Blue Hydrogen Production
by
Membrane Carbon Capture System

Return to 18th century

Introduction

- The practice of "**Net Zero by 2050**" through greenhouse gas reduction is an international promise and action to make a better world to live in.
- CO_2 accounts for about 76 % of total greenhouse gas emissions. CO_2 reduction is the most effective way to reduce greenhouse gases.
- The clean fuel hydrogen market is expected to grow to $12 trillion by 2050. Steam Methane Reforming (**SMR**) is the most common and cost-effective method for hydrogen production, and it contributes about 50% of the world's hydrogen production.
- Hydrogen produced by SMR is termed **'grey hydrogen**' when the waste carbon dioxide is released to the atmosphere and **'blue hydrogen**' when the carbon dioxide is captured and sequestered.
- To recover and purify hydrogen, a pressure swing adsorption (PSA) technology is applied. It operates at high pressure and high temperature to separate hydrogen, and this results in high initial facility cost as well as operational cost.
- Astroma's membrane carbon capture device is an innovative method for capturing CO_2 and separating hydrogen from the gas that has passed through SMR. It operates at low pressure and ambient temperature, so the initial equipment cost and production cost are low. It is expected that the production cost of blue hydrogen is reduced by 25% to 50%, thereby increasing the competitiveness of the blue hydrogen produced with natural gas.
- Natural gas markets in the USA, Canada, and the Middle East can benefit from the low cost of blue hydrogen production and contribute to the expansion of the hydrogen market.
- Arstroma's carbon capture technology is already being used in the CCUS market, and with additional experiments to find out optimal conditions to apply the same technology to blue hydrogen production, it will be a promising technology to produce cost competitive blue hydrogen.

