# Ideal performance analysis of membrane-based vacuum dehumidification systems

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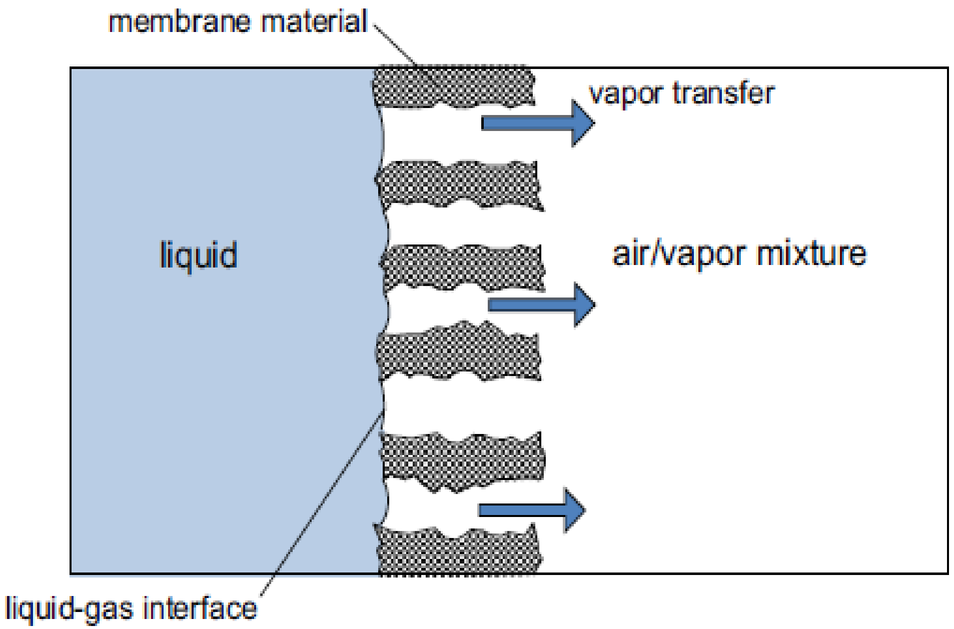
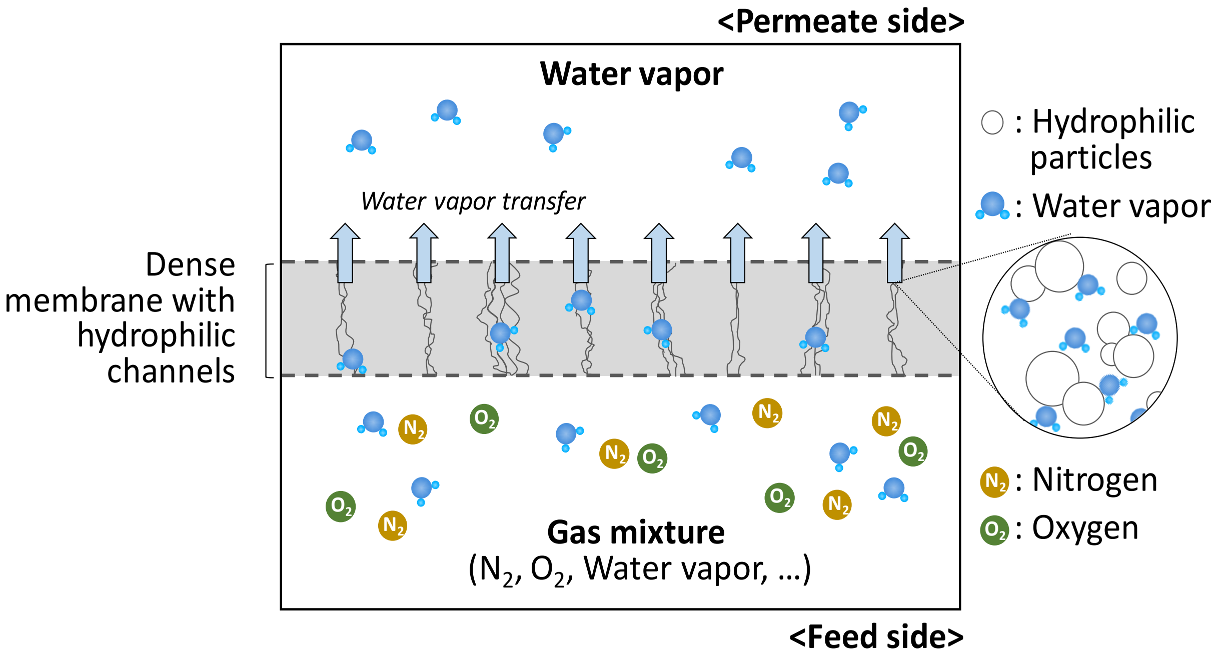
# Background

