Membrane dehumidification for building HVAC applications

Jae-Weon Jeong, Ph.D.

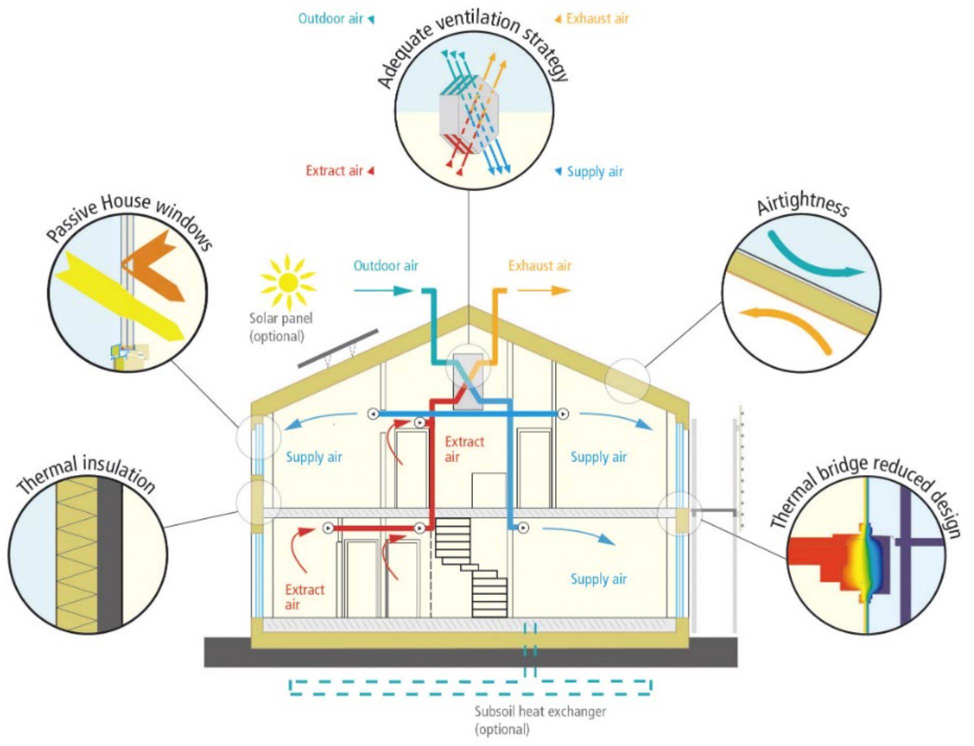
Professor, Department of Architectural Engineering

Hanyang University, Republic of Korea

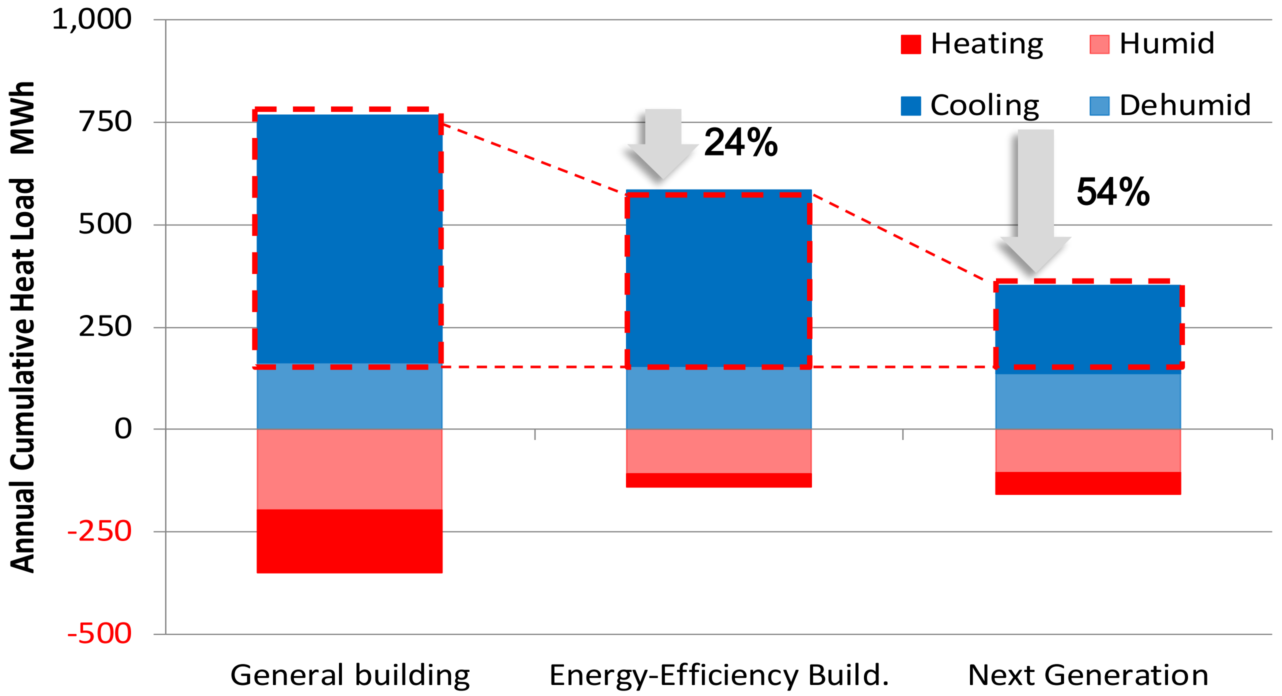
(jjwarc@hanyang.ac.kr)

Current energy conservation approach on building sector

Improvement of energy efficiency for zero energy buildings



<Passive solutions to enhance building energy efficiency>

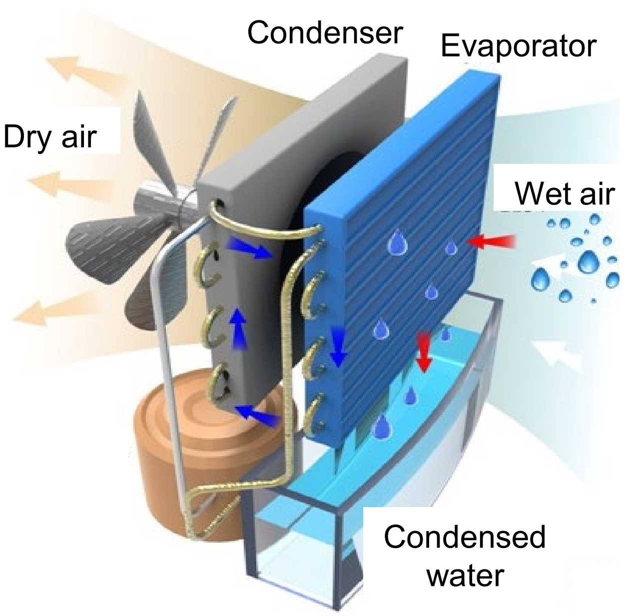


<Annual building thermal loads according to building energy efficiency>

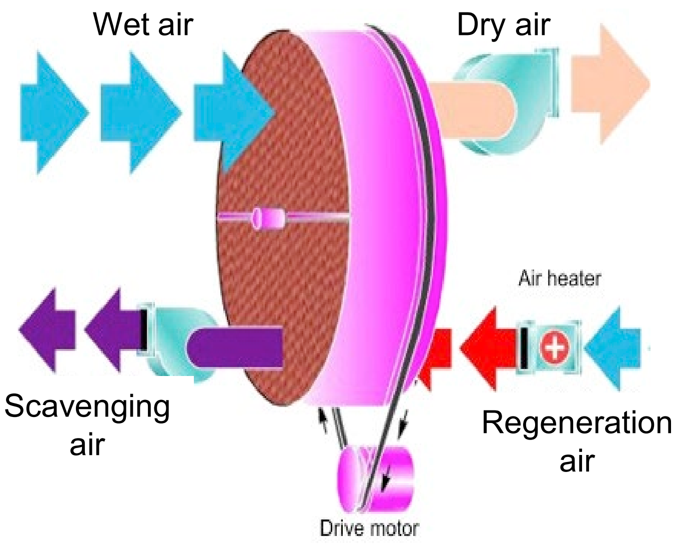
- Energy-efficient buildings exhibit decreased indoor sensible load and increased latent (dehumidification) load
  - ➢ Dehumidification becomes more important for energy efficient buildings