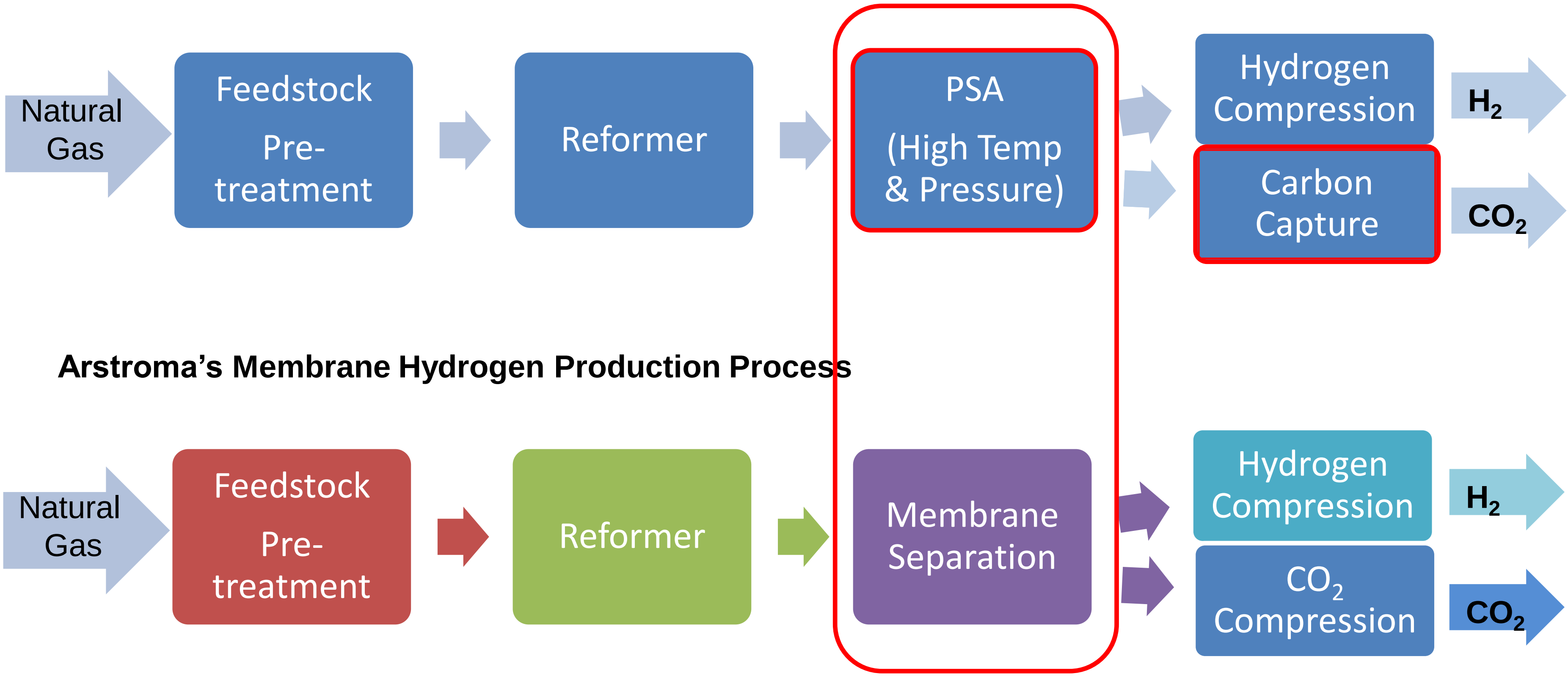
Conclusion

- H_2 has been extracted from natural gas without CO_2 capture for a long time.
- Now that CO_2 cannot be emitted, an additional CO_2 capture device must be installed, and hydrogen is produced as blue hydrogen.
- When a CO_2 capture device is added to the existing hydrogen production process, the production cost of hydrogen has risen sharply. For this reason, various alternative technologies for separating hydrogen are being developed.
- Arstroma's CO_2 capture technology can be used semi-permanently by using a sheet-type membrane applied with nano technology. Its CAPEX and OPEX costs are low because high temperature and high pressure conditions are not required to separate gases.
- In the Arstroma's hydrogen production process using SMR process, PSA equipment is not required, which reduces CAPEX and lowers production cost, thereby lowering hydrogen production cost.
- In the case of hydrogen production that captures 85% of CO_2 in an experiment using Arstroma's carbon capture facility, **H_2 can be produced at about 30% cheaper** than the process using conventional PSA.
- Additional experiments are needed to find the optimal conditions for H_2 production. The cost of H_2 production can be further reduced by changing the size of the carbon capture system and membrane compositions and using catalysts.

Comparison of Hydrogen Production Process

Conventional Hydrogen Production Process

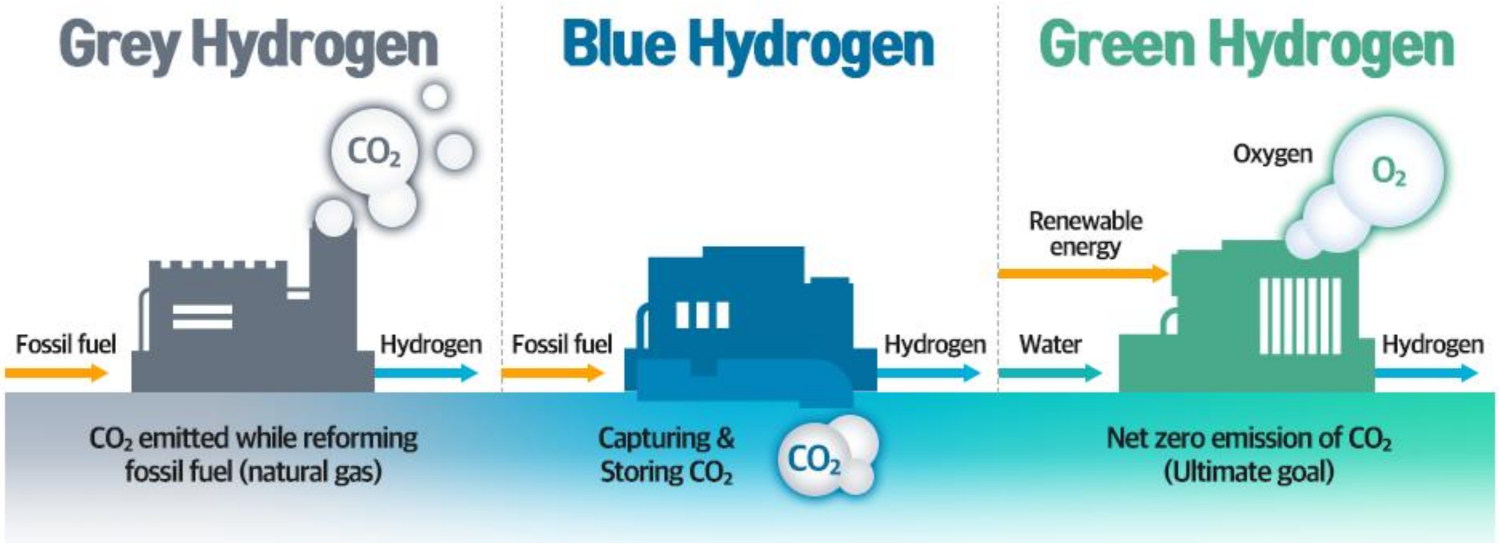
Arstroma's Membrane Hydrogen Production Process