## ➢Membrane for Dehumidification

- **Types** : Porous (consists of nano-to-micro size pores) / Dense (consists of ion- nanochannels)
- **Driving force** : Chemical potential gradient (ex : pressure, concentration, temperature)




< Porous membrane >

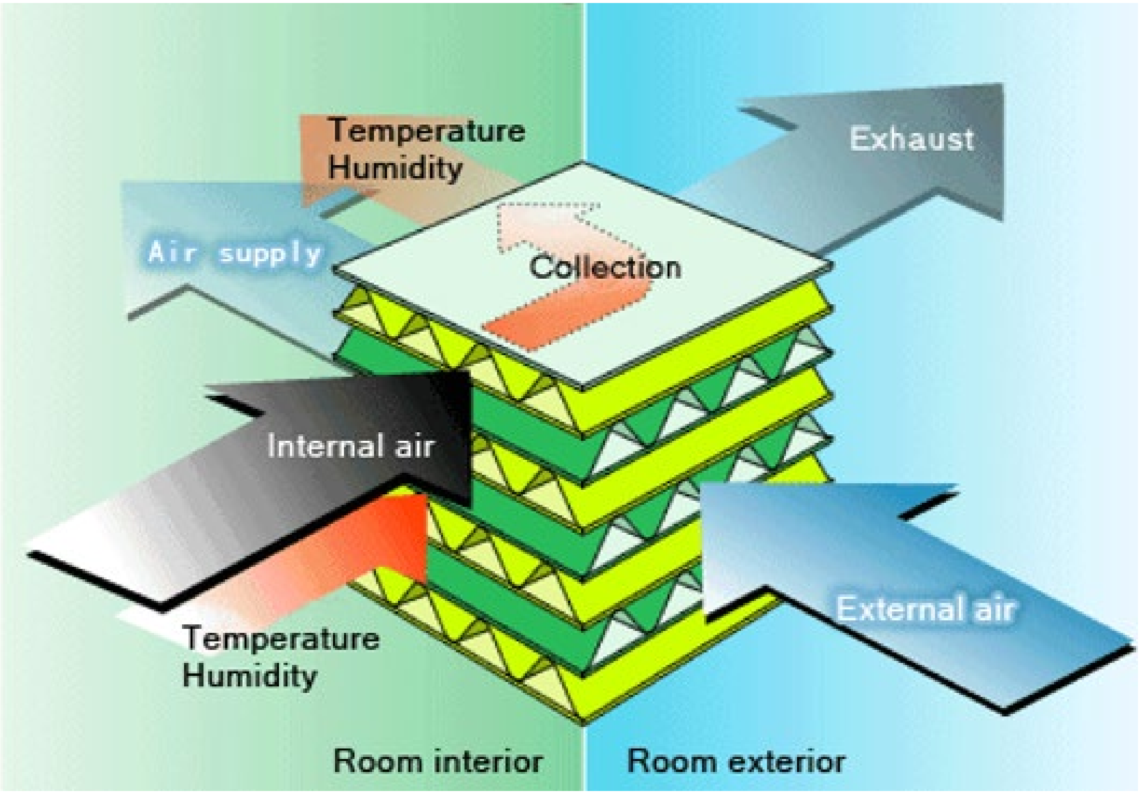



< Dense membrane >

# Background

## ➢Total Heat Exchanger

- Using membrane to **recover heat and moisture** from indoor air
- **Simple structure** and easy to manufacture
- Capable of performing **dehumidification/cooling** or **humidification/heating**
- Clear limitations with **passive** cooling/heating technology

