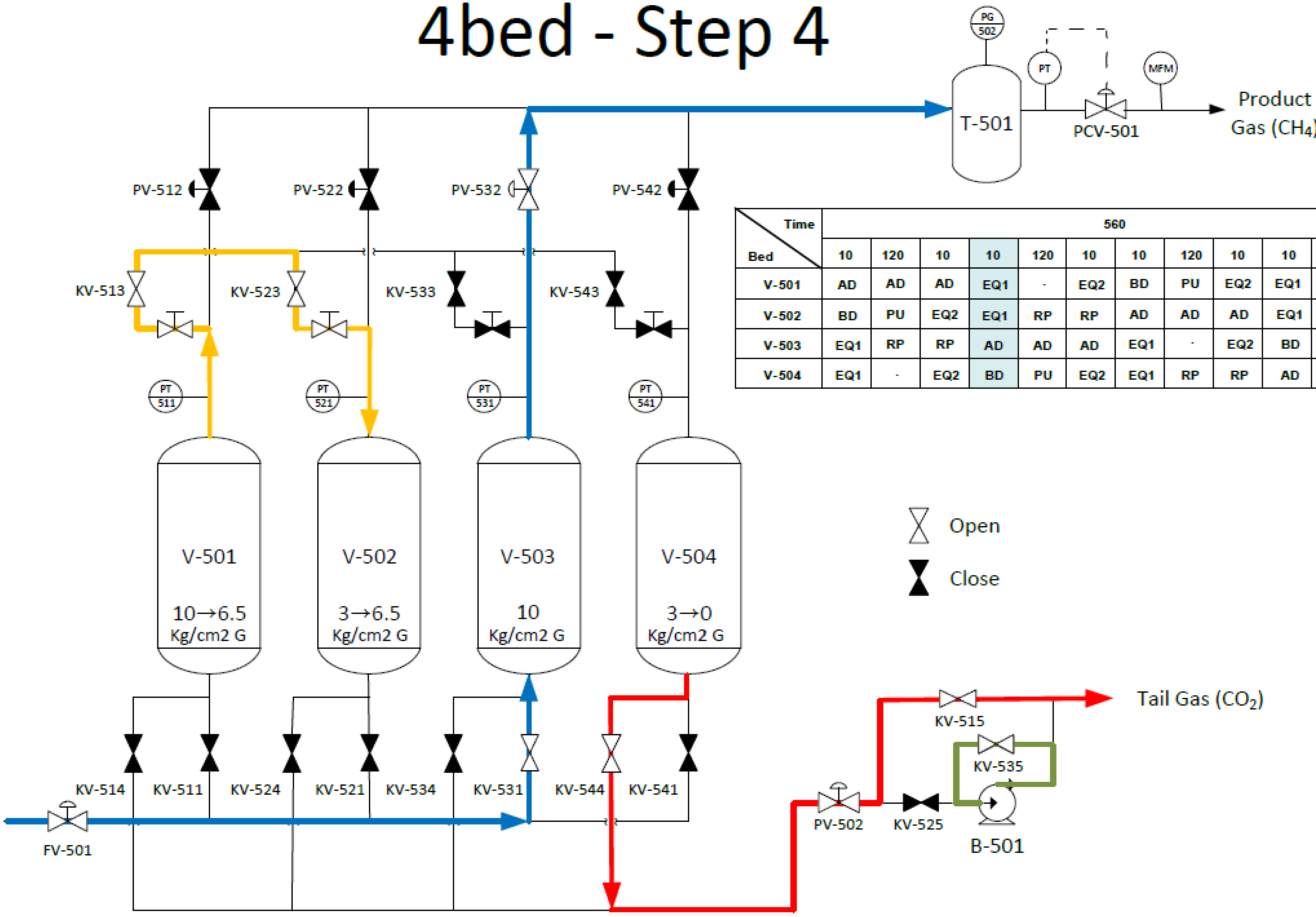


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 4

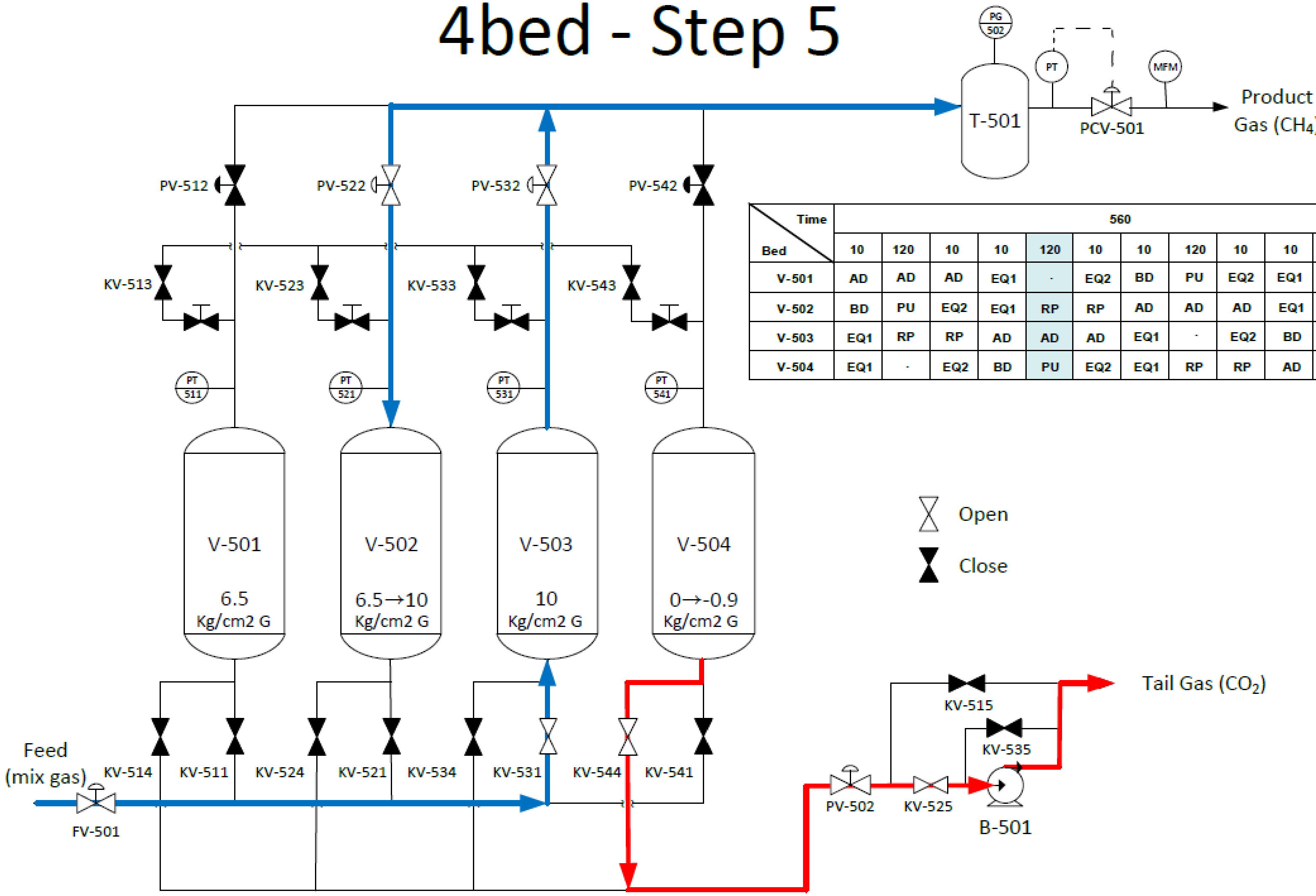


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 5

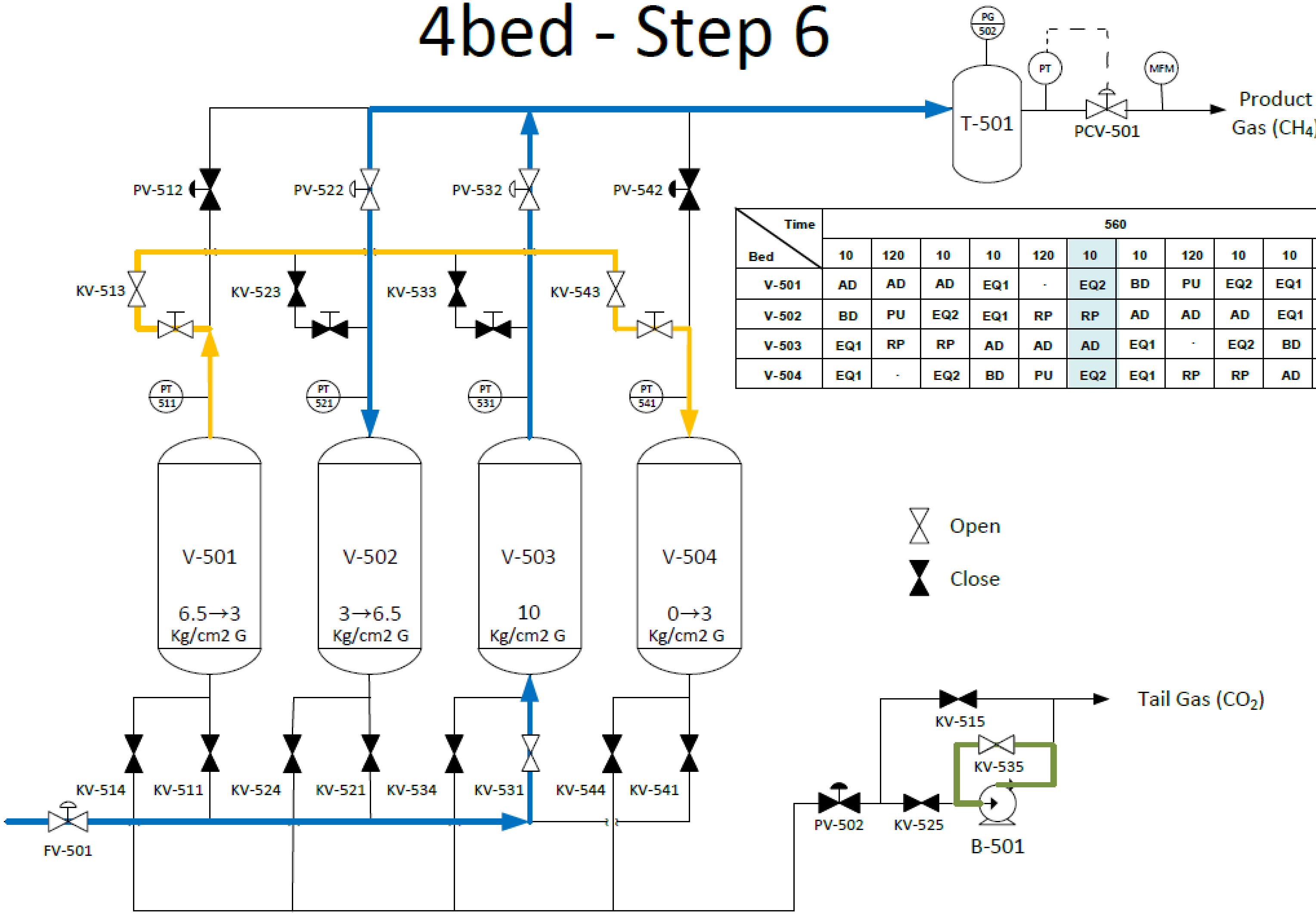


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

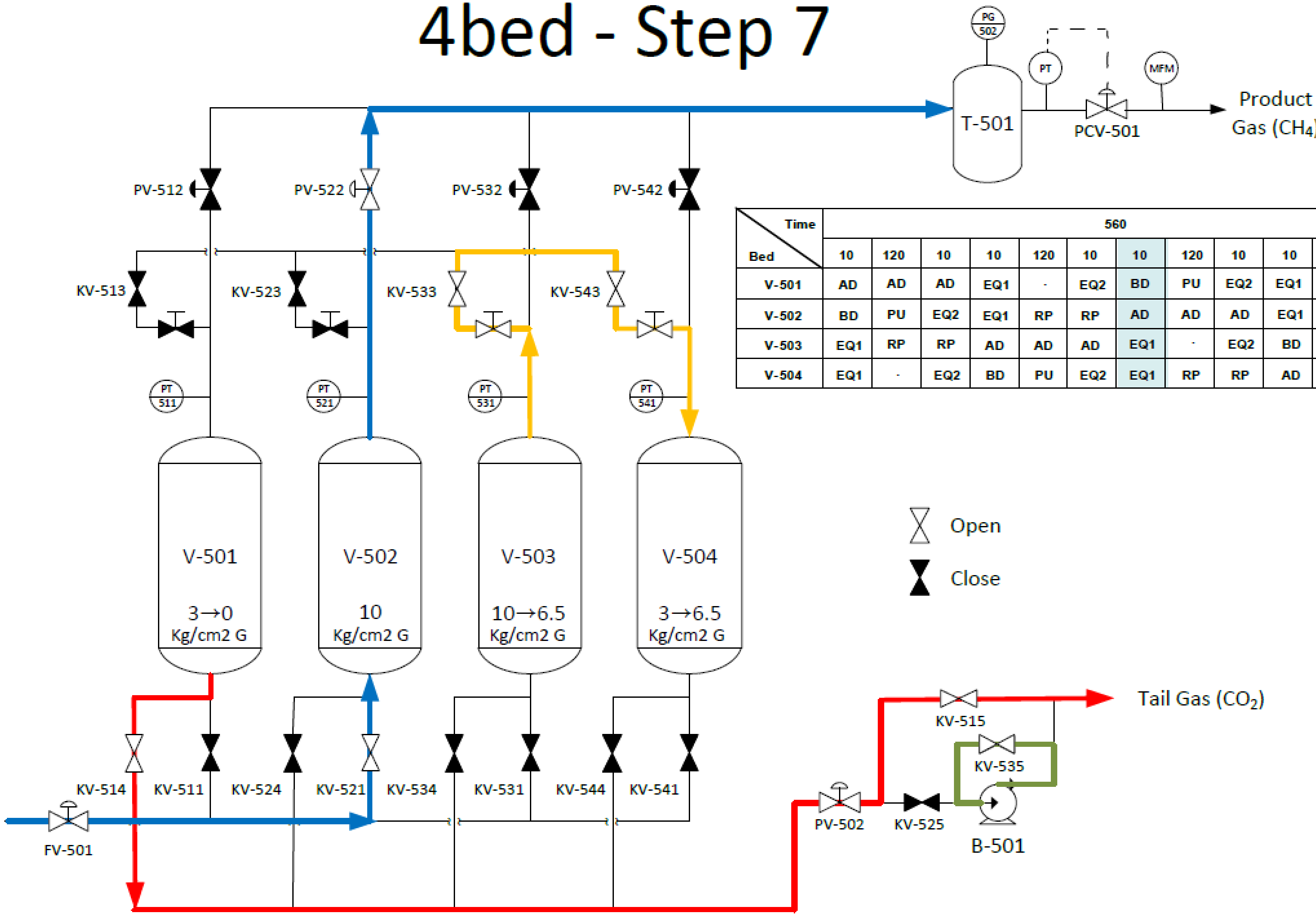
4bed - Step 6



Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

Four Bed Twelve Operating Step PSA Process

4bed - Step 7

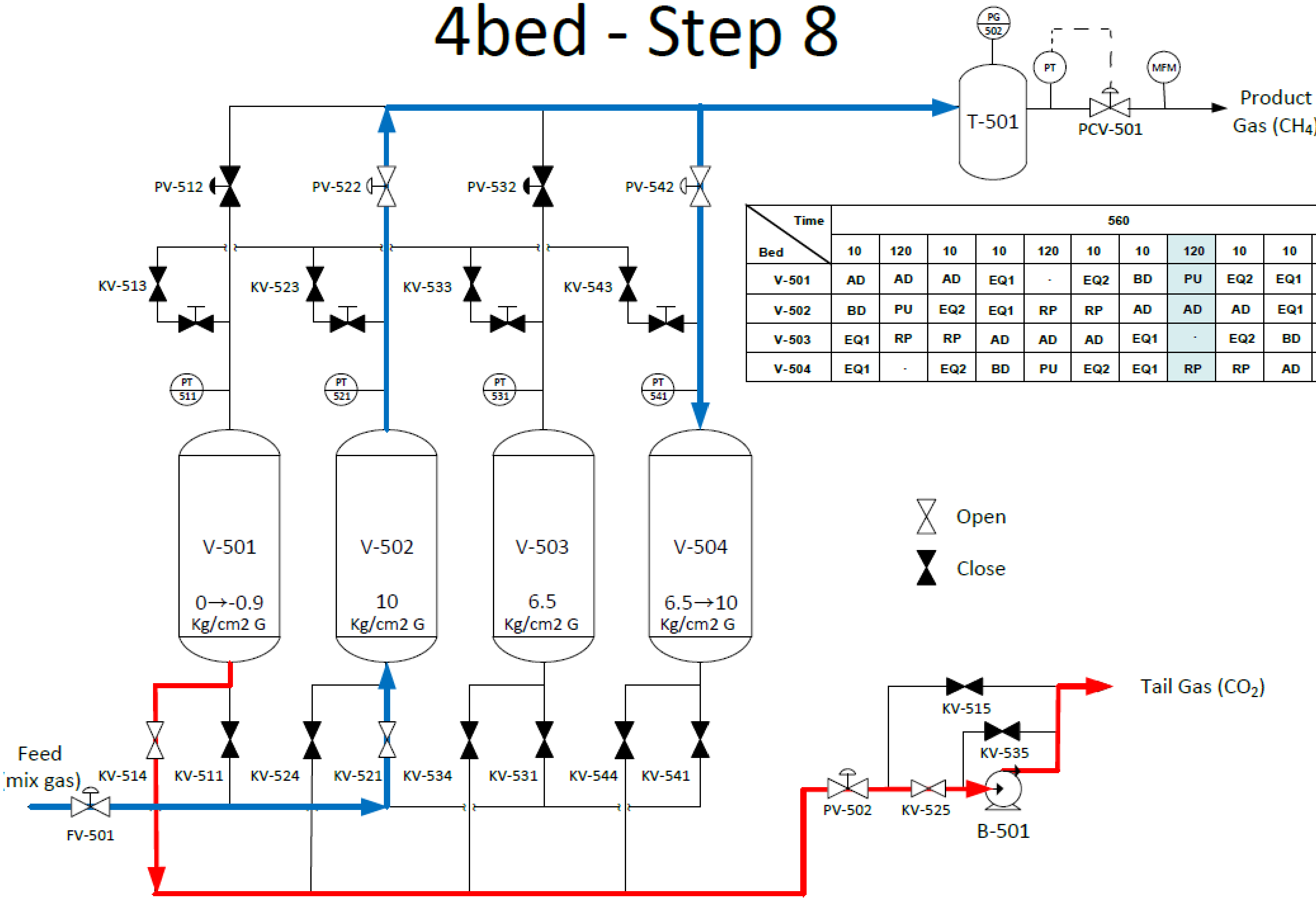


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 8

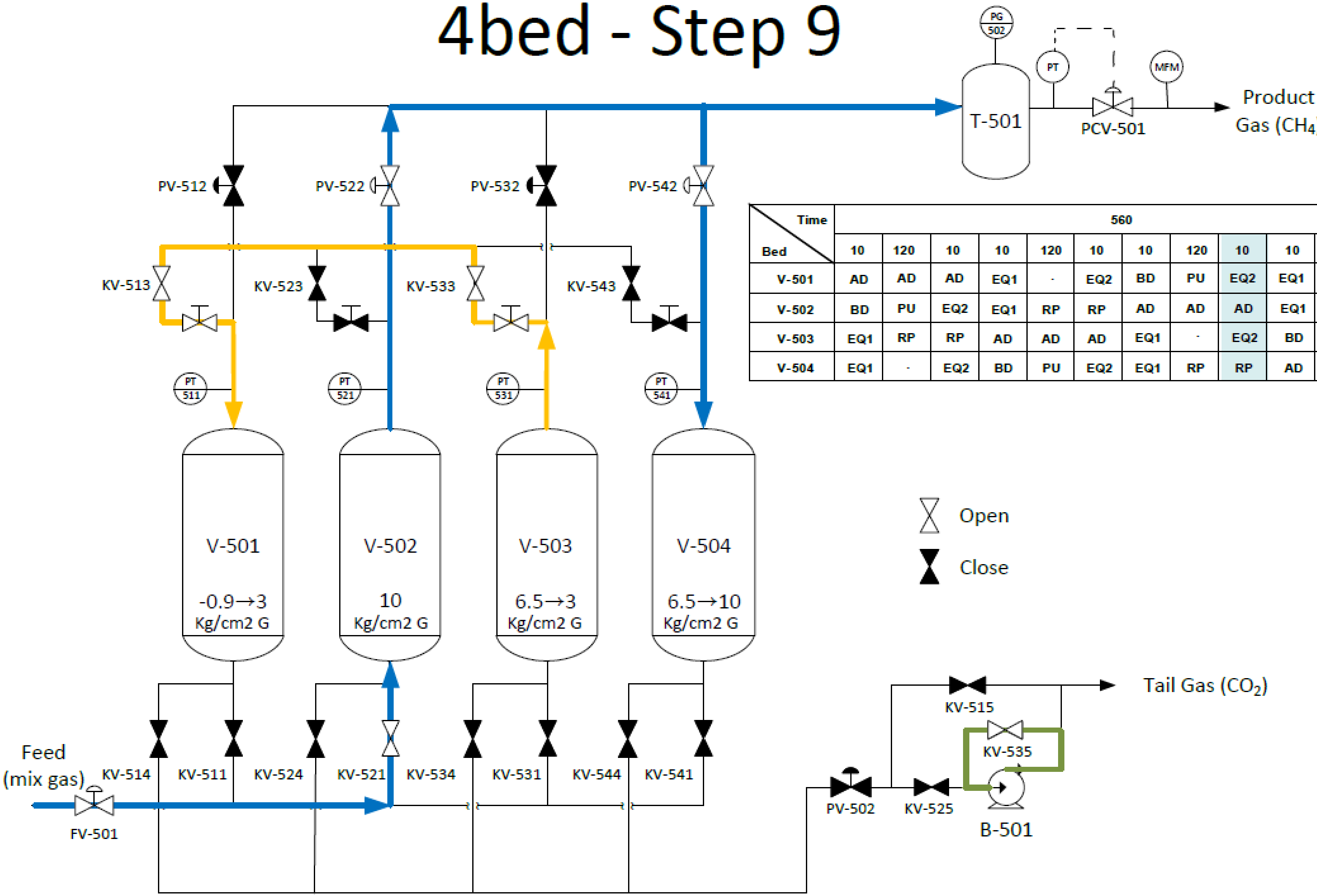


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 9

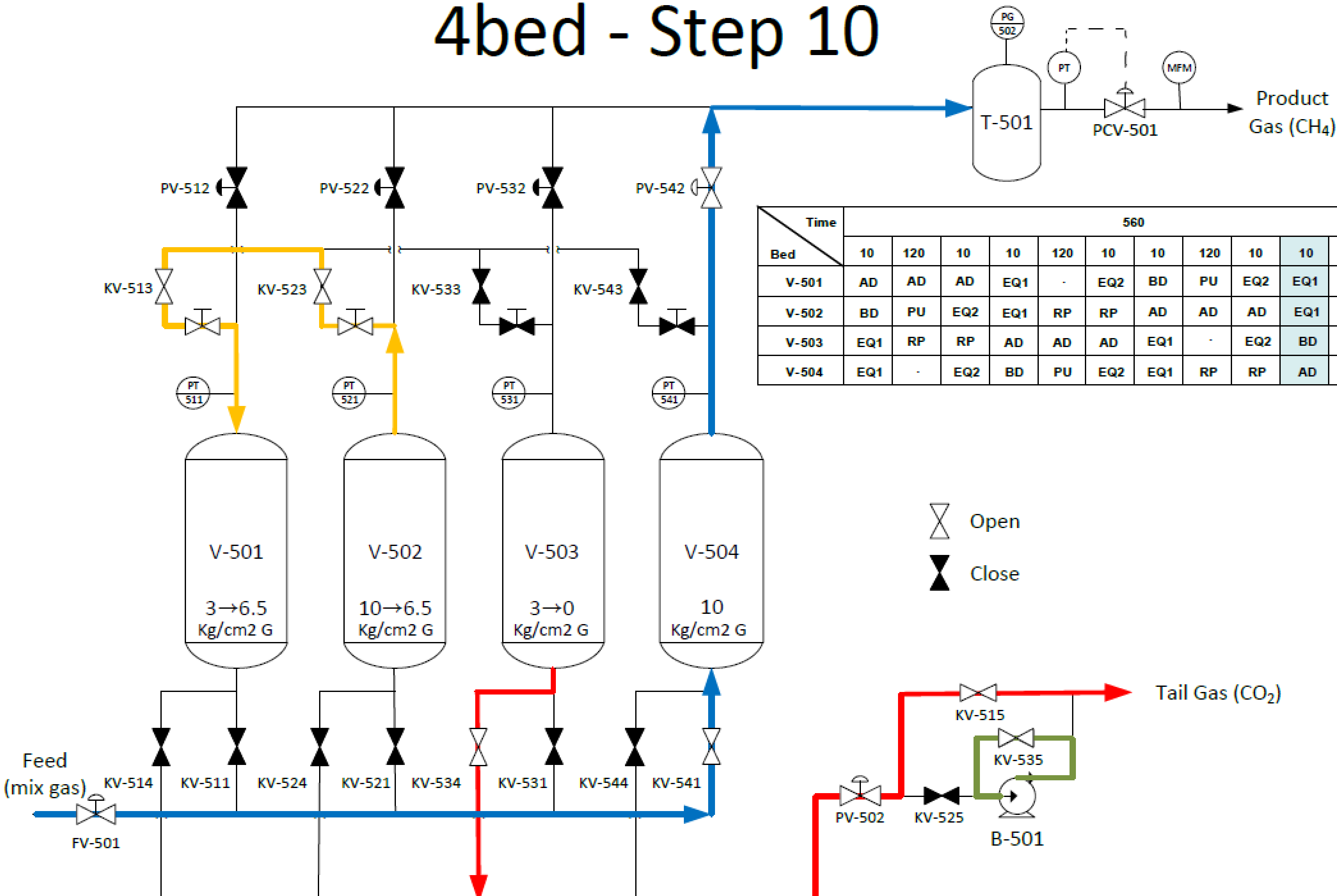