Arstroma's system does not require high temperature nor pressure.
Less CAPEX and OPEX. ➡ Lower Hydrogen Production Cost

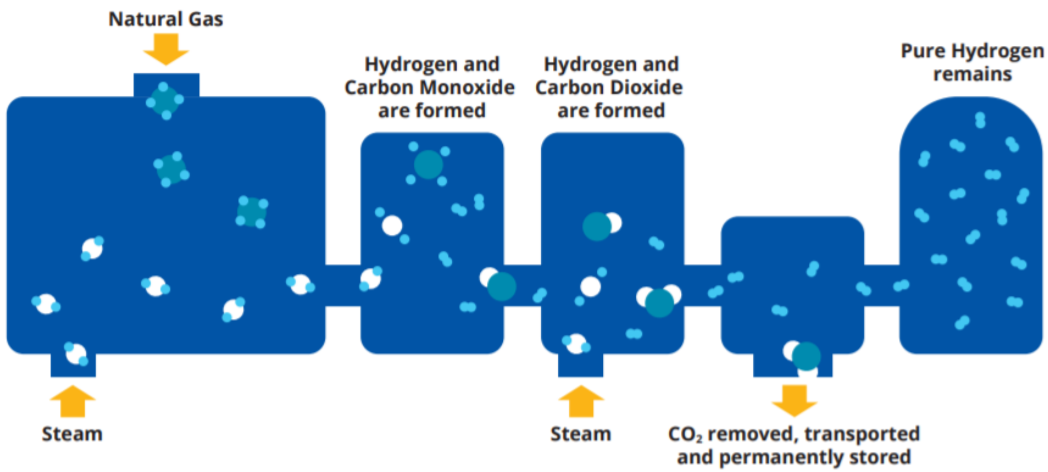
Net Zero by 2050

- According to the International Energy Agency (IEA), there are currently 100 CCUS plants and 3,400 will be operational by 2050.
- 87% of the 29 million tons of carbon dioxide captured is treated by EOR.
- According to IEA, to achieve carbon neutrality by 2050, 7.6 billion tons of carbon dioxide must be captured, of which 1.355 billion tons must be captured during hydrogen production.
- In 2020, the total amount of CO_2 captured was only 40 million tons.
- CCS is relatively capital-intensive and requires energy for operations.



Hydrogen Production

- Blue hydrogen is when natural gas is split into hydrogen and CO_2 either by Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR), and the CO_2 is captured and then stored.
- In the absence of breakthrough technological developments, blue hydrogen may become less cost-competitive than green hydrogen by 2030.
- Blue hydrogen appears to have two major advantages over green hydrogen. Cost and scale.
- Hydrogen production costs are dominated by natural gas and the extra capital required for carbon capture and storage.
- Adding CC to a SMR plant increases the Hydrogen production cost and is not economically competitive.



Hydrogen Production Cost

- Today, blue hydrogen is less expensive to produce than green hydrogen. This is because the underlying technology for removing hydrogen molecules from coal or gas is commercially mature.

- In regions where natural gas is as cheap as $3-4 per MMBtu, it is possible to produce blue hydrogen for less than $2 per kilogram. In contrast, green hydrogen costs more than $4 per kilogram to produce at the same location.