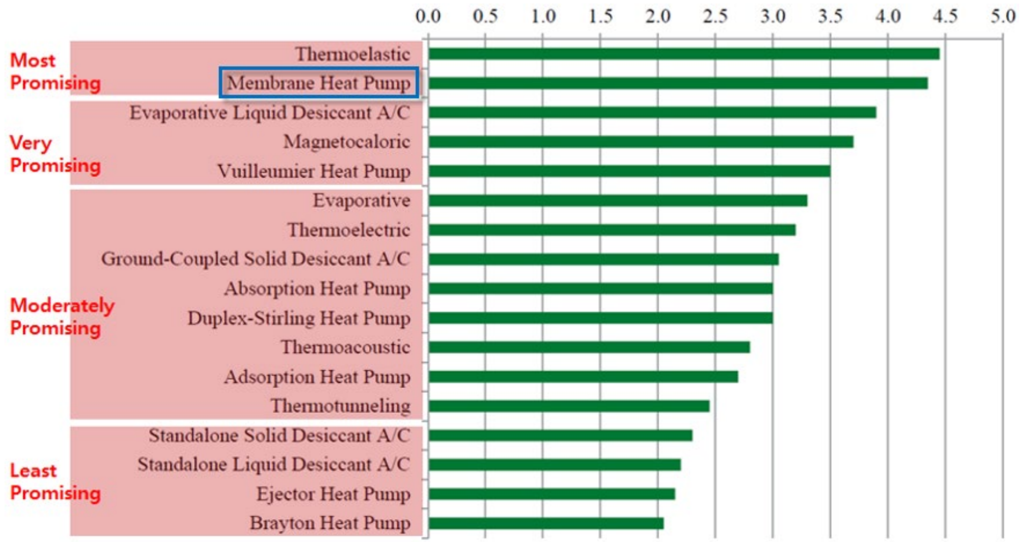


< Total heat exchanger>

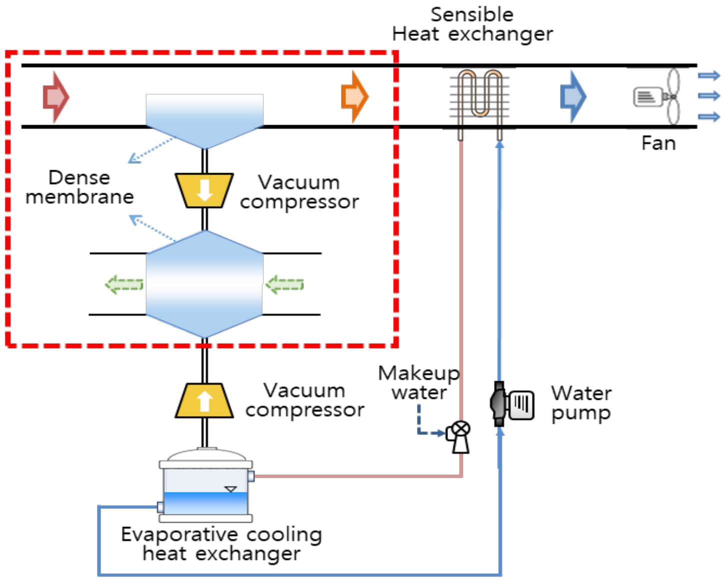
# Background

## ➢Membrane Heat Pump

- An **active dehumidification system** using water vapor selective dense membrane
- An **eco-friendly air conditioning system** to replace conventional vapor compression systems
- Divided into a **latent heat** removal unit and a **sensible heat** removal unit