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 10

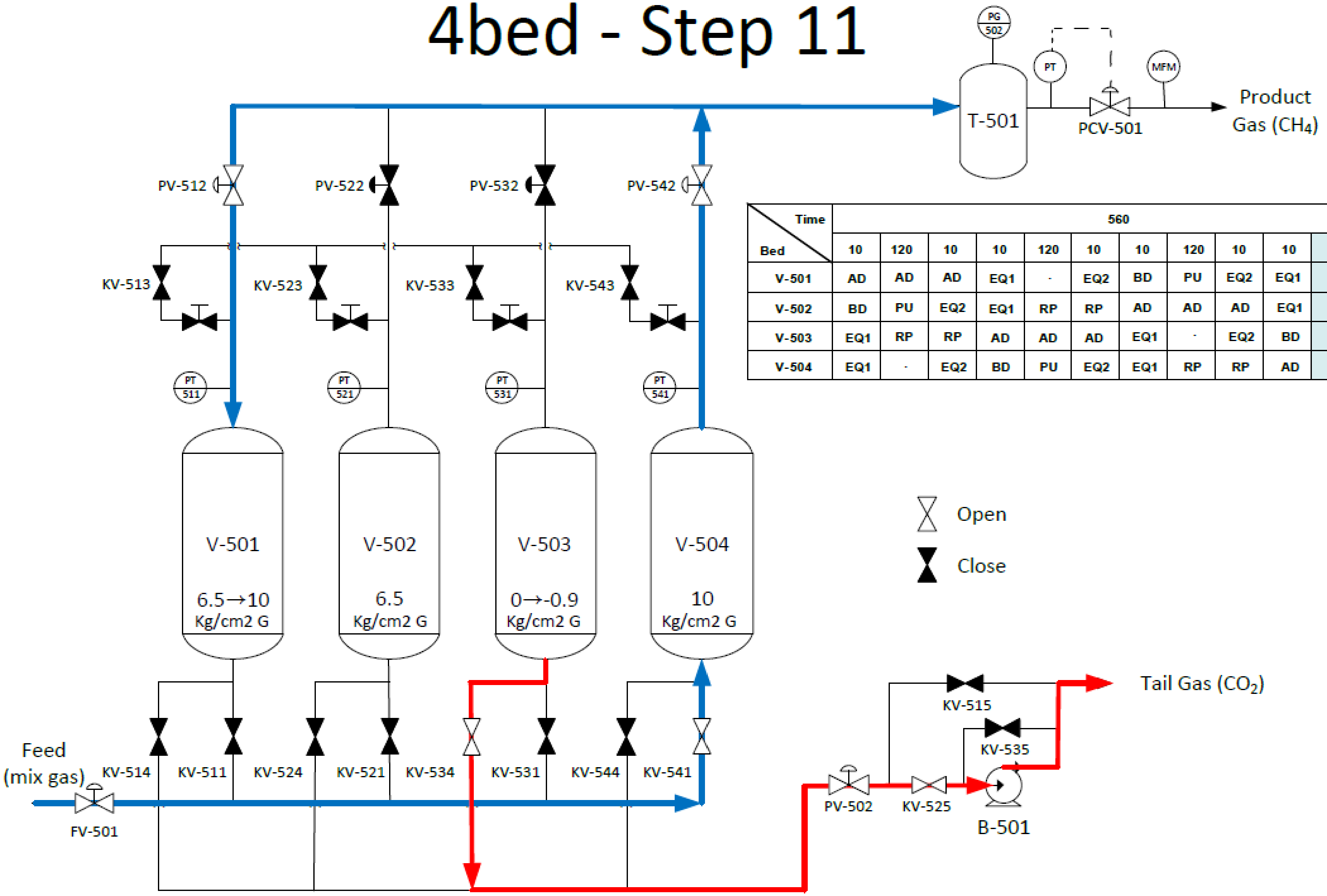


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 11

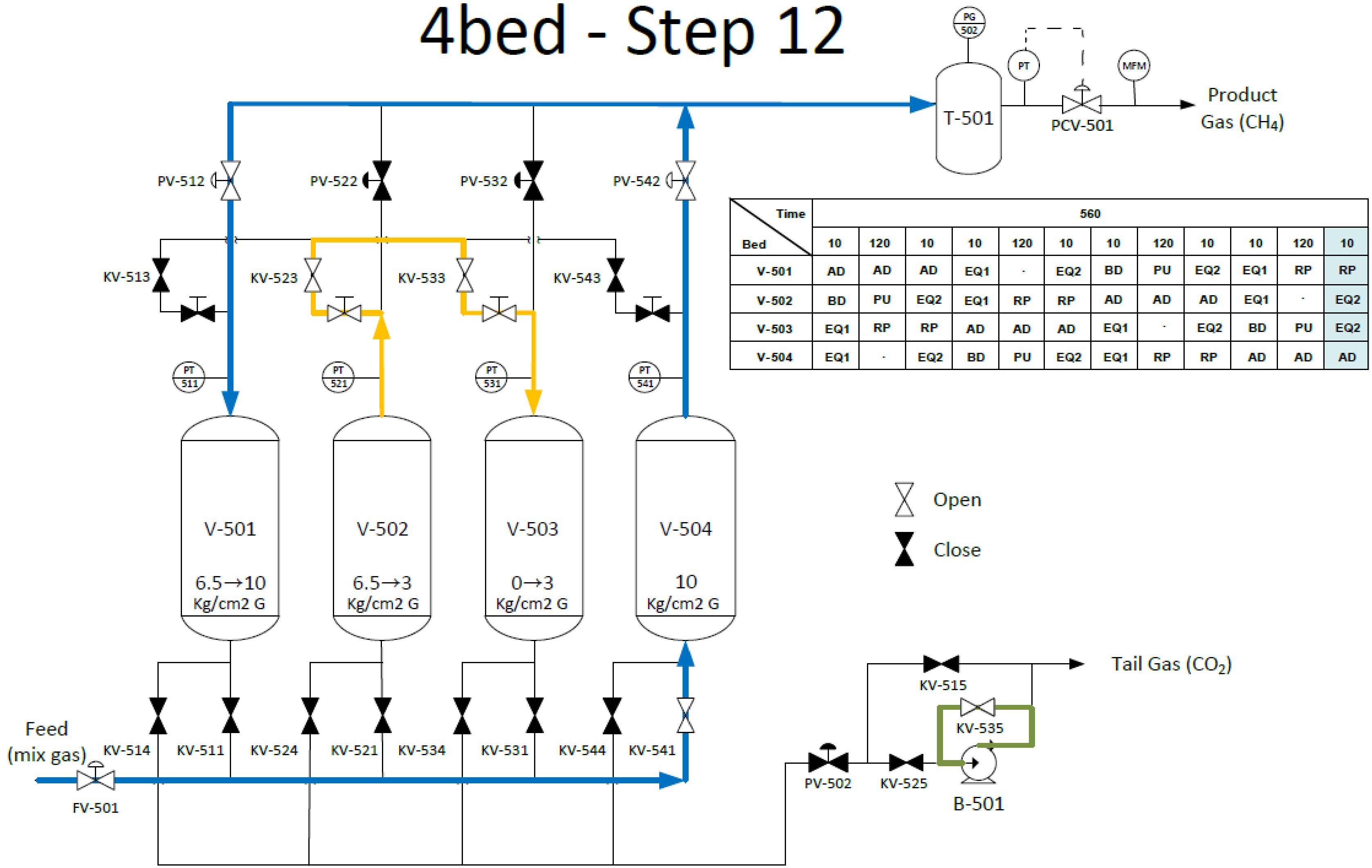


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	-	EQ2	BD	PU	EQ2
V-504	EQ1	-	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A2. Operation step of four bed PSA process