- Although expensive today, the cost of green hydrogen is expected to drop significantly by 2030 as the manufacturing of electrolyzers, a basic technology, expands rapidly. With the technology development and mass production system of the electrolyzer, an electrolyzer-based project can produce hydrogen at 2-3 dollars per kilo.

- Under these circumstances, green hydrogen may be cheaper to produce than conventional blue hydrogen produced from natural gas anywhere in the world by 2030. Even in oil producing countries in the Middle East, where gas costs only $1.5 per MMBtu, Blue Hydrogen will outperform the competition. The cost of green hydrogen production is projected to fall below $2/kg in almost all countries by 2030 and below $1/kg by 2050.

- Blue hydrogen production price has little reduction in cost due to technology development because most of the cost is fuel price.

- Arstroma's membrane carbon separation technology replaces expensive PSA equipment and lowers production costs by eliminating the need for high temperature and high pressure. As a result, it became possible to produce inexpensive blue hydrogen.

Hydrogen Production Cost: 607 ton/day H_2 production

- The cost of producing blue hydrogen with effective CO_2 capture system is estimated at $2.36 per kilogram for 85% CO_2 capture, while the cost of producing green hydrogen is about $5.00.

Cost breakdown of natural gas-based technologies at a plant capacity of 607 tons/day

Parameter	Grey Hydrogen			Blue Hydrogen			
	SMR	ATR	NGD	SMR (52%)	SMR (85%)	ATR - CCS	NGD - CCS
Capital cost ($M)	764	1090	1143	1063	1347	1536	1363
Operating cost ($M/year)	121	75	165	167	254	91	201
Hydrogen cost ($/kg H_2)	1.22	1.23	2.12	1.69	**2.36**	1.66	2.55

* currency unit: Canada $ (2020)

- Arstroma's Hydrogen Production Cost for 85% CO_2 capture

Parameter	Arstroma's System		
	85% Carbon Capture	**Factor**	**Memo**
Capital cost ($M)	1279	1.15	5 yr depreciation
Operating cost ($M/year)	114.6	0.52	
Hydrogen cost ($/kg H_2)	**$1.67**		

Operating Cost: 607 ton/day H_2 production

Operating cost breakdown

Categories	SMR		ATR		NGD	
	Cost ($M)	% Contribution	Cost ($M)	% Contribution	Cost ($M)	% Contribution
Operation and maintenance	30	25%	25	33%	45	27%
Utilities	39	32%	11	14%	40	24%
Raw materials	48	40%	33	44%	78	47%
Labor	2	2%	4	5%	2	1%
Supervision and administration	1	1%	3	4%	2	1%
Total	**120**		**76**		**167**	

* Currency unit: Canada $ (2020)

Arstroma's Hydrogen Production System OPEX

Categories	Arstroma's Membrane System	
	Cost ($M)	Memo
Operation and maintenance	27	90% of SMR
Utilities	31.2	80% of SMR
Raw materials	48	
Labor	2	
Supervision and administration	1	
Total	**109.2**	

Capital Cost Breakdown with CCS: 607 ton/day H_2 production

Capital cost breakdown (with CCS)

Categories	SMR-52%		SMR-85%		ATR-91%		NGD-61%		Arstroma-85%	
	Cost ($M)	% Contribution	Cost ($M)	% Contribution	Cost ($M)	% Contribution	Cost ($M)	% Contribution	**Cost ($M)**	**Memo**
Reformer	182	17.1%	182	13.5%	108	7.0%			182	
FBR							311	22.8%		
ASU					198	12.9%				
WGS	22	2.1%	23	1.7%	61	4.0%			23	
CO_2 capture	74	7.0%	248	18.4%	230	15.0%	125	9.2%	300	Membrane Carbon capture
PSA	155	14.6%	156	11.6%	246	16.0%	407	29.9%	0	
H_2 compression	20	1.9%	20	1.5%	15	1.0%	54	3.9%	50	
H_2 storage	368	34.6%	368	27.3%	366	23.9%	367	26.9%	368	
CO_2 compression	12	1.1%	15	1.1%	31	2.0%	23	1.7%	20	
CO_2 storage	2	0.2%	4	0.3%	4	0.3%	2	0.1%	4	
CO_2 pipeline	114	10.7%	166	12.3%	138	9.0%	38	2.8%	166	
CO_2 sequestration	114	10.7%	166	12.3%	138	9.0%	38	2.8%	166	
Total	**1063**		**1348**		**1535**		**1365**		**1279**	