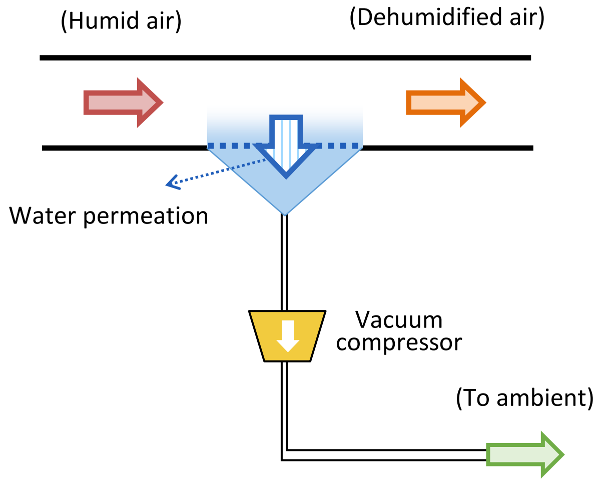

< Final ranking of technology options. DOE report on March 2014 >



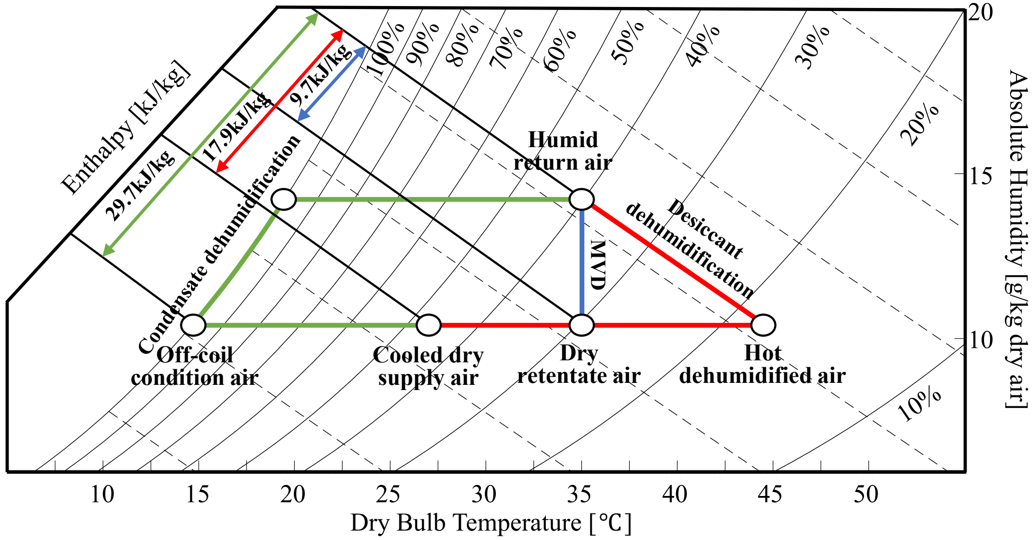

< Air conditioning system using dense membrane >

# ➢Membrane-based Vacuum Dehumidification System(MVD)

- Consists of **a water vapor selective membrane** and a **vacuum compressor**
- Maintains the permeate side under **a vacuum pressure** lower than the **vapor partial pressure**
- Removes water vapor from indoor air through **a vapor pressure difference** with the feed side
- Achieves **isothermal dehumidification** without any phase change