Typical dehumidification in buildings

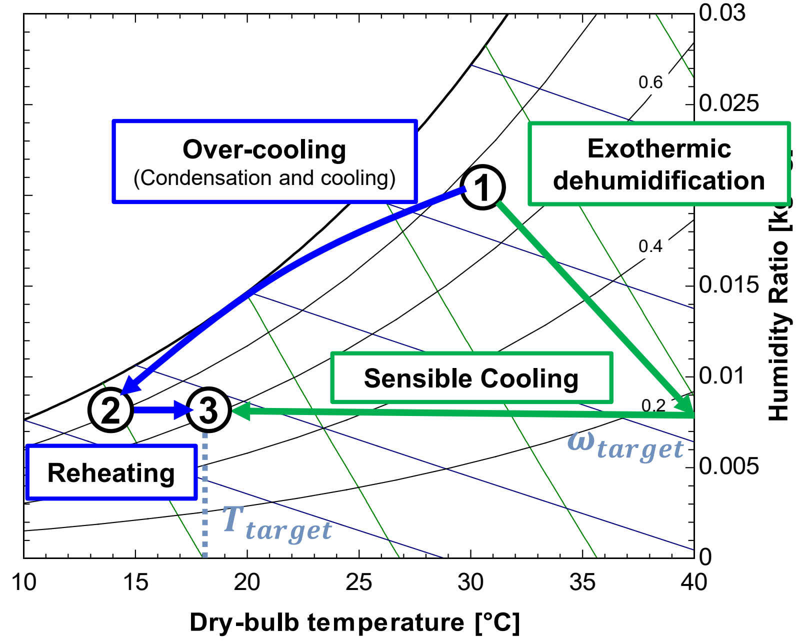
- **Vapor compression system**



- **Desiccant wheel**



- **Thermal behaviors of process air**



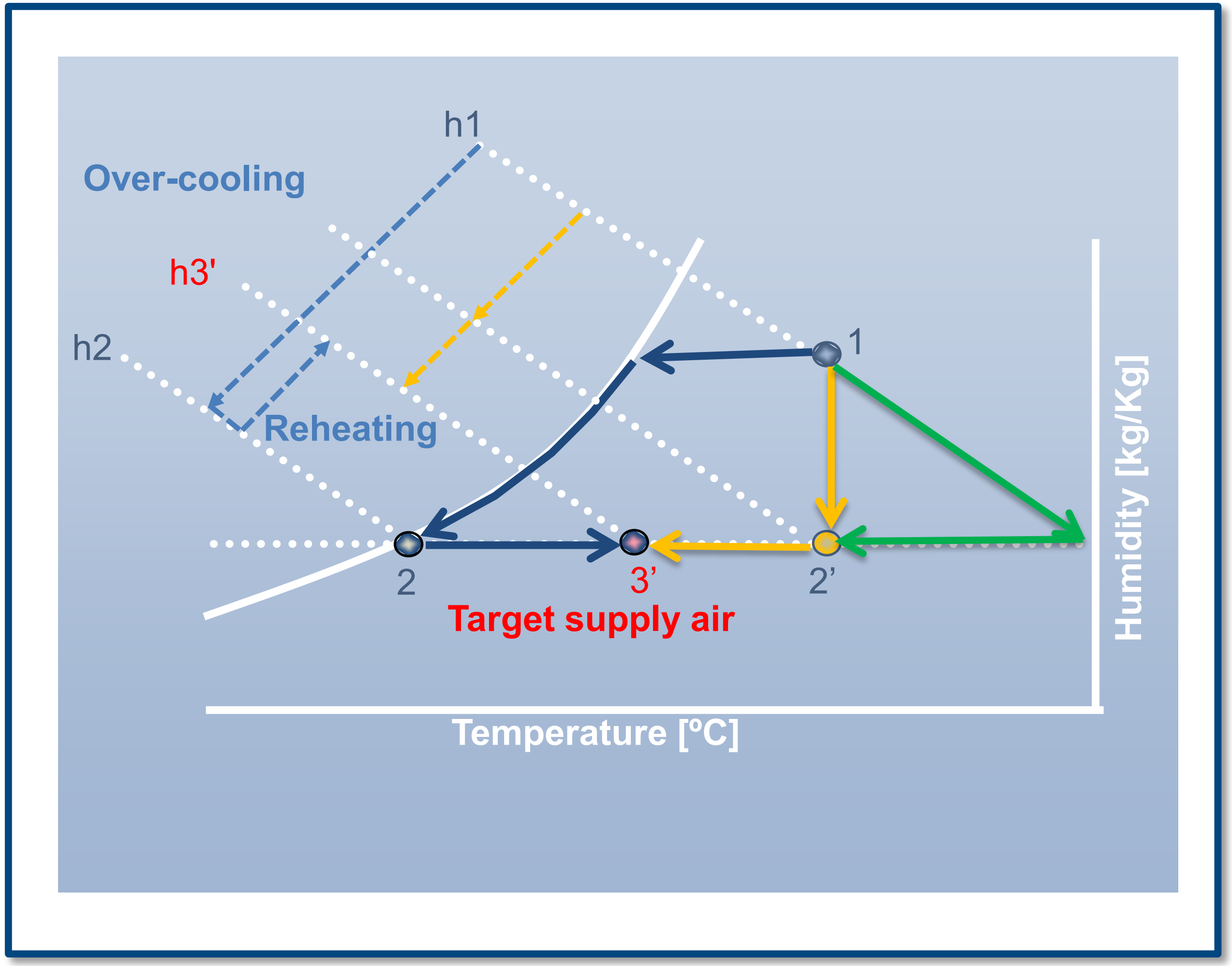
✓ Simultaneous sensible and latent cooling

✓ Condensation-based dehumidification
: Over-cooling and reheating process

✓ Decoupled sensible and latent cooling

✓ Exothermic dehumidification
: Additional cooling to meet target temperature

Dehumidification in energy-efficient buildings



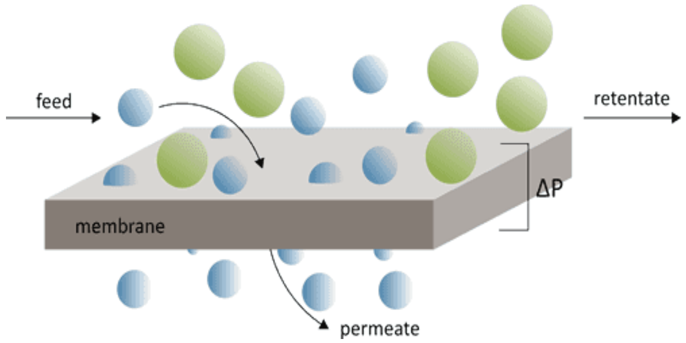
- Decoupling of sensible and latent cooling functions are required
- Isothermal dehumidification + Sensible cooling

Emerging dehumidification technology in building applications

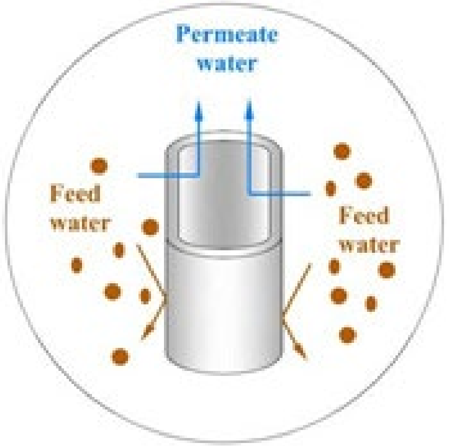
Membrane separation technology

Membrane application

- Water protection
- Air protection
- Soil protection
- Energetics
- Medicine
- Food
- Agriculture



<Flat-sheet membrane>

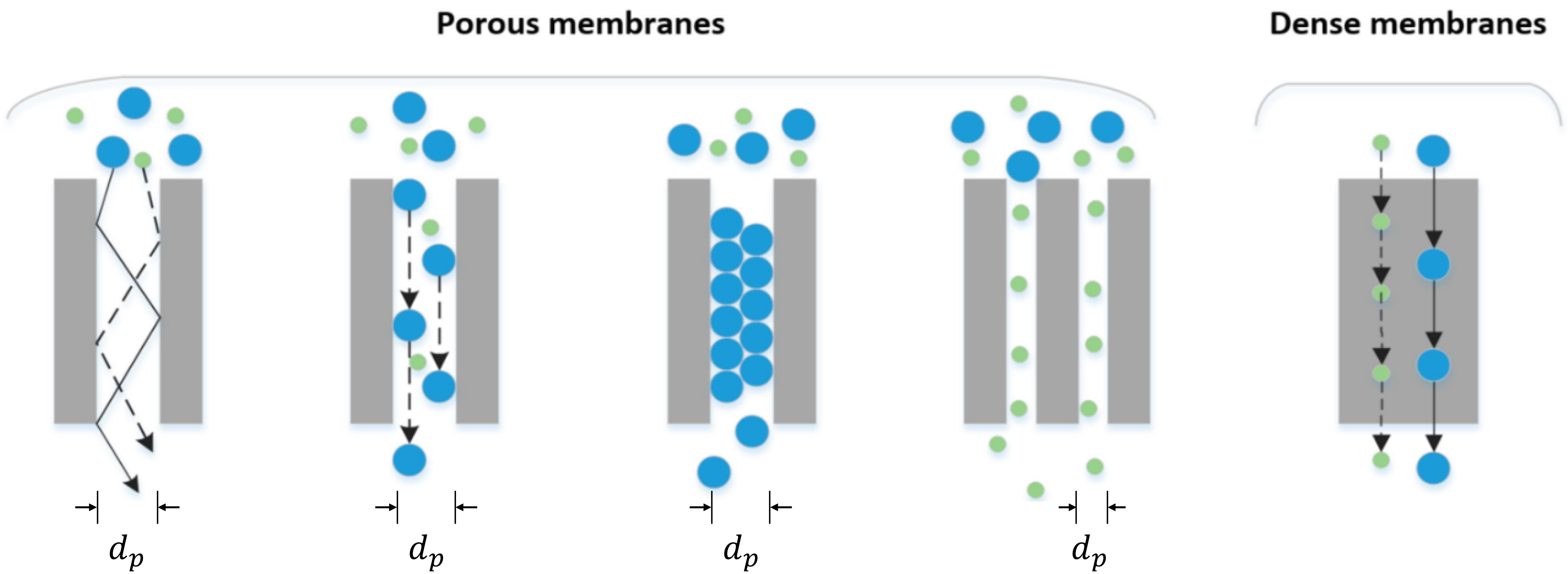


<Hollow fiber membrane>

✓ Membrane technology is a technology that **separates specific components, species, or substances.**

Membrane separation technology

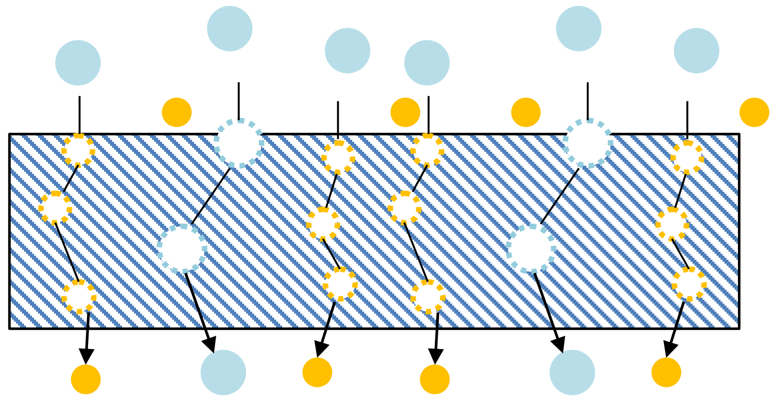
Membrane material



- Mass transfer in membrane is based on permeance, selective adsorption, and diffusion
- Membrane characteristics are determined by a pore size
  - Porous membrane: 0.1–10 nm
  - Dense membrane: < 0.1 nm