Four Bed Twelve Operating Step PSA Process

4bed - Step 12

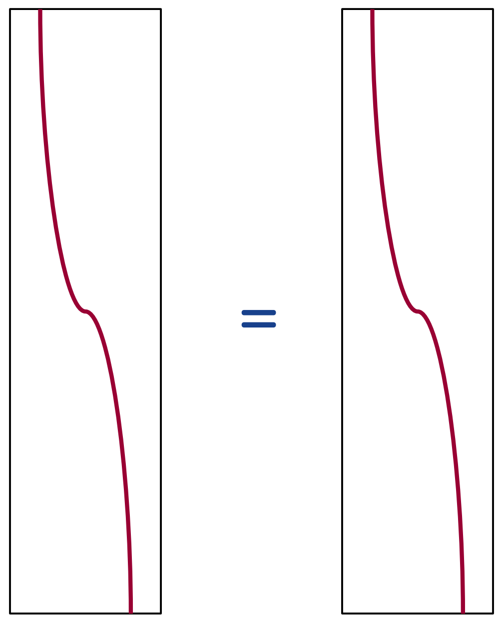


Bed \ Time	560											
	10	120	10	10	120	10	10	120	10	10	120	10
V-501	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP
V-502	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2
V-503	EQ1	RP	RP	AD	AD	AD	EQ1	·	EQ2	BD	PU	EQ2
V-504	EQ1	·	EQ2	BD	PU	EQ2	EQ1	RP	RP	AD	AD	AD

A3. Definition of cyclic steady state (CSS)

What does cyclic steady state mean?

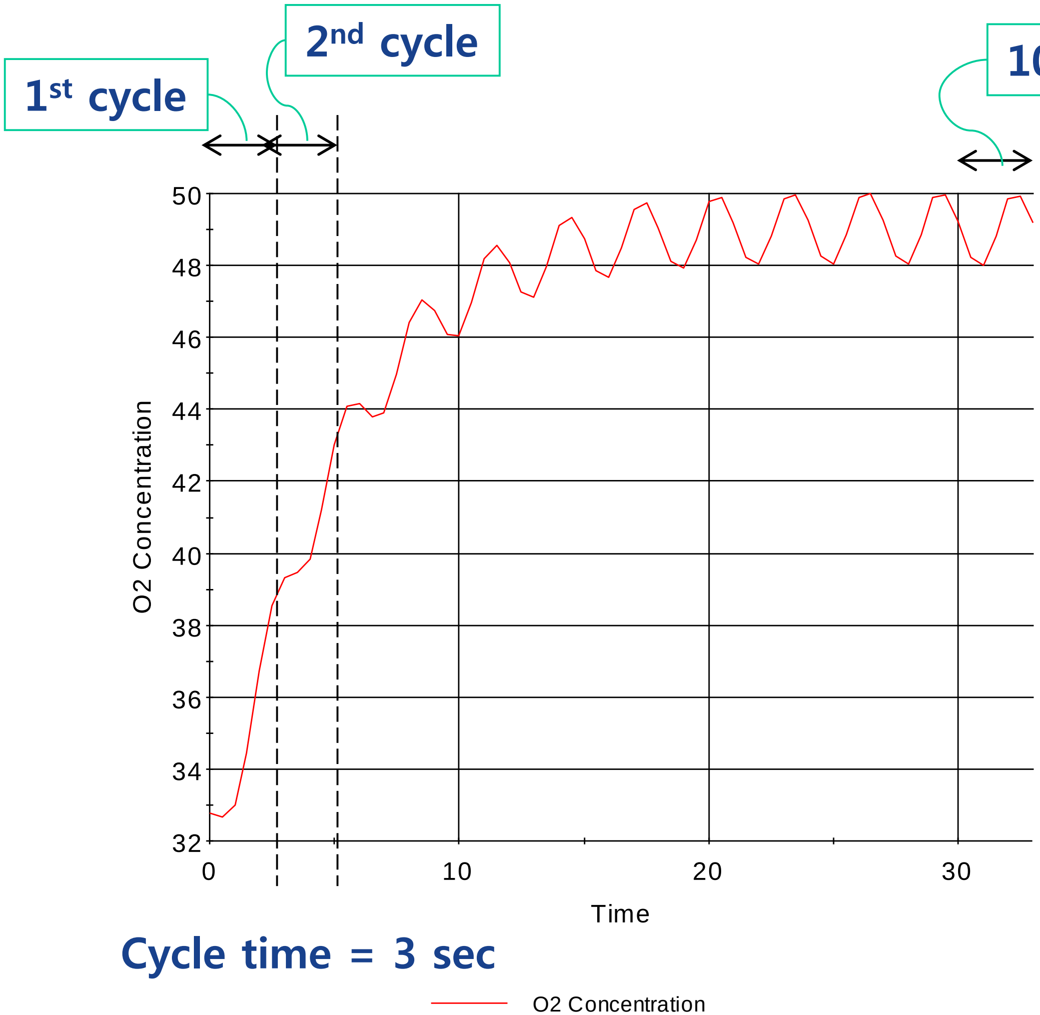
Variable profiles (temperature, concentration, adsorbed amounts) **within the bed at the start of a cycle are same as those at the end of the cycle**