< D-MVD structure>

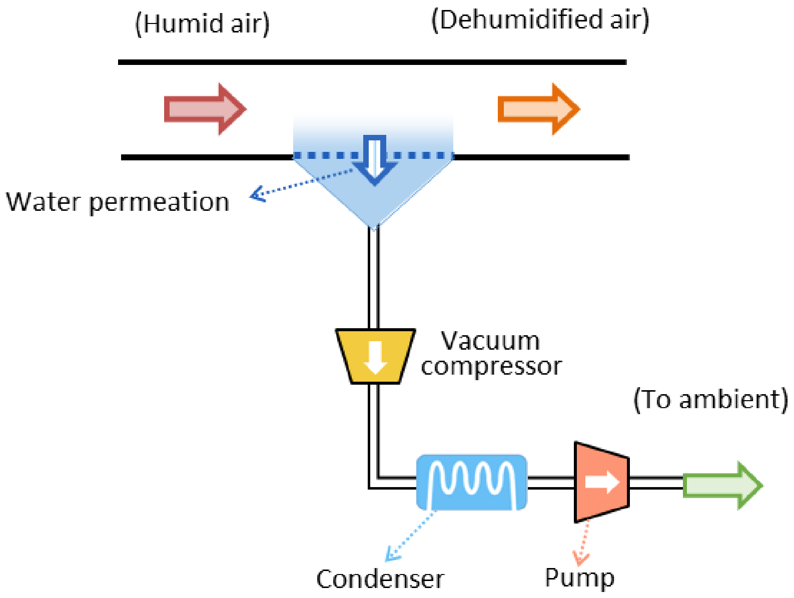


# ➢Permeation Characteristics of Membrane

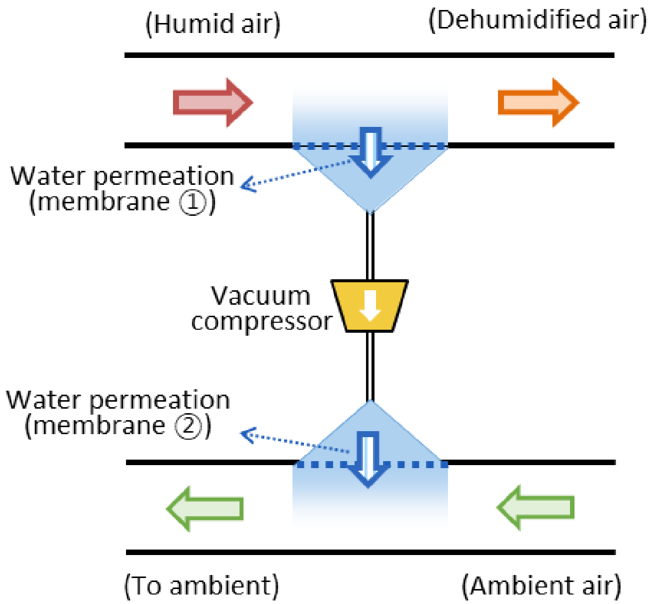
- **Permeance** [g/m2·Pa·s]
  : Permeating amount of a particular substance per unit time, unit area, unit pressure difference
  (Higher water vapor permeance → more water vapor removal)
- **Selectivity** [-]
  : Permeance ratio of two different substances
  (Higher water vapor selectivity → purer water vapor removal)

| Membrane | Permeance ($\mathcal{P}$) [$g/m^2 \cdot Pa \cdot s$] | Selectivity ($\mathcal{S}$) [-] | Reference |
|---|---|---|---|
| **Sulfonated poly (ether ether ketone)** | $9.0 \times 10^{-6}$ | 300000 | Sijbesma et al. (2008) |
| **Ionic liquid [emim][$BF_4$]** | $6.3 \times 10^{-6}$ | 16300 | Scovazzo (2013) |
| **Porous Ni-supported NaA Zeolite** | $122.4 \times 10^{-6}$ | 178 | Xing et al. (2013) |
| **Poly(vinylalcohol)-LiCl** | $8.1 \times 10^{-6}$ | 450 | Bui et al. (2015) |
| **polyethylene-amide** | $21.4 \times 10^{-6}$ | 808 | Lee et al. (2021) |

## ➢Improved MVDs




< Condenser combined MVD, C-MVD >




< Water vapor discharge MVD, W-MVD >

- Install **additional membrane** at compressor outlet
- Discharge **water vapor** by additional membrane mass exchanger

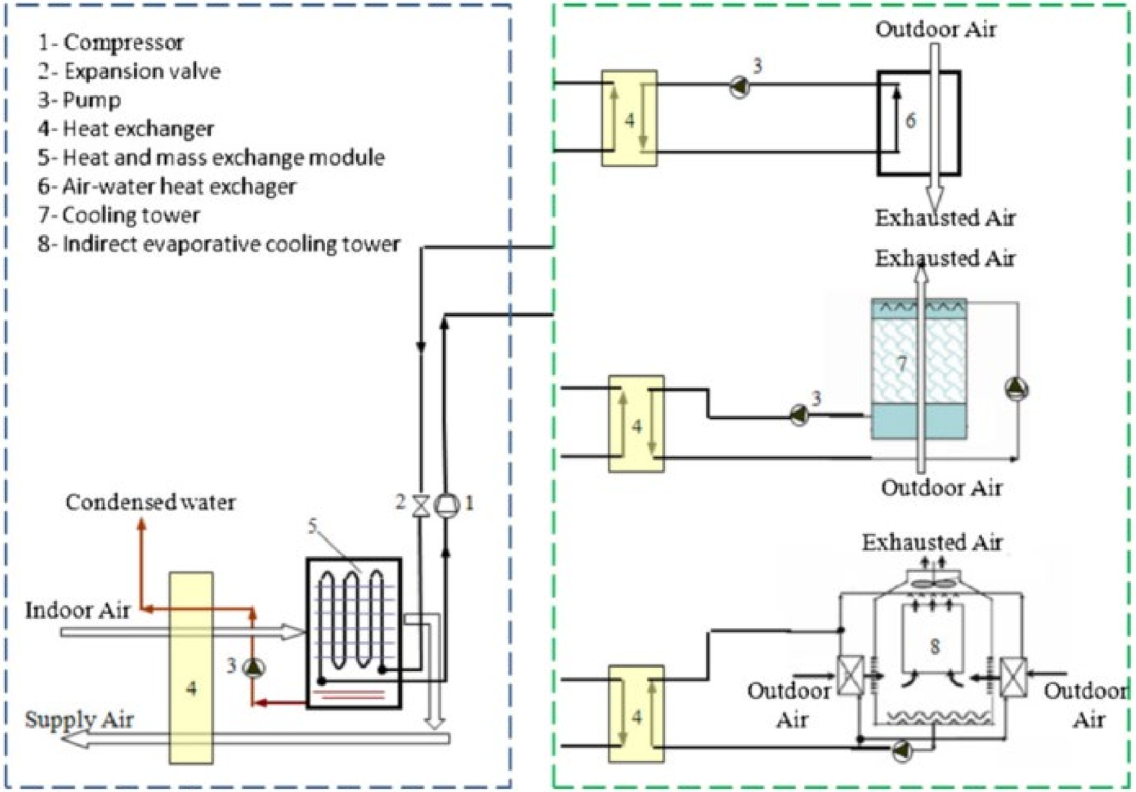
- Compress **water vapor** to saturation pressure at ambient temperature
- Discharge **liquid water** after condensing compressed water vapor