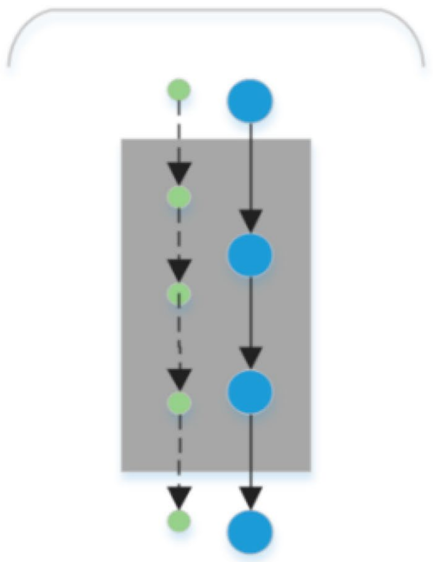
Membrane material

Characteristics of dense membrane



- **Permeance:** Diffusion rate of permeated molecules across the membrane
- **Selectivity**: Ratio of the permeance of more permeable molecules to others

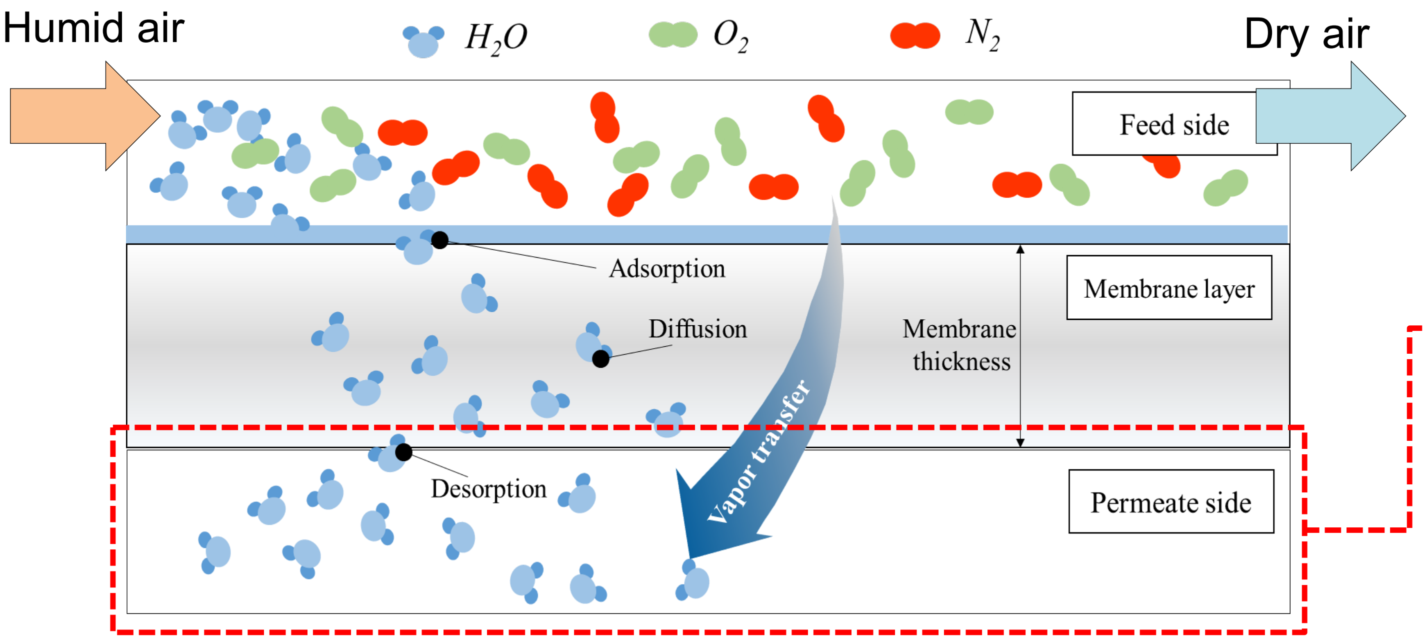
Dense membranes



Membrane material for "air dehumidification"

- Dense membrane is appropriate for dehumidification because gas separation requires membranes with a smaller pore size to selectively remove water vapor from air (mixed gas)

Dehumidification in membrane



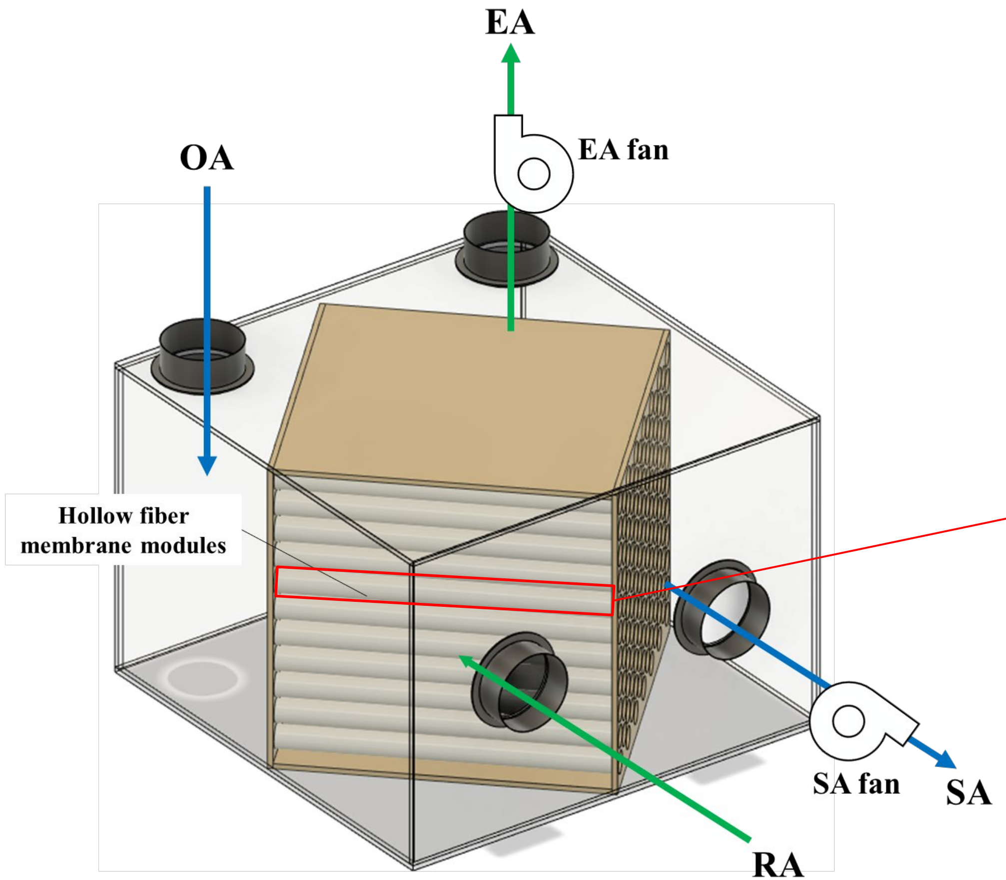
❖ **Vapor pressure gradient for dehumidification**

- **Generated by supplying relatively dry air**
  (e.g. Exhausted room air)
  ➢ **Latent heat recovery** in ventilation

- **Generated by depressurization**
  (e.g. Vacuum pump)
  ➢ **Dehumidification** in air-conditioning

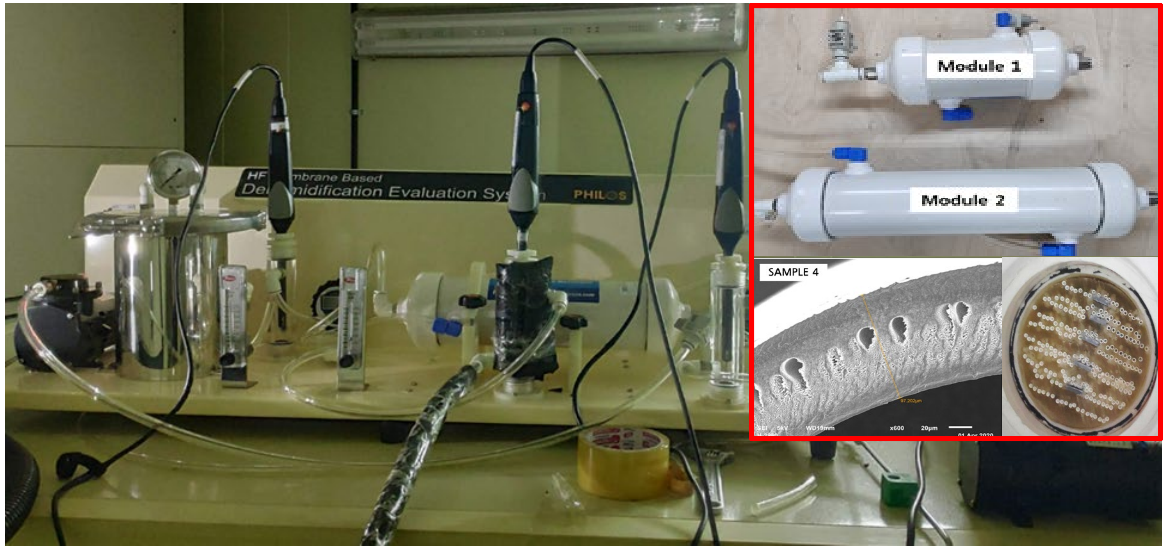
- Water vapor in humid air is transferred when existing vapor pressure gradient between feed and permeate sides
  - ➢ Isothermal process is more thermodynamically efficient than others to eliminate humidity
  - ➢ Heating or cooling source is not required during dehumidification