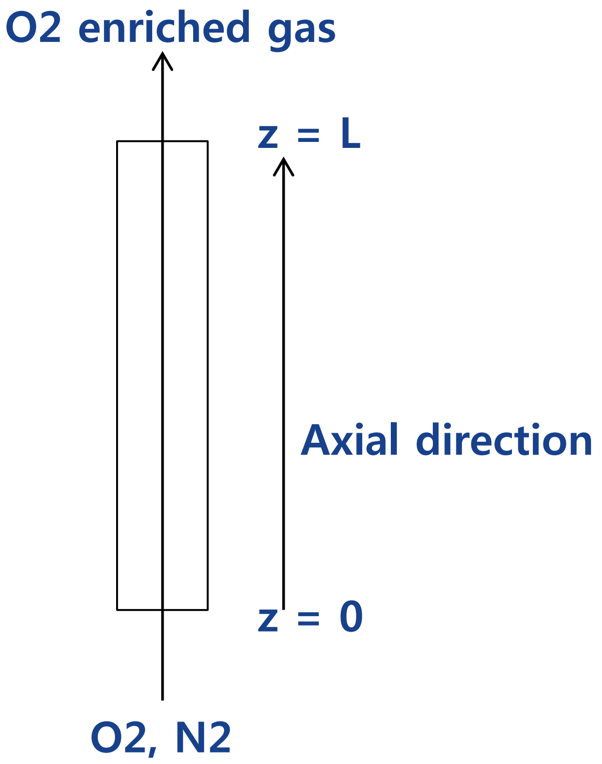
Time = 0 Time = t_{cycle}

A3. Definition of cyclic steady state (CSS)

What does cyclic steady state mean?



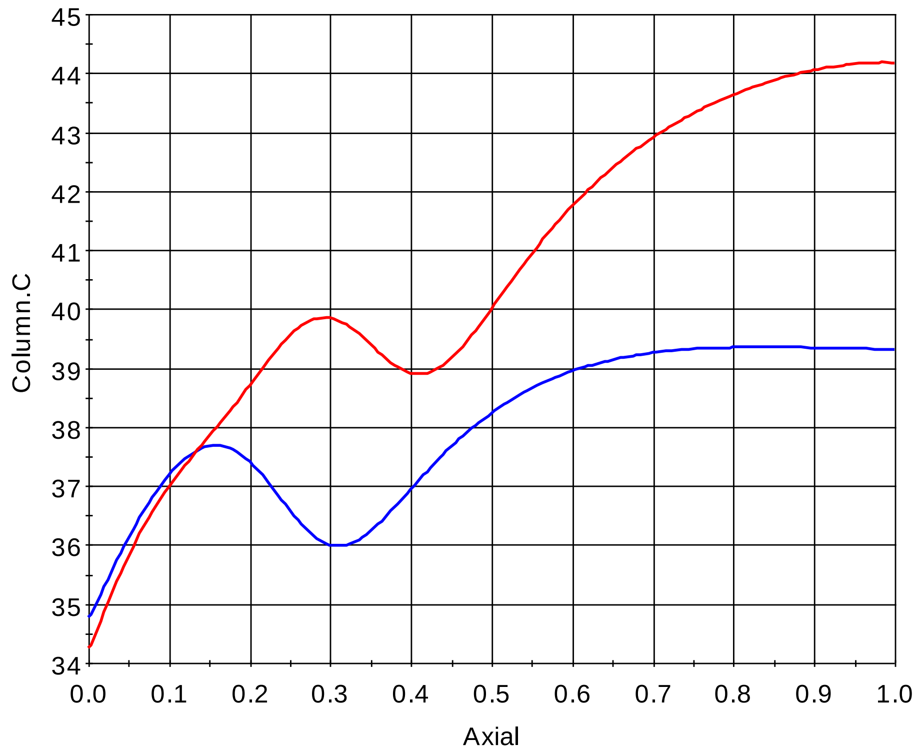
Cycle time = 3 sec



A3. Definition of cyclic steady state (CSS)

What does cyclic steady state mean?

2^{nd} cycle



$\phi|_{t=0} \neq \phi|_{t=tcycle}$

Not Yet
Cyclic Steady State

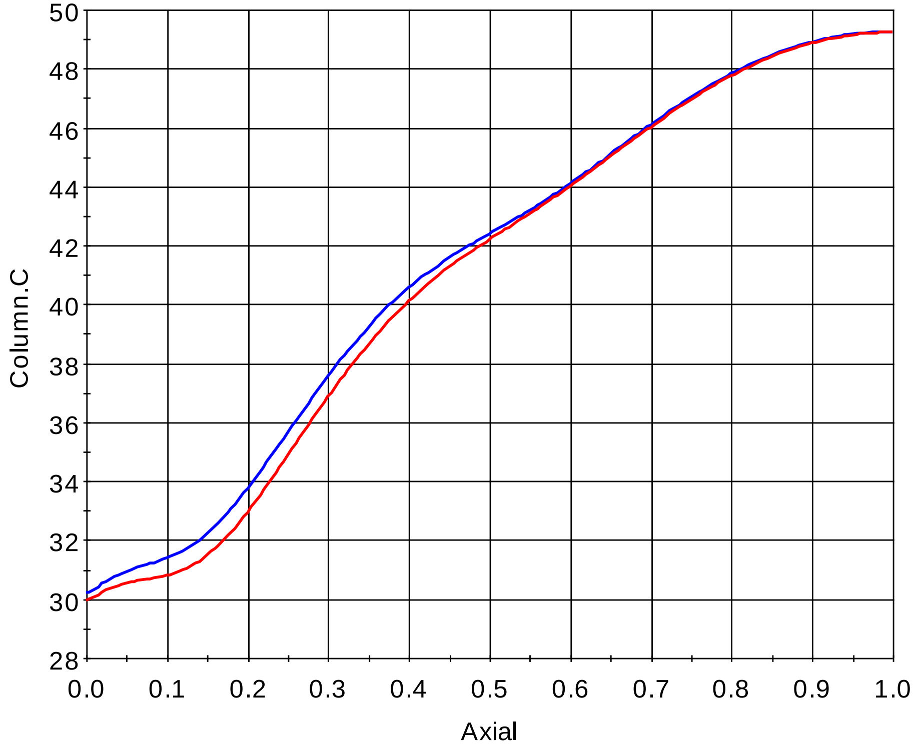
t = 3sec   t = 6sec

Fig. O_2 concentration at the start time of the 2^{nd} cycle &
the end time of the 2^{nd} cycle

A3. Definition of cyclic steady state (CSS)

What does cyclic steady state mean?