# Ideal COP of Dehumidification Systems

## ➢Condensing Dehumidification

- System-based approximation
- Heat reduction to heat sink
- Three way to exhaust heat
- Highly influenced by **heat sink temperature**

$$COP_{con} = \frac{T_{DP.I}}{T_R - T_{DP.I}}$$




< Schematic of condensing dehumidification system, Zhang(2013) >

# Ideal COP of Dehumidification Systems

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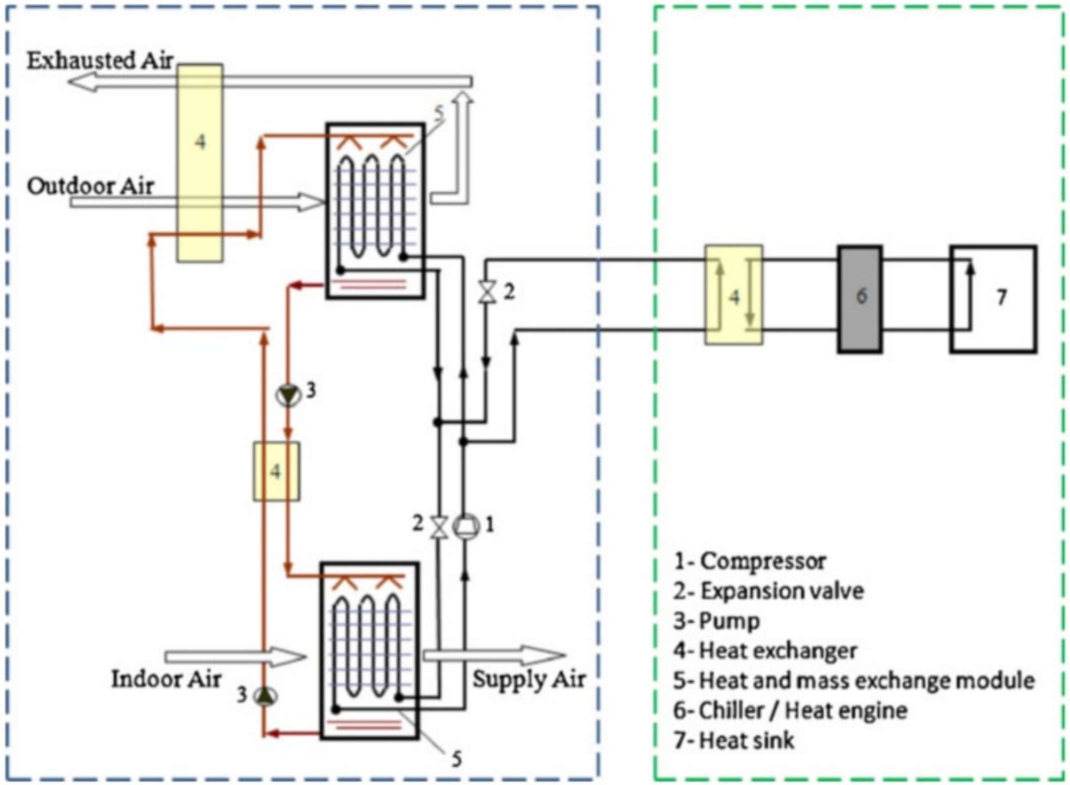
## ➢Liquid Desiccant Dehumidification