Hollow fiber membrane-based latent heat exchanger for ventilation



<Hollow fiber membrane-based latent heat exchanger (HFM-LHX)>

<Pre-test of hollow fiber membrane module>

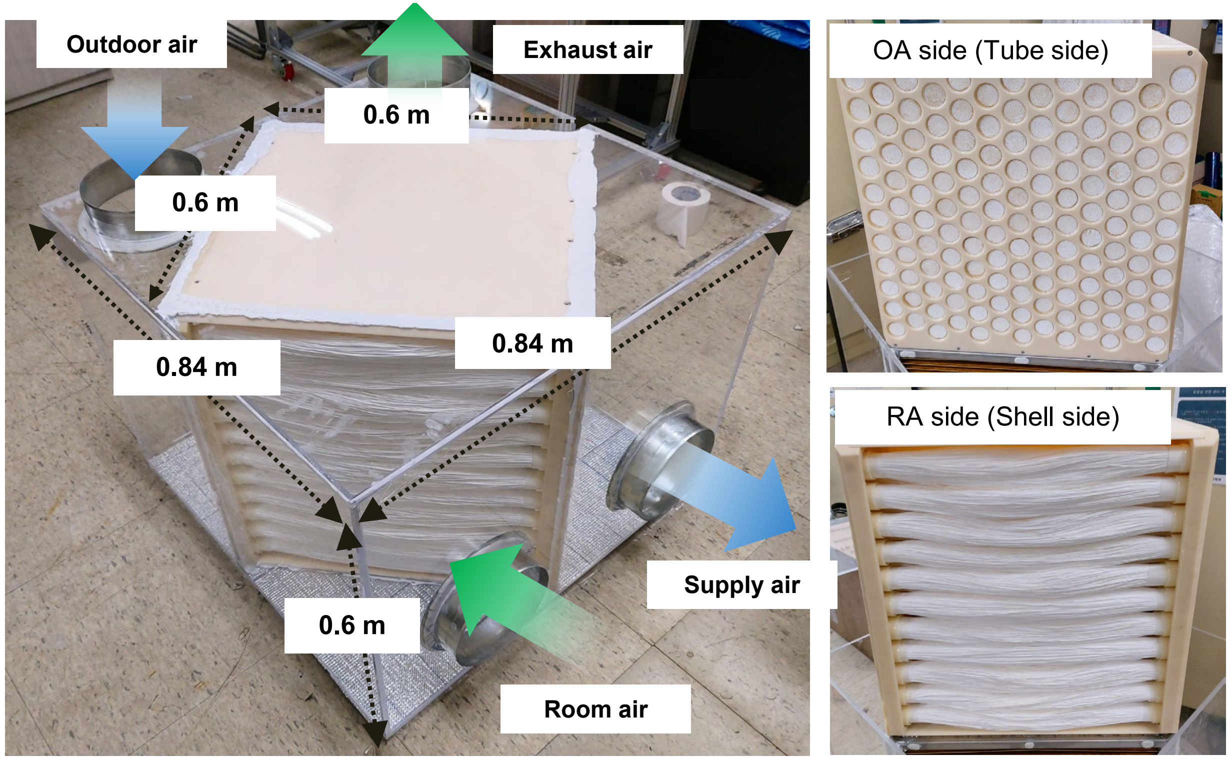


- Material: Polyethersulfone (PES) with Polyvinylpyrrolidone (PVP)
  - ❖ Hydrophilicity on the top layer, component diffusion on the porous substrate
- Effect of design factors was experimentally analyzed
  - ❖ Membrane surface area, moisture transfer coefficient, process air flow rate
- Design index of HFM-LHX (NTU_m) was derived based on test data

Preliminary study on air-to-air latent heat exchanger fabricated using hollow fiber composite membrane for air-conditioning applications, Energy Conversion and management, Cho et al., 2022.

Hollow fiber membrane-based latent heat exchanger for ventilation

<Prototype of HFM-LHX>



<Test condition of the prototype of HFM-LHX>

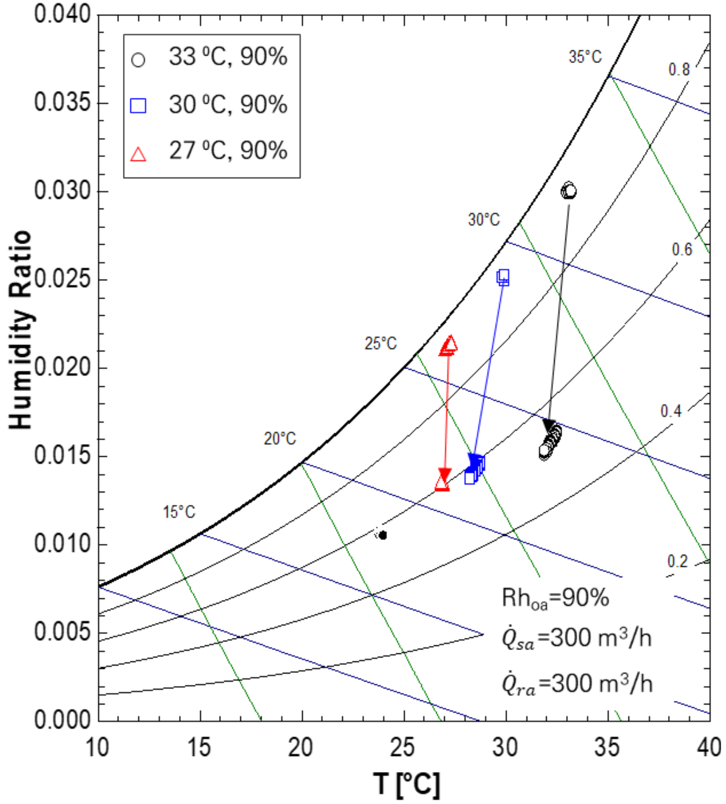
Parameter	Operating range
Outdoor air temperature (T_{oa})	27–33 ºC
Outdoor air relative humidity (Rh_{oa})	55–90 %
Room air temperature (T_{ra})	24 ºC
Room air relative humidity (Rh_{ra})	50 %
Outdoor air flow rate ($\dot{Q}_{oa}$)	300–600 m^3/h
Room air flow rate ($\dot{Q}_{ra}$)	

- Prototype with 450 m^3/h of air flow rate was built
- Thermal behaviors of HFM-LHX was experimentally examined under various outdoor air conditions

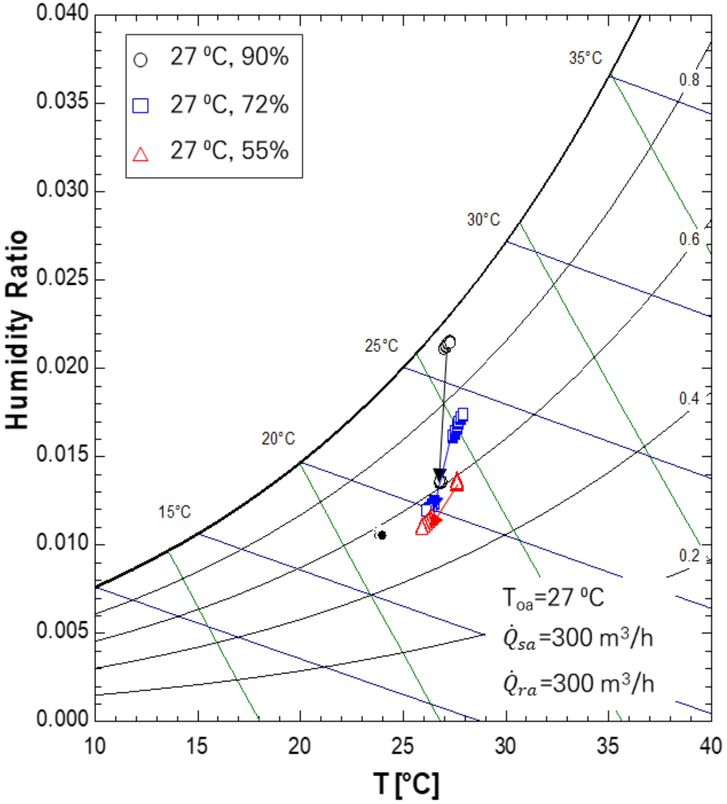
Development of empirical models to predict latent heat exchange performance for hollow fiber membrane-based ventilation system, Applied Thermal Engineering, Cho et al., 2022.

Current research on membrane dehumidification in HYU

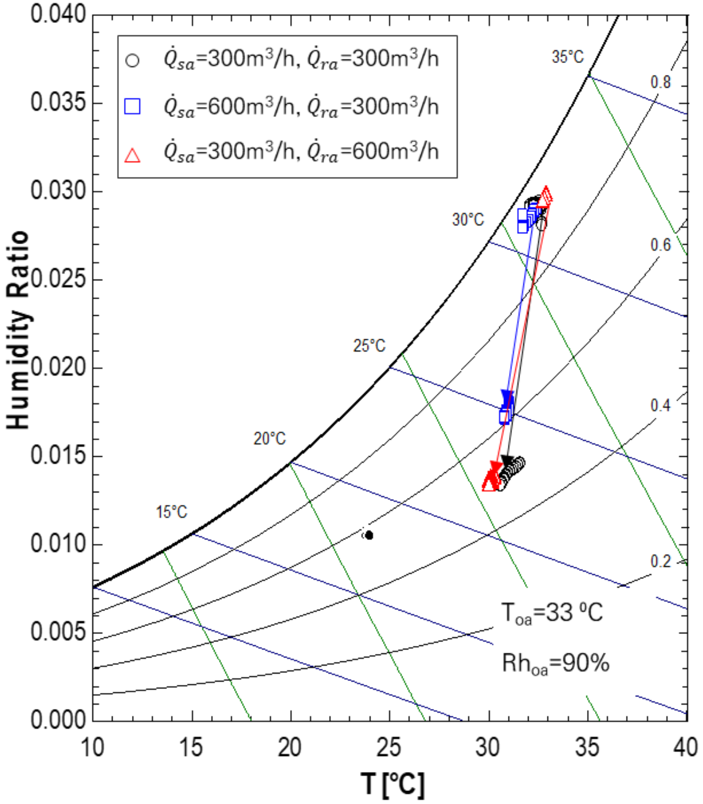
Hollow fiber membrane-based latent heat exchanger for ventilation