9th cycle



$\phi|_{t=0} \neq \phi|_{t=tcycle}$

Not Yet

Cyclic Steady State

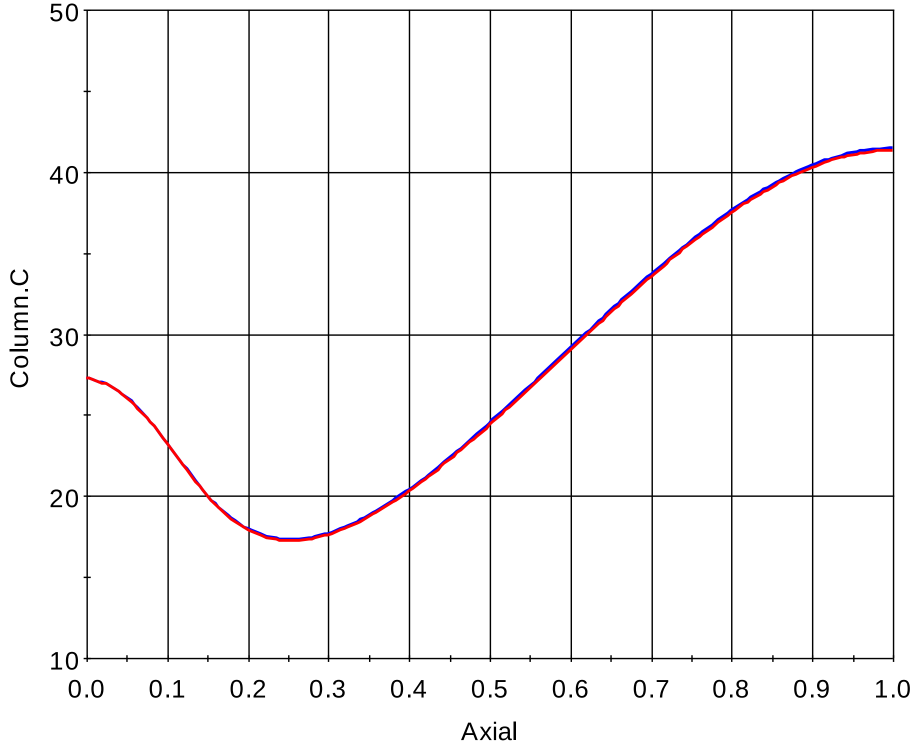
t = 27sec t = 30sec

Fig. O_2 concentration at the start time of the 9th cycle & the end time of the 9th cycle

A3. Definition of cyclic steady state (CSS)

What does cyclic steady state mean?

33rd cycle



$\phi|_{t=0} = \phi|_{t=tcycle}$

Almost Cyclic Steady State (CSS)

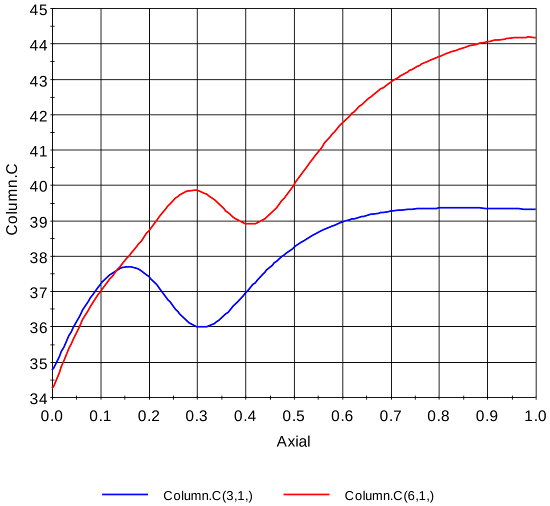
t = 267sec t = 270sec

Fig. O_2 concentration at the start time of the 33rd cycle & the end time of the 33rd cycle

A3. Definition of cyclic steady state (CSS)

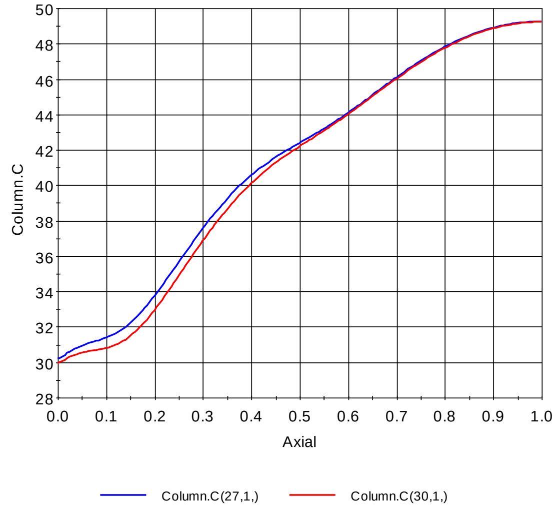
What does cyclic steady state mean?

2nd cycle



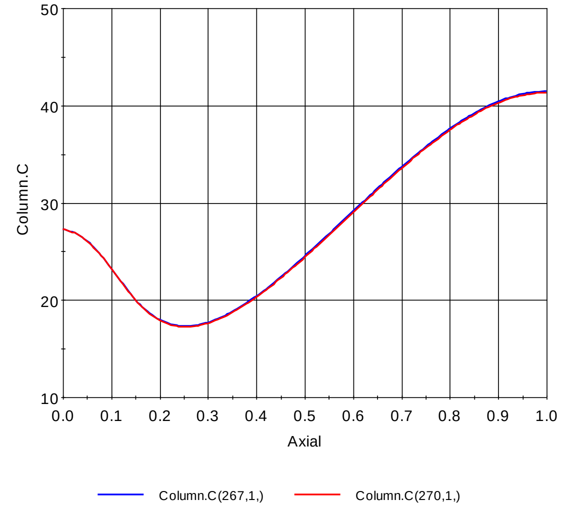
$\phi|_{t=0} \neq \phi|_{t=tcycle}$

9th cycle



$\phi|_{t=0} \neq \phi|_{t=tcycle}$

33rd cycle



$\phi|_{t=0} = \phi|_{t=tcycle}$

Cyclic Steady State = CSS

How to optimize cyclic adsorption processes (CAP) in a mathematical way?

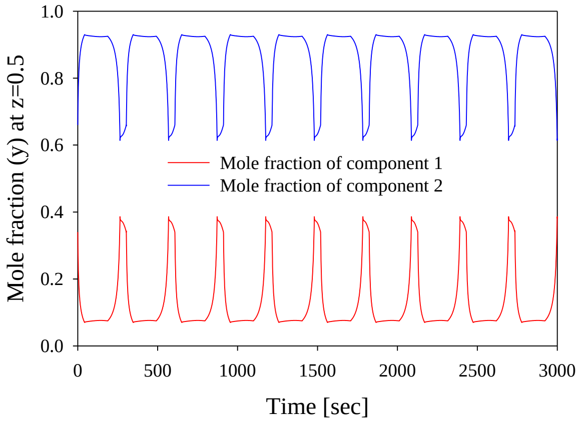
Characteristics of CAP

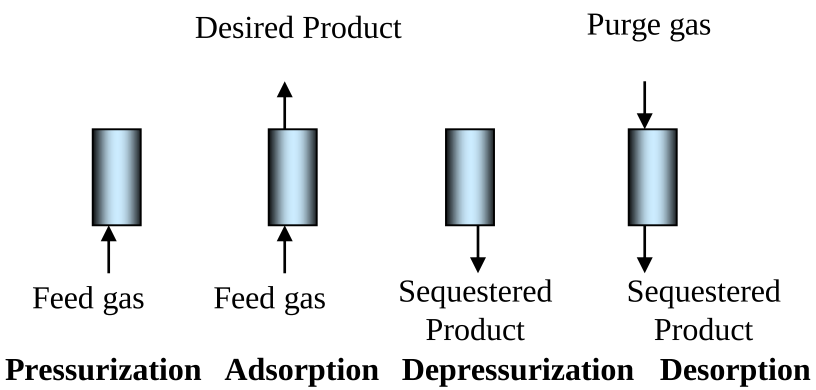
- **Cyclic Steady State (CSS):**
  Not steady state but dynamic steady state
  Periodical operation
- Nonlinear PDE bed model
- **More than one operating steps**
- Difficult to express CSS for optimization

One of the **most difficult** processes **to be optimized**

Improved Mathematical Optimization method

- Tailored Single Discretization (TSD) method (Ko et al., 2003)
- updated Tailored Single Discretization (uTSD) (Ko et al., 2005)