- System-based approximation
- Ideal solution analysis
- Need liquid desiccant regeneration cycle
- Highly influenced by **absolute humidity of regeneration air**

$$COP_{\text{des}} = \frac{1}{T_{\text{R}}} \frac{T_{\text{iso.O}} T_{\text{iso.}I}}{T_{\text{iso.O}} - T_{\text{iso.}I}}$$




< Schematic of liquid desiccant dehumidification system, Zhang(2013) >

# Ideal COP of Dehumidification systems

## ➢Minimum Work for Gas Separation

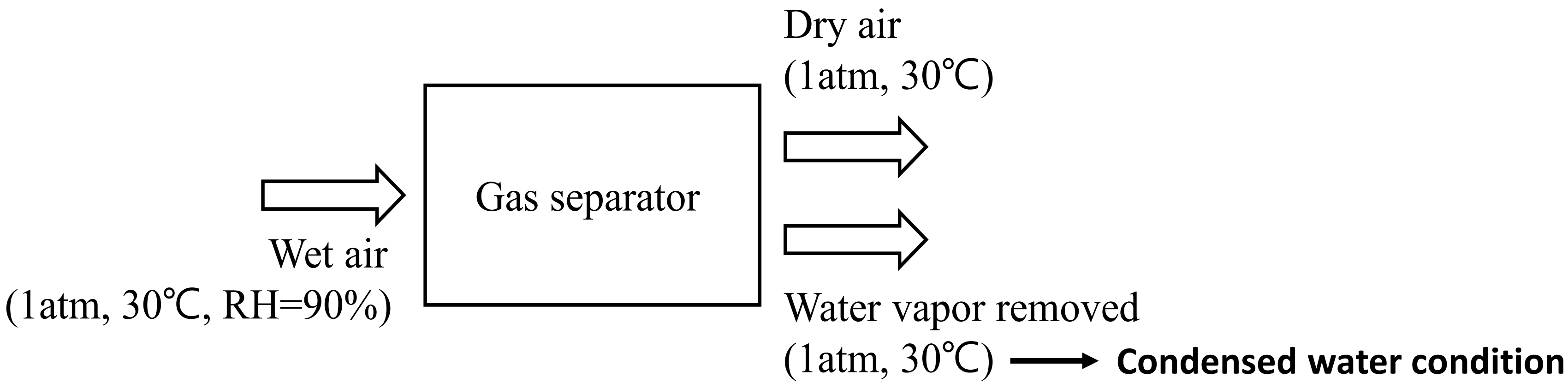
- **Complete gas separation work**

\- **The reversible minimum work** required for complete separation under **isobaric** and **isothermal** conditions

- Defined as the **complete gas separation work change**

$W_{sep} = -nRT(X_a lnX_a + X_w lnX_w)$, $W_{min} = \Delta W_{sep}$

→ **Not feasible** in the MVD due to the **condensation** of water vapor




< Schematic of dehumidification by gas separation at constant pressure and temperature >

# Ideal performance analysis

## ➢Assumptions

- Water vapor **permeance** and **selectivity** are infinite.

- Water vapor can permeate through the membrane **without any pressure difference** between both sides.
- **Only water vapor** can pass through the membrane.

- There is **no irreversibility** in the compression and heat exchange processes.

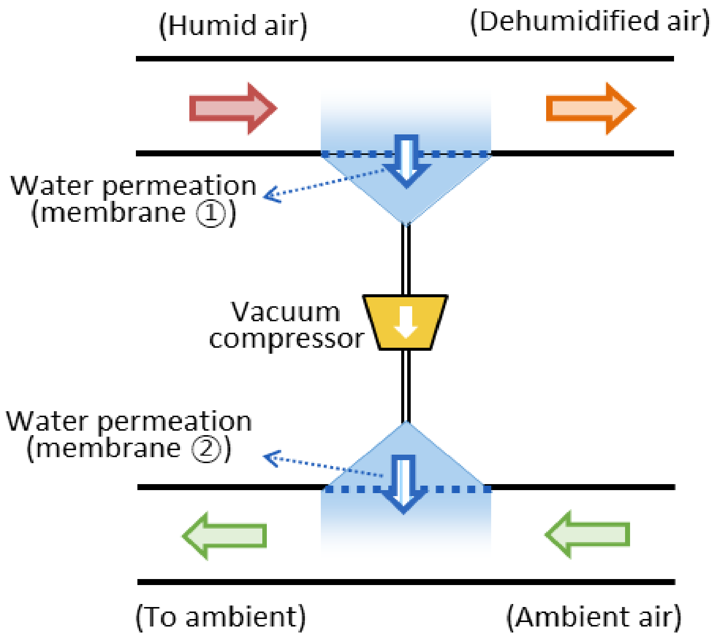
- The separated vapor follows **a reversible adiabatic compression** followed by an **isothermal compression**.
- The heat exchange occurs at the outdoor air temperature, **without any temperature difference**.