<OA temperature>



<OA relative humidity>



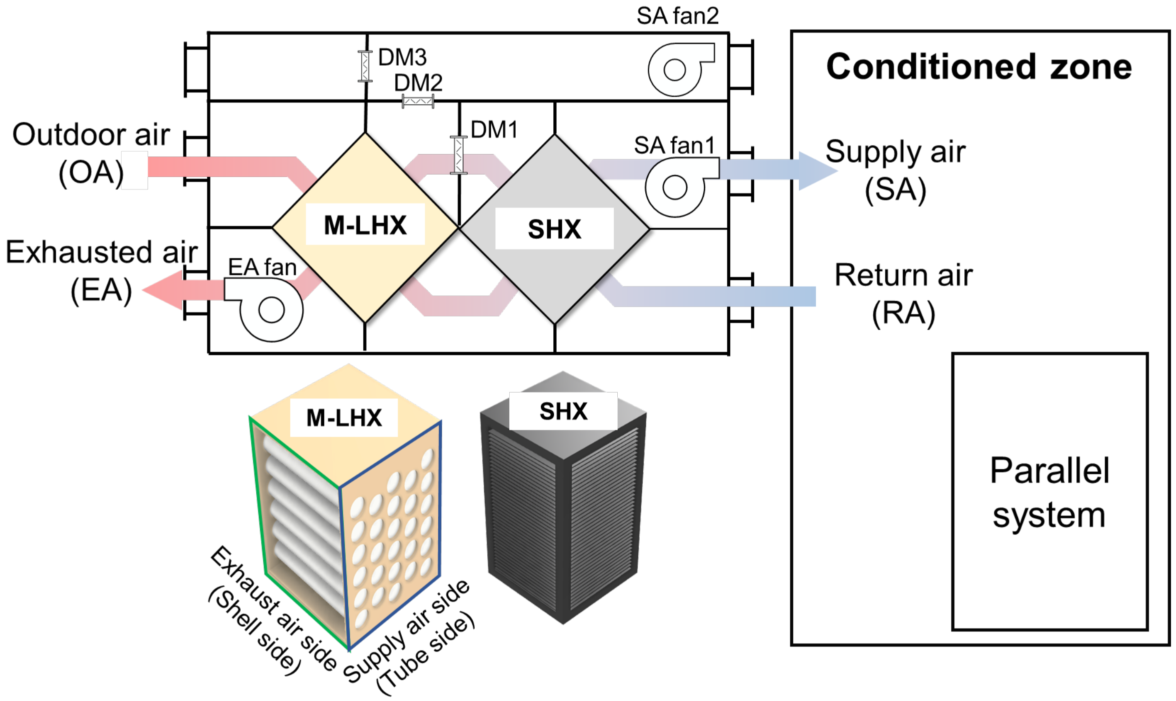
<RA/OA flow ratio>

- Latent heat exchange effectiveness: 60 – 82%
  - Latent effectiveness of conventional ERV core*: 20 – 60%

Development of empirical models to predict latent heat exchange performance for hollow fiber membrane-based ventilation system, Applied Thermal Engineering, Cho et al., 2022.

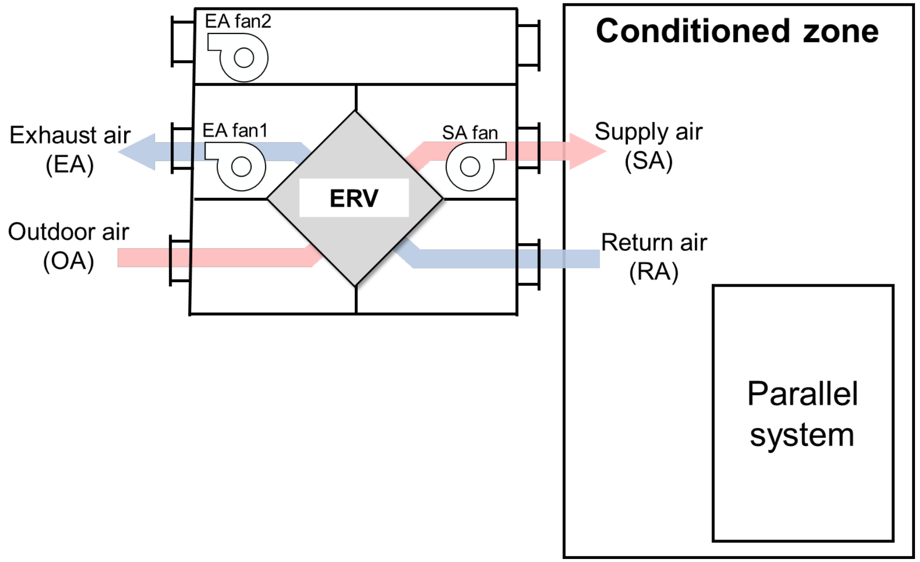
Hollow fiber membrane-based latent heat exchanger for ventilation

- **Proposed system: Latent heat exchanger-integrated ERV + A/C system**



- Enhanced latent heat recovery from M-LHX
  - ✓ Latent effectiveness: 63 – 80 %
- Additional sensible heat recovery from SHX
  - ✓ Sensible effectiveness: 65 – 70 %

- **Reference system: Conventional ERV+A/C system**

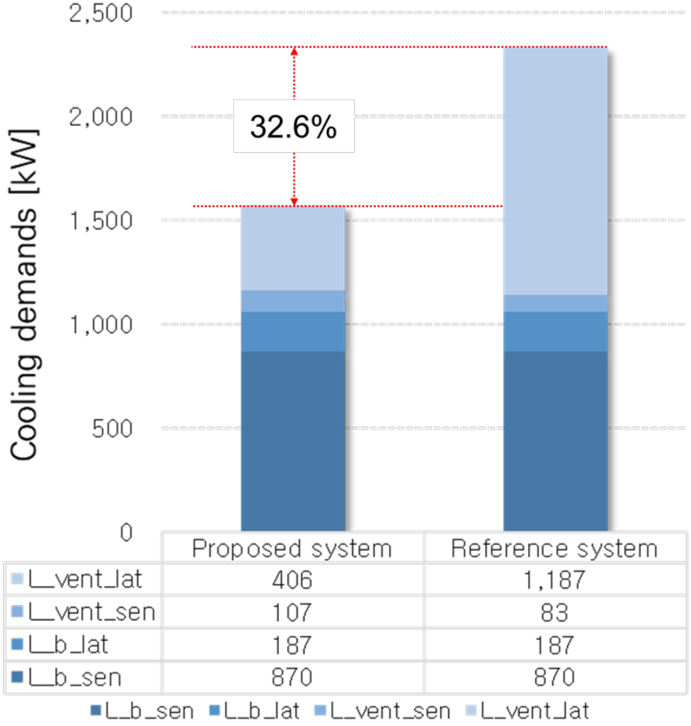


- Latent/sensible heat recovery effectiveness of Ref. ERV
  - ✓ Latent effectiveness: 50 – 55 %
  - ✓ Sensible effectiveness: 68 – 70%

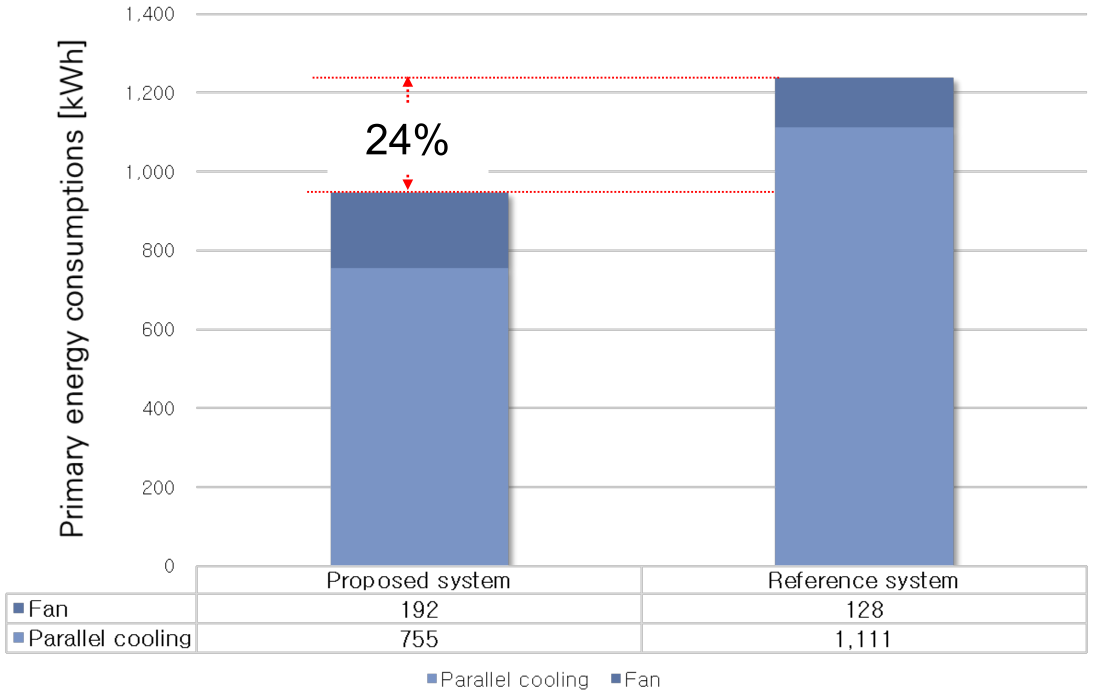
Energy saving potential of latent heat exchanger-integrated dual core energy recovery ventilator, Applied Thermal Engineering, Cho et al., 2023.

Hollow fiber membrane-based latent heat exchanger for ventilation

❖ **Comparison of energy demands in summer**



❖ **Comparison of primary energy consumptions in summer**

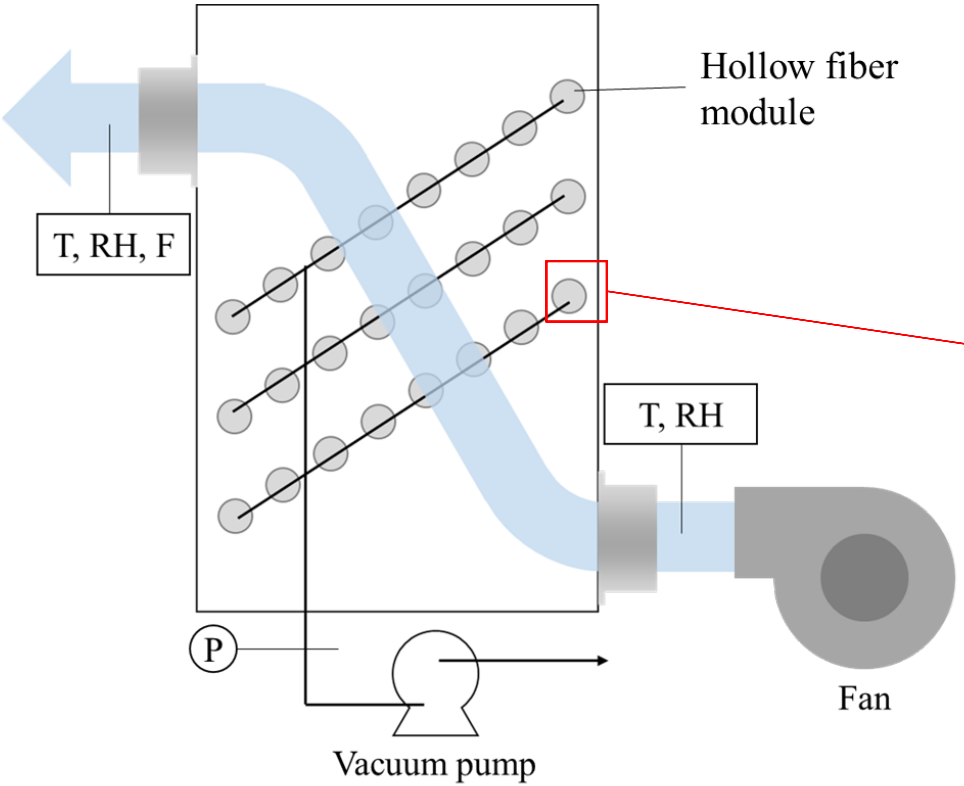


- Proposed system showed **32.6 % lower cooling demands** owing to reduced latent cooling load by the HFM-LHX
- Reduction of cooling demands contributes to **24% of energy conservations** although proposed system consumed 50% more fan energy