Hydrogen Production Cost Estimates

Table 3. Recent published estimates of cost of clean hydrogen production.(IEA 2019; Bruce et al. 2018; International Renewable Energy Agency 2019; Hydrogen Council 2020)

ALL COSTS IN USD PER KG OF HYDROGEN	DEDICATED RENEWABLE ELECTRICITY SUPPLY	OTHERWISE CURTAILED RENEWABLE ELECTRICITY SUPPLY	STEAM METHANE REFORMATION WITH CCS	BLACK COAL GASIFICATION WITH CCS
CSIRO 2018[3]	**$7.70** (35% capacity factor, electricity price 6c/kWh)	**$18.20** (10% capacity factor, electricity price 2c/kWh)	**$1.60 - $1.90** (Gas price is $8/GJ)	**$1.80 - $2.20** (Coal price is $3/GJ)
IEA 2020	**$2.30 – $6.60**[4] (Low end is 57% capacity factor and electricity cost 2c/kWh. High end is 57% capacity factor and electricity cost 10c/kWh)	N/A	**$1.40 – $2.40** (Low end is gas price $3/GJ. High end is gas cost $9/GJ)	**$2.05 - $2.20** (Low end is coal price 43c/GJ. High end is coal cost $1.15/GJ)
IRENA 2019	**$2.70 – $6.90** (Low end is wind; 48% capacity factor & electricity price 2.3c/kWh. High end is PV; 26% capacity factor & electricity price 8.5c/kWh)	N/A	**$1.50 – $2.30** (Low end is gas price $3/GJ. High end is gas price $8/GJ)	**$1.80** (Coal price is $1.50/GJ)
Hydrogen Council 2020	**$6.00** (50% capacity factor & electricity price 5.7c/kWh)	N/A	**$2.10** (assumes “European gas prices”)	**$2.10** (Coal price is $60/tonne)

Introduction of Arstroma's Nano-ceramic Membrane Carbon Separation System

Arstroma's Nano Membrane Separation Technology

- **Polarity-assisted gas separation technology** applied with nano-ceramic coating
  - There is no need to worry about clogging because there are no pores.
  - It can be applied to dirty flue gases.
- Membrane Separation technology, which is differentiated from the existing carbon capture technologies, and applied the membrane in the form of a sheet. – **No need to replace membranes**
- Mambrane made by nano-material technology **operates at high temperature**, so it can be used semi-permanently, resulting in low maintenance costs.
- Efficiently separate specific gases by applying "**Surface Diffusion Mechanism**" technology.
- Because it is a **modular system**, it is easy to expand and the collection rate and purity can be adjusted by changing the connection method.
- It does not require a toxic solvent and operates at room temperature and low atmospheric pressure – the initial installation is relatively simple and the **CAPEX is low**.
- The membrane is made of very stable and durable material and has a **long service life**.
- It is stable even at high temperature (200℃) and operates under ambient pressure, H2S 200ppm, 0.1μm to 10μm (SiO2, Al2O3, etc.) dust mixture. Can be used directly on flue gas without pretreatment.
- Parallel and series combinations are possible depending on the required CO_2 concentration and capture rate.