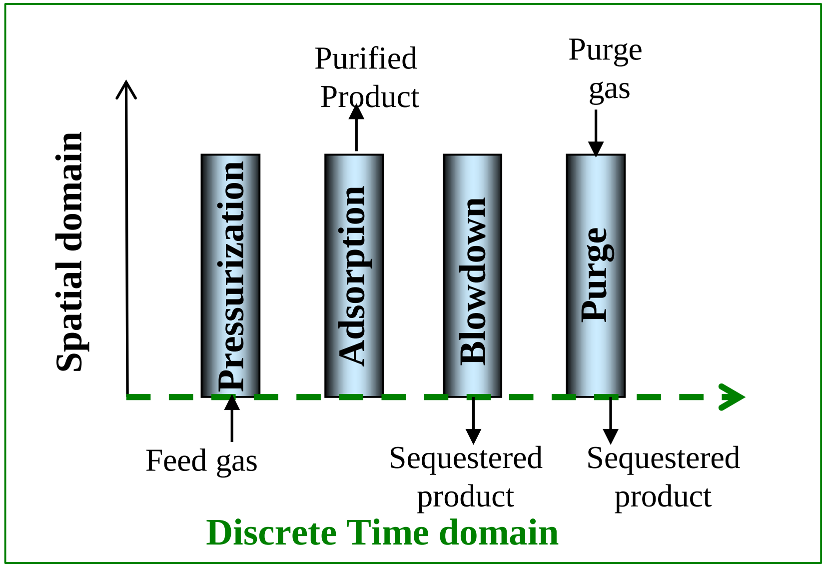


A4. PSA optimisation approach at CSS

The Concept of CD and SD

CD approach

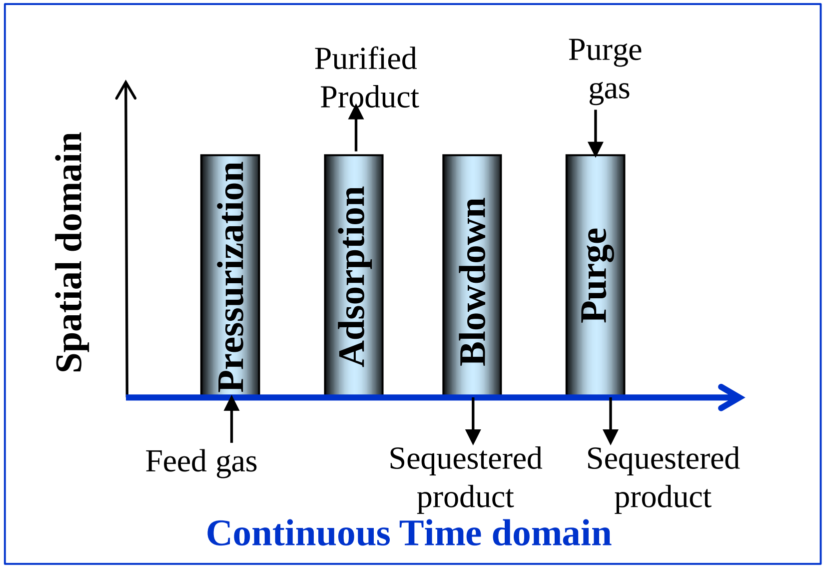
Complete discretization (CD) means the dynamic simulation adopts two discretization of the spatial domain as well as **the time domain as a new axis.**



Time domain is discretized by FDM(finite difference method) or OCFEM(orthogonal collocation finite element method) Then, **the discrete time domain** is used in the cyclic steady state(CSS) expression for the CSS optimization.

SD approach

Single discretization (SD) means the dynamic simulation adopts only one discretization of the spatial domain, not the time domain as a new axis. Instead, **variable time step (=continuous time) is adopted within the simulation solver.**

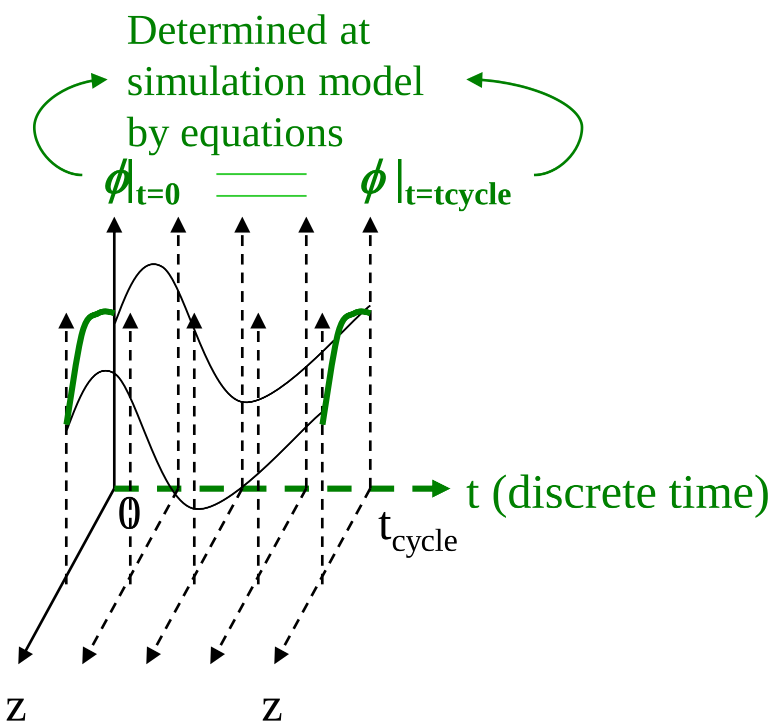


Continuous time domain model can be used in the cyclic steady state expression for the CSS optimization by **using binary variables**

A4. PSA optimisation approach at CSS

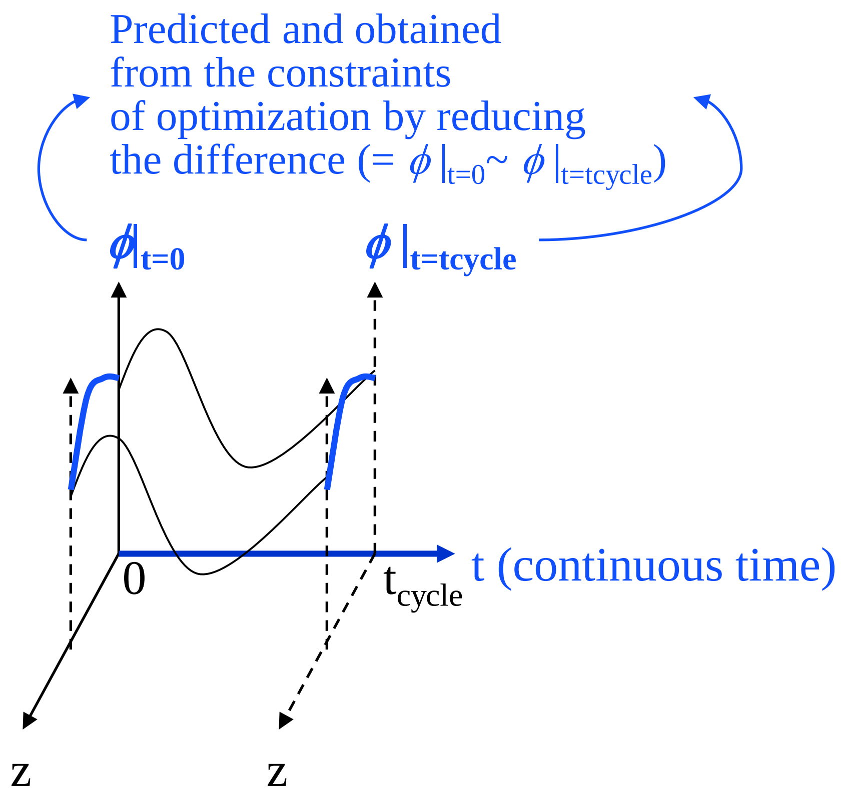
Implementation of CD and TSD (Ko et al., 2003 & 2005)

CD (Complete Discretization) approach,
also called "Double Discretization"



CSS Expression:
Discrete Time model
By adopting new time axis

TSD(Tailored Single Discretization) approach



CSS Expression:
Continuous Time model
by using binary variables