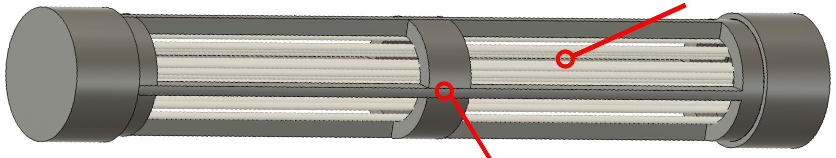
Energy saving potential of latent heat exchanger-integrated dual core energy recovery ventilator, Applied Thermal Engineering, Cho et al., 2023.

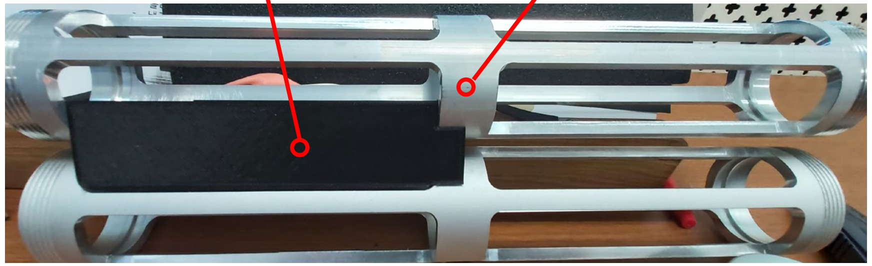
Current research on membrane dehumidifier in HYU

Vacuum-based membrane dehumidifier



- **Membrane module design**





✓ Hollow fiber membrane: Increase of membrane area and pressure resistance
✓ Module frame design: capable of supplying process air by a fan

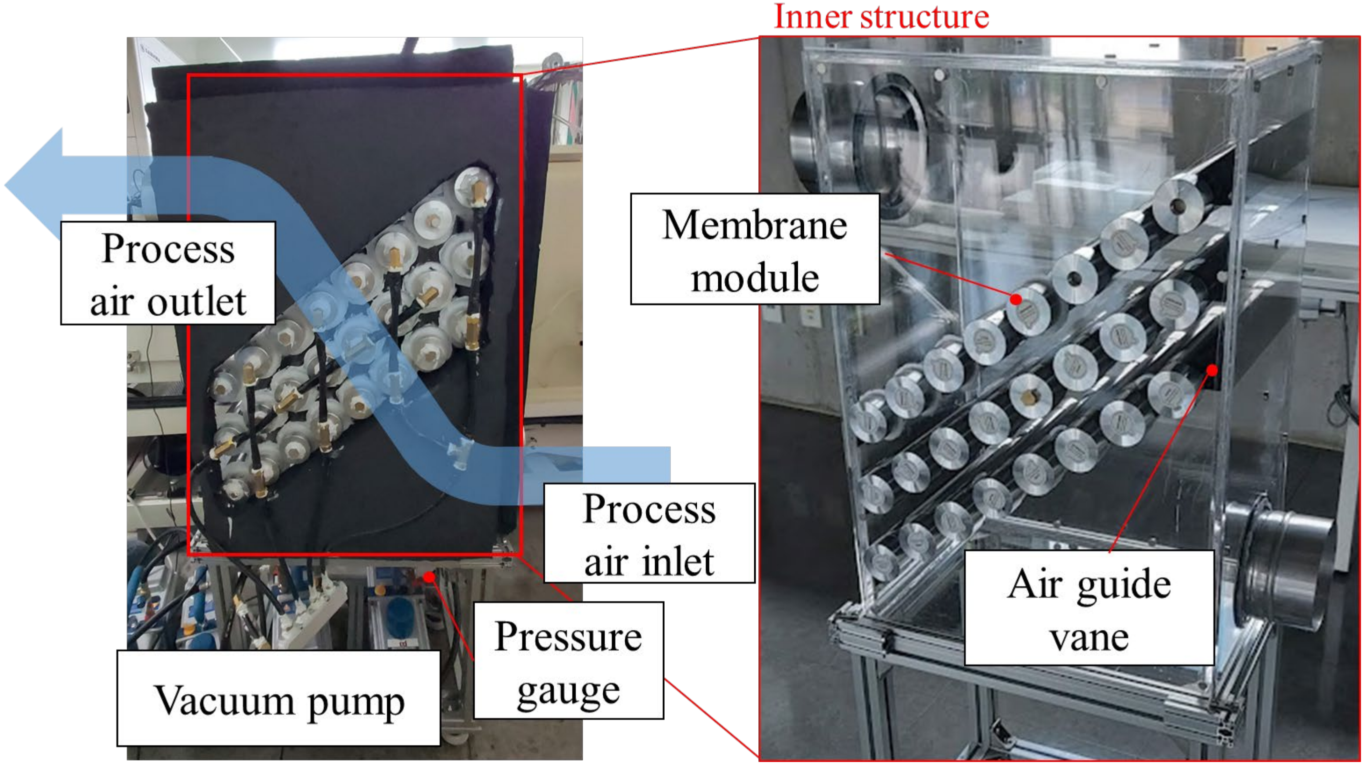
- Gas separation membrane dehumidifier is composed of **a gas separation membrane (selective moisture removal in the air) and a vacuum pump (mass transfer driving force).**

Current research on membrane dehumidifier in HYU

Vacuum-based membrane dehumidifier

- Pre-test: 5 module version

- Prototype: 24 modules(8 parallel, 3 series)



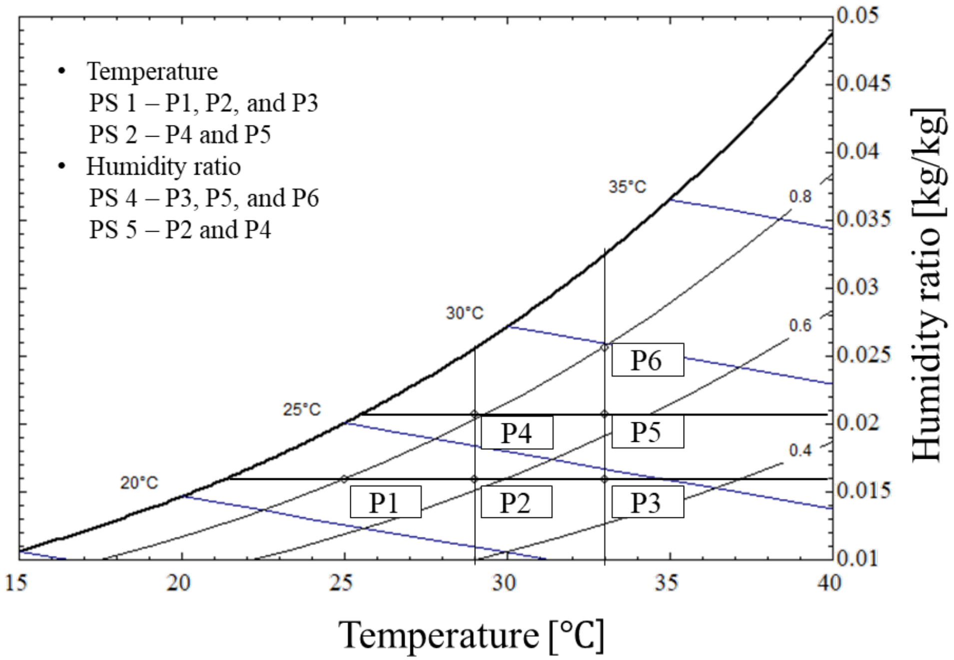
- Material: Polysulfone (dense membrane)
  - 50~100 (Selectivity), 680 GPU (Permeance)
- Maximum capacity of the prototype : 150 m^3/h

Vacuum-based membrane dehumidifier

- **Test condition of the prototype of VMD system**

Independent parameters	Range
Temperature [°C]	25 to 33
Humidity ratio [g/kg]	15.95 to 25.75
Airflow rate [m^3/h]	30 to 150
Permeate side pressure [kPa]	2.1 and 3.3