In collaboration with KEPCO, a carbon capture pilot plant was built in Dangjin, Korea and a three-year test was conducted. We have developed an optimal system to achieve the purity and capture rate of carbon dioxide, and the following are the test results**.**

Technical overview

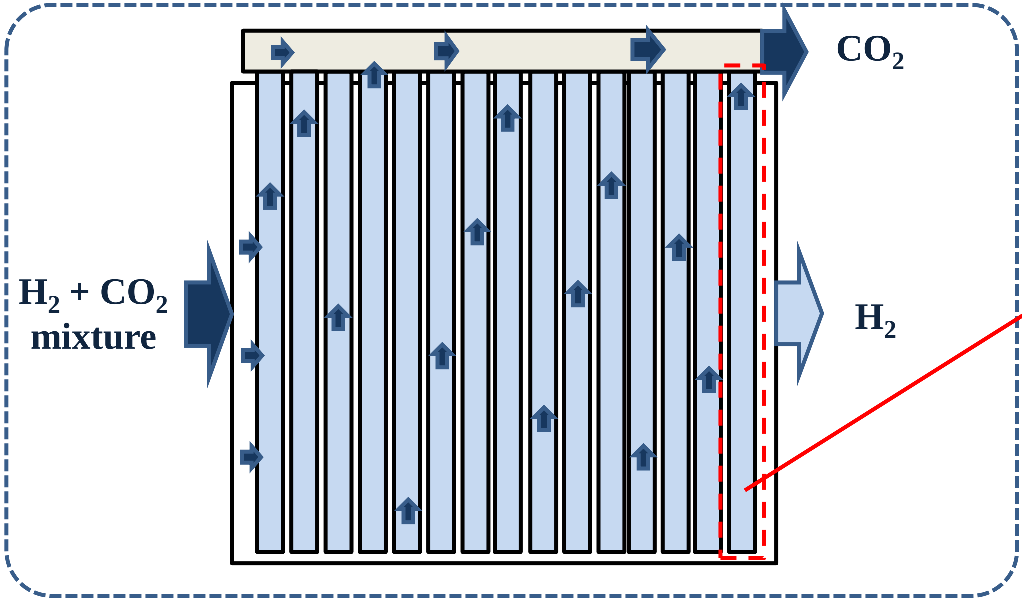
- Technology that separates and captures CO_2 in combustion flue gas by the difference in permeation rate and molecular size using a separation membrane
- Easy to upgrade in modular form, and easy to install in existing facilities as no separate heat source is required
- The process is simple as it consists only of modules and compressors, and business diversification is possible without size and location restrictions
- Environmentally friendly technology without the use of chemical and harmful substances, and energy-efficient process that does not require membrane regeneration.

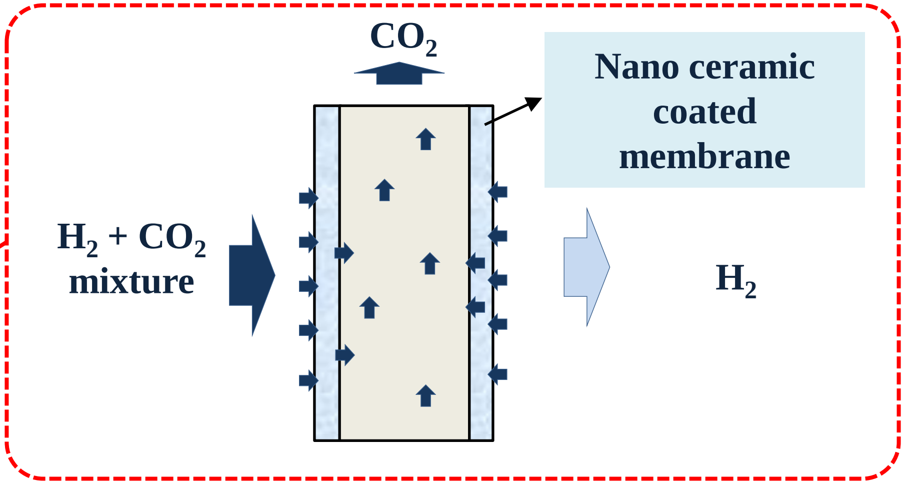
Test Result

- Membrane material and module
  - Intrinsic polymer membrane with permeance of 1153 GPU and selectivity of 10 - Establishment of mass production system with quality error < 3%
  - Compact membrane module with membrane density of $400m^2/m^3$

- Preferential adsorption of CO_2 molecules with a larger quadrupole moment and higher polarizability.
- This is known as the "**surface diffusion mechanism**" along with the blocking of H_2 molecules due to the adsorbed CO_2 molecules.