* Air test conditions: dehumidifier evaluation of ASHRAE and domestic standards



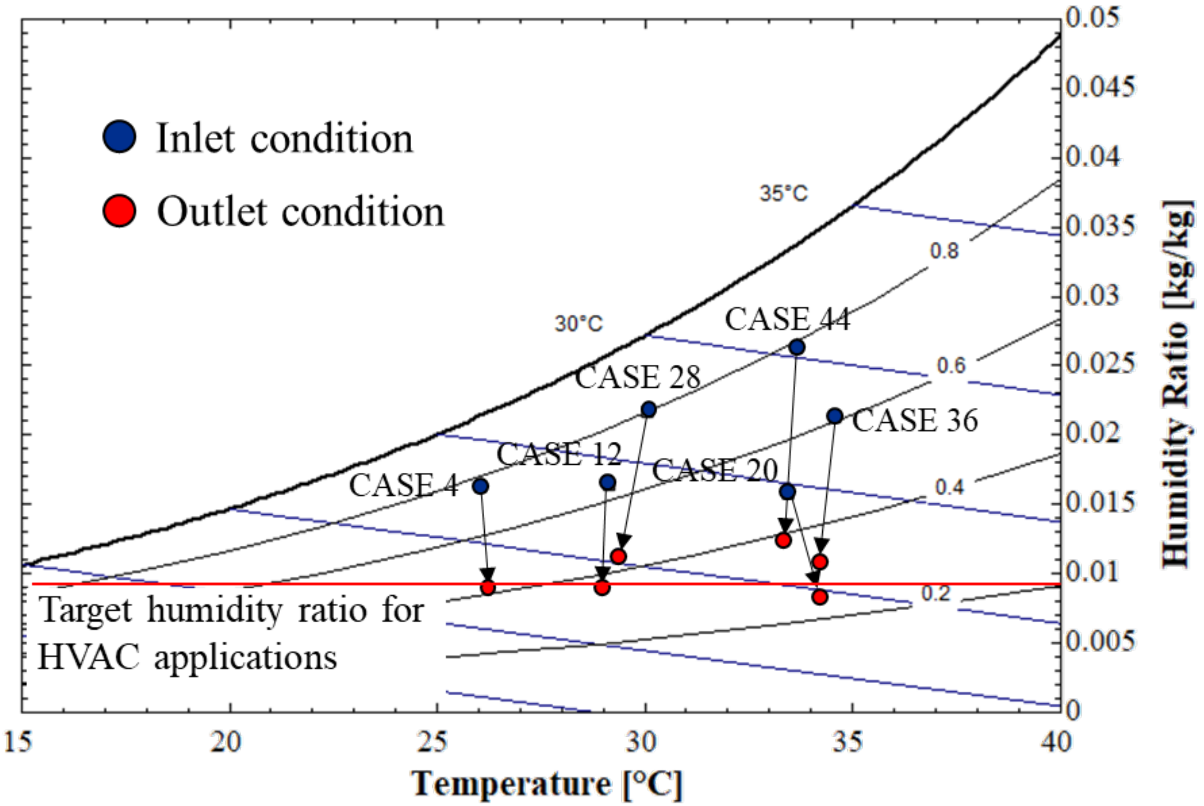
- **Performance index:** $\Delta\omega$, $\dot{m}_w$, $\boldsymbol{\varepsilon_d}$, **Coefficient of performance ($\boldsymbol{COP}$)**

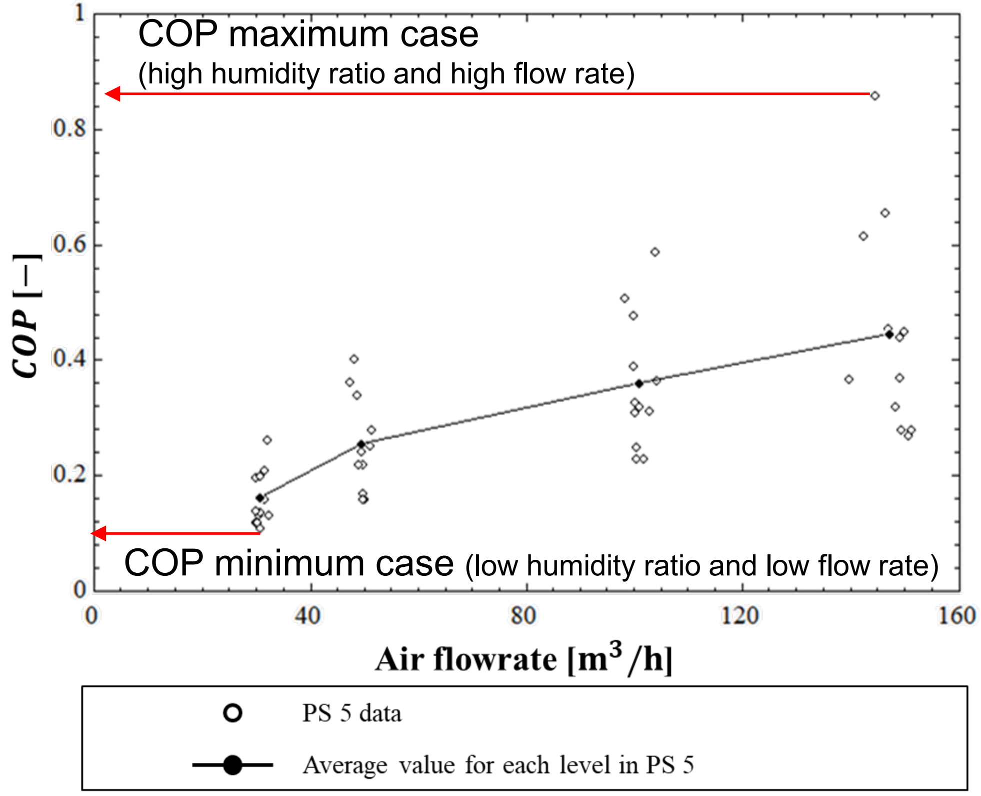
$$\Delta\omega = \omega_{oa} - \omega_{sa} \qquad \dot{m}_w = \dot{m}_{sa}(\omega_{oa} - \omega_{sa}) \qquad \varepsilon_d = \frac{w_{pro,in} - w_{pro,out}}{w_{pro,in} - w_{eq}} \qquad \text{COP} = \frac{\dot{m}_a(h_{a,in} - h_{a,out})}{\dot{P}_{vac}}$$

- Identification of **dehumidification performance (isothermal dehumidification)** and analysis of **influencing factors for dehumidification performance** in various outdoor conditions of the prototype

Current research on membrane dehumidifier in HYU

Vacuum-based membrane dehumidifier

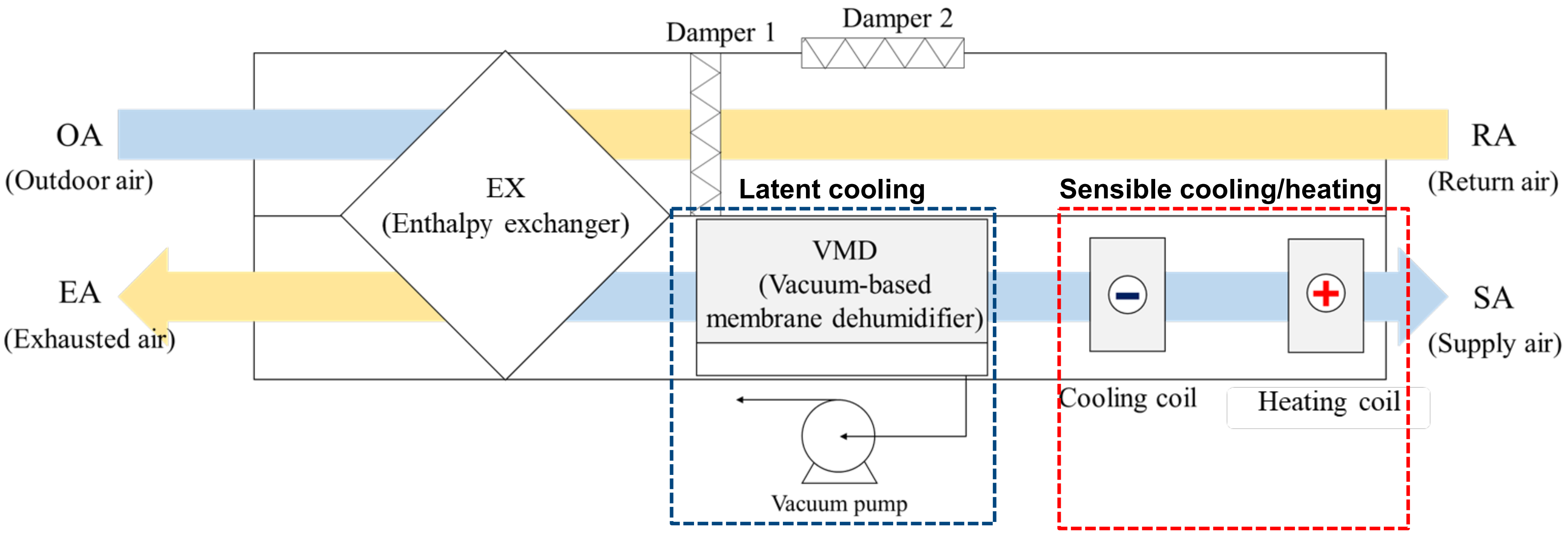




- Isothermal dehumidification in Psychometric chart
  - ✓ **Inlet and outlet temperature difference is lower than 1℃ (Isothermal dehumidification)**
- Energy performance (COP)
  - ✓ Experiment results: 0.1 ~ 0.8
  - ✓ **0.4 ~ 0.7 (9 g/kg of outlet humidity ratio in HVAC)**

Current research on membrane dehumidifier in HYU

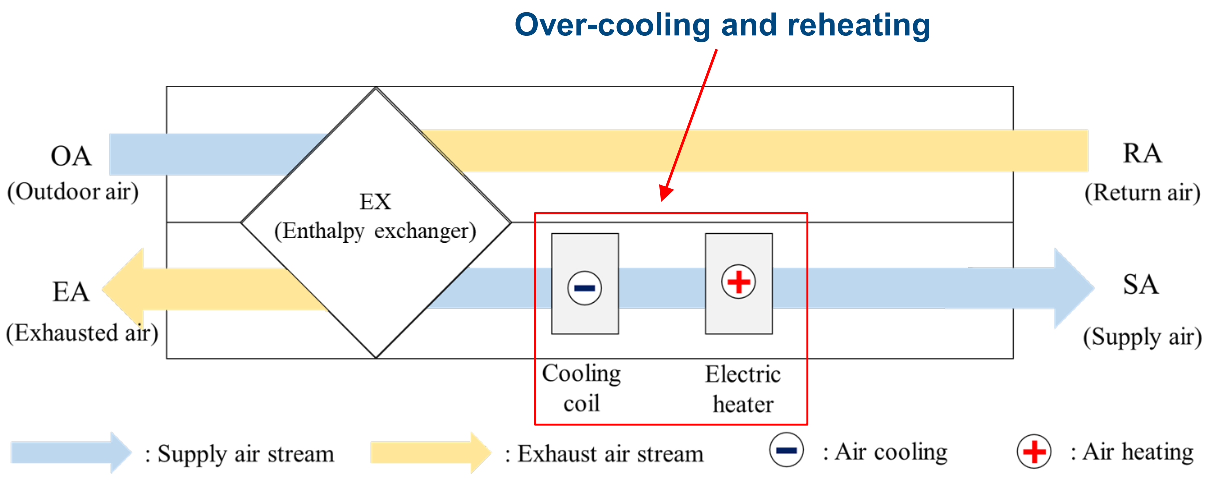
Proposed system: VMD-DOAS



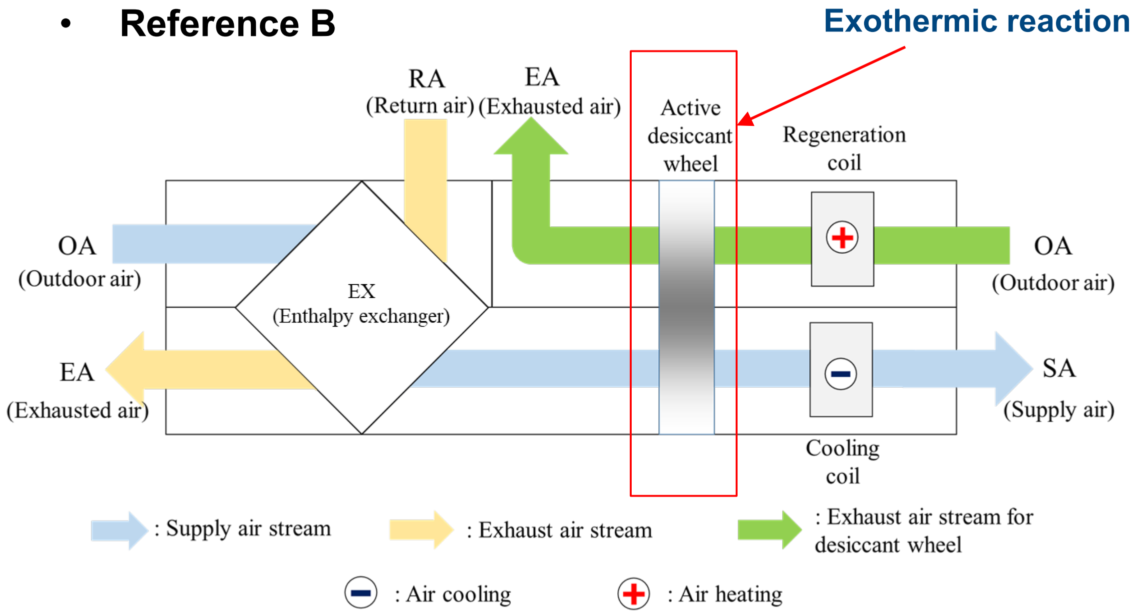
- **The proposed system consists of enthalpy exchanger, vacuum membrane dehumidifier, and cooling/heating coils**
- EX: pre-conditioning, VMD: Latent heat (Isothermal dehumidification), cooling/heating coils: sensible heat

Reference systems

- **Reference A**



- **Reference B**



- Reference A: **Cooling coil**
- Reference B: **Desiccant wheel**

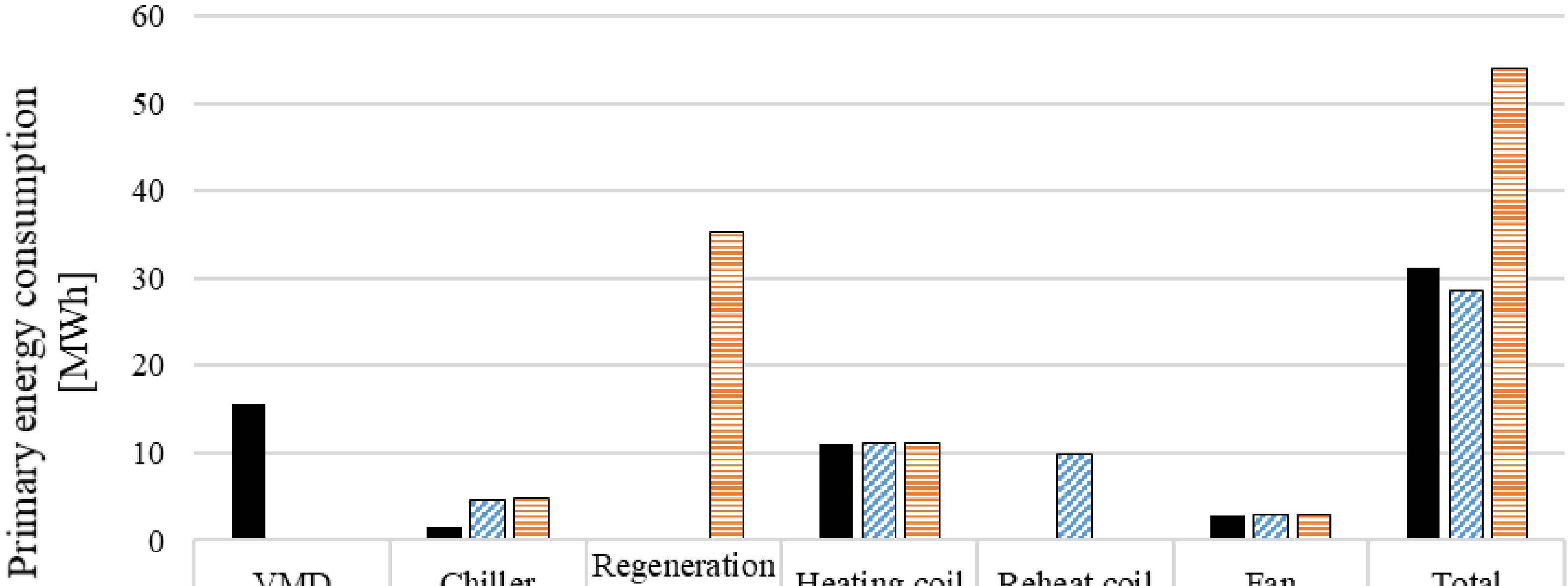
Studied DOASs: Identical operation condition

- Minimum ventilation amount (ventilation load) supply
- Indoor dehumidification load
- Supply air condition (Temp: Neutral Temp.(e.g., 24 ℃), humidity ratio: 9g/kg))

※ Parallel cooling/heating system: Mechanical heating and cooling system

Current research on membrane dehumidifier in HYU

Primary energy consumption

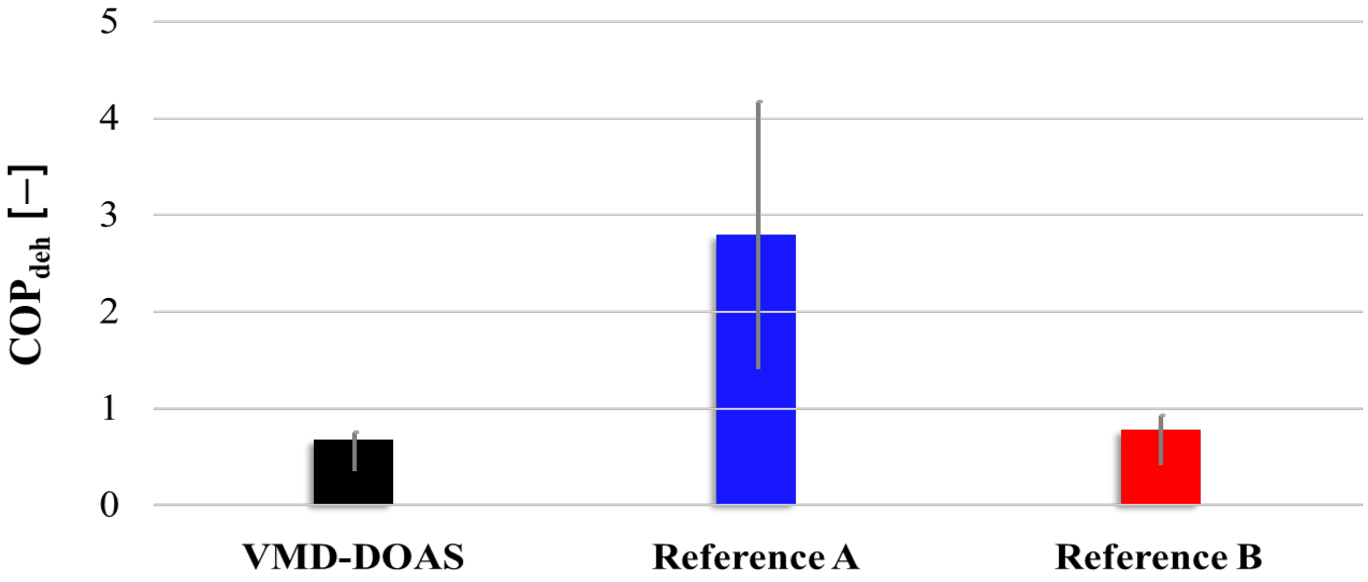


	VMD	Chiller	Regeneration heating coil	Heating coil	Reheat coil	Fan	Total
Proposed	15.55	1.52	0	11.11	0	2.92	31.1
Reference A	0	4.7	0	11.11	9.94	2.92	28.67
Reference B	0	4.75	35.26	11.11	0	2.92	54.04

- VMD-DOAS consumed **8.4% more energy than Ref. A, and 45.5% less energy than Ref. B.**

Current research on membrane dehumidifier in HYU

Comparison of COP_{deh}



	VMD-DOAS	Reference A	Reference B
AVG.	0.67	2.71	0.71
MIN.	0.35	1.40	0.41
MAX.	0.76	4.17	0.93
SD.	0.06	0.52	0.09

- **Low energy efficiency of VMD (COP_{avg} = 0.67)** requires more energy to process dehumidification.

Future works

Improvement of membrane materials

- **Selectivity and pemeance enhancement**
  - ➢ Desiccant coating

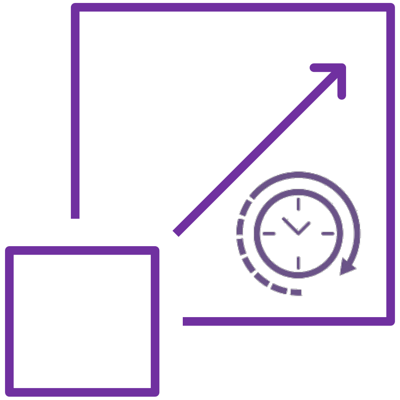
Optimization of membrane dehumidification system

- **Membrane structure and system configuration**
  - ➢ Air flow and thermal dynamics optimization

Membrane durability and stability

- **Membrane contamination and stability**
  - ➢ Bio-contamination and fouling effect test and stability

Scale up and field test



- **Real scale module and field test operation**
  - ➢ Long-term operation and evaluation with feasibility analysis

Thank you for your attention