→ **Effect of charge is very important in understanding diffusion as well as osmosis.**

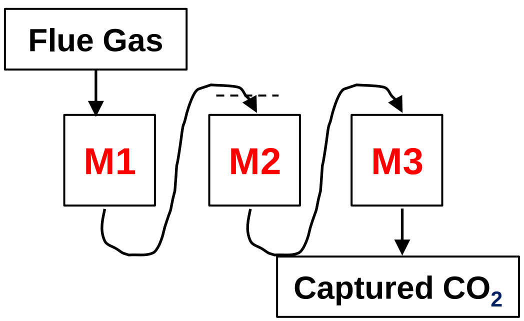




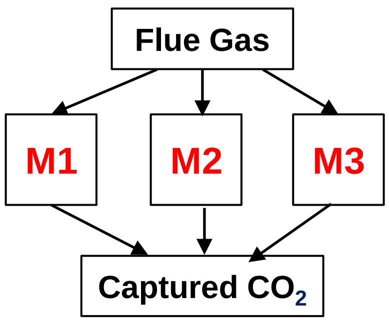
Not a hollow fiber type. Membrane in a sheet form.

- To achieve targeted gas capture rates, Arstroma's modular units can be operated in serial, in parallel or in combination.

*Serial operation for high CO_2 concentration

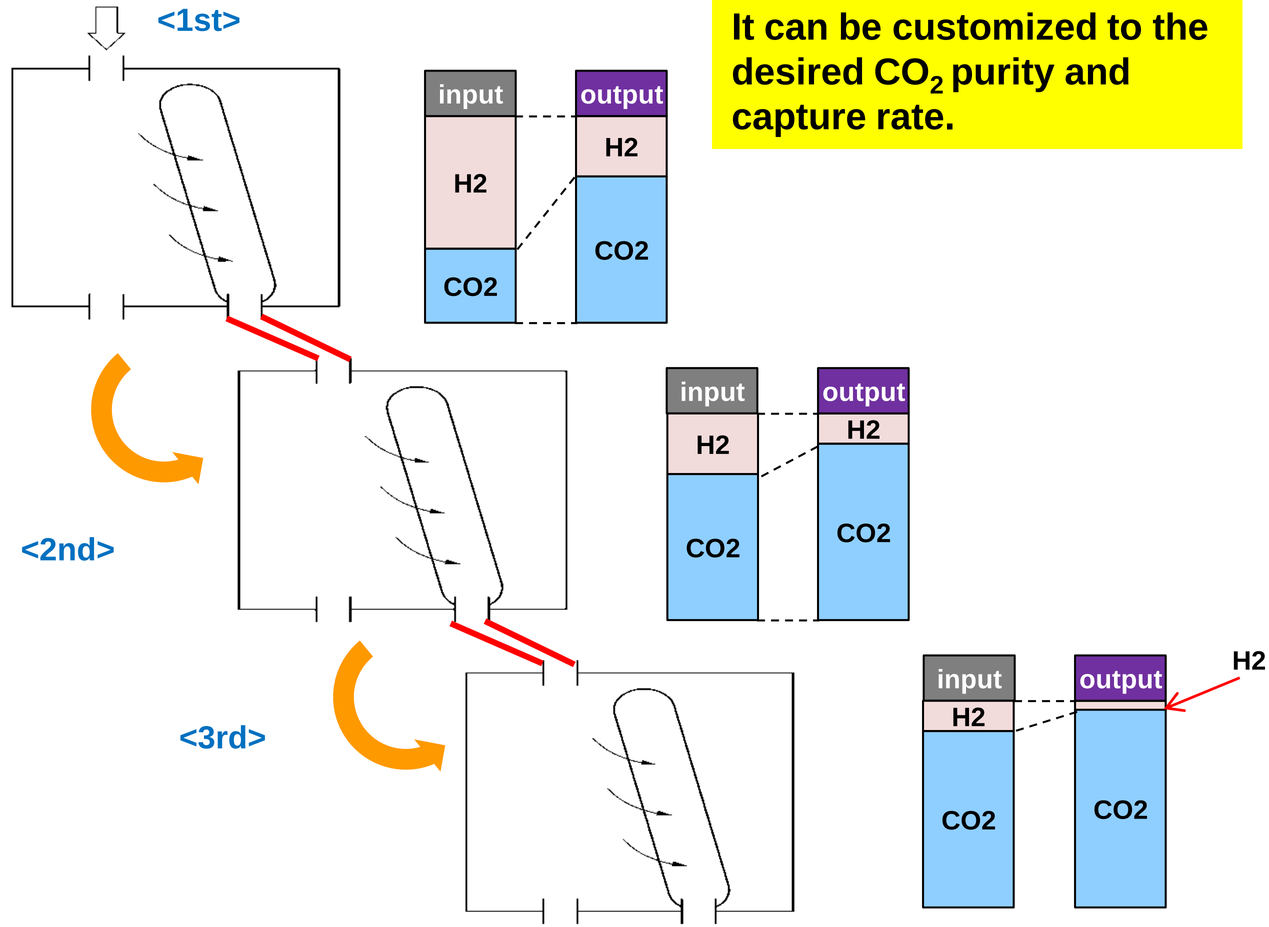


*Parallel Operation for large capacity capture



Serial Operation Process for high Concentration of CO_2

It can be customized to the desired CO_2 purity and capture rate.



Modular System: Benefits

- Provides a flexible solution to the demands of various CO_2 capture capacities by adjusting the number of modules and process stages.
- Enables shorter construction period and lower cost by factory manufacturing rather than on-site total construction.
- Allows immediate partial operation while construction is ongoing.
  - No need to wait for full operation until the construction is finished.
  - Likewise, enables maintenance of units while allowing continued operation of other units.
- Easy operation and maintenance as the Arstroma separation system is an aggregation of a standardized modular unit.

Arstroma Modular Membrane Unit

- No pores, durable life
- Easy assembly and cleaning
- Easy expansion

Patents: Partial List

No.	Country	Application Number / Filing Date	Patent Number / Registration Date	Title of Invention	Current status
1	KR	10-2013-0053058 2013-05-10	10-1354680-00-00 2014-01-16	Carbon dioxide separating apparatus using silicone separators	registered
2	KR	10-2013-0119091 2013-10-07	10-1522252-00-00 2015-05-15	Manufacturing method of membrane for separating carbon dioxide and apparatus using the same	registered
3	KR	10-2015-0040454 2015-03-24	10-1657045-00-00 2016-09-07	Fluid separating device	registered
4	KR	10-2015-0040455 2015-03-24	10-1794885-00-00 2017-11-01	Fluid separating tube and fluid separating device including the same	registered
5	KR	10-2015-0040524 2015-03-24	10-1677492-00-00 2016-11-14	Apparatus for separating fluid	registered
6	KR	10-2015-0040525 2015-03-24	10-1677494-00-00 2016-11-14	Apparatus for separating fluid	registered
7	KR	10-2016-0014820 2016-02-05	10-1981010-00-00 2019-05-16	Fluid separating membrane and method for fabricating the same	registered
8	KR	10-2016-0014822 2016-02-05	10-1981041-00-00 2019-05-16	Fluid separating membrane and fluid separating device including the same	registered
9	KR	10-2016-0014828 2016-02-05	10-1981042-00-00 2019-05-16	Fluid separating device	registered
10	KR	10-2016-0014833 2016-02-05	10-1981043-00-00 2019-05-15	Fluid separating tube and fluid separating device	registered
11	KR	10-2016-0014835 2016-02-05	10-1981044-00-00 2019-05-15	Fluid separating film module	registered
12	KR	10-2016-0035306 2016-03-24	10-1981045-00-00 2019-05-15	Fluid separating device	Registered
13	KR	10-2016-0035302 2016-03-24	10-2014211-00-00 2019-08-20	Fluid separating membrane module	Registered

Contact Information

	Arstroma Company Limited (Attention: Mr. Keith Lee, CFO
	801 Software Venture Tower 117 Dongbuk-ro, Buk-gu Daegu, Korea
	keithfuture@gmail.com
	+82-10-7289-5578