- **Thermal changes** inside and outside due to permeation can be ignored.

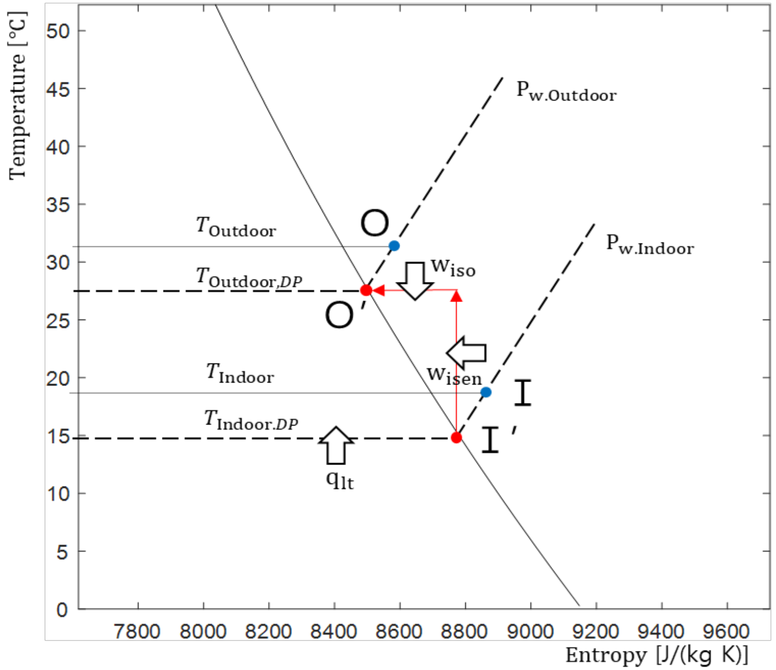
- **The amount of water vapor permeating through the membrane** is much smaller than the amount of air inside and outside.

# Ideal performance analysis

## ➢Ideal Dehumidification COP of W-MVD




< W-MVD structure >



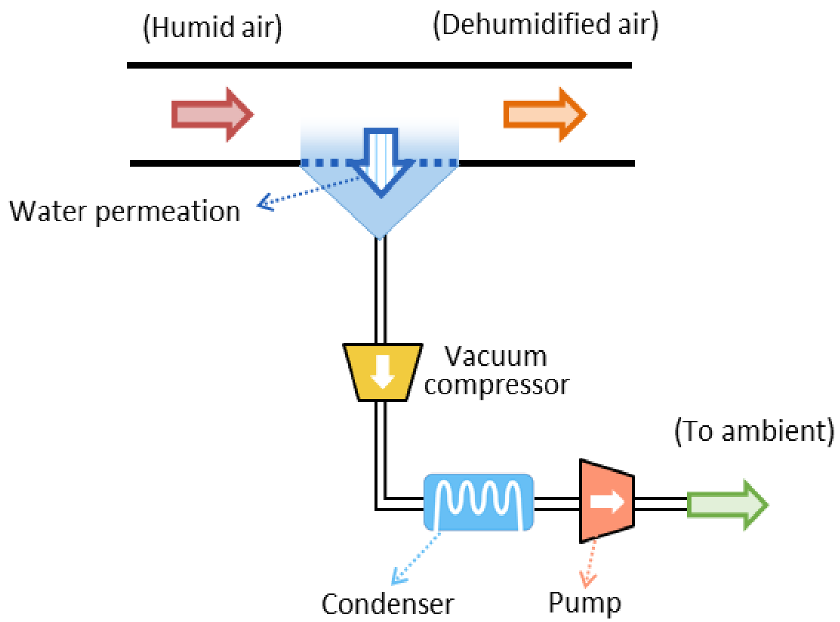

< The water vapor T-s diagram of the ideal W-MVD >

$RH_{Indoor}, RH_{Outdoor} \neq 100\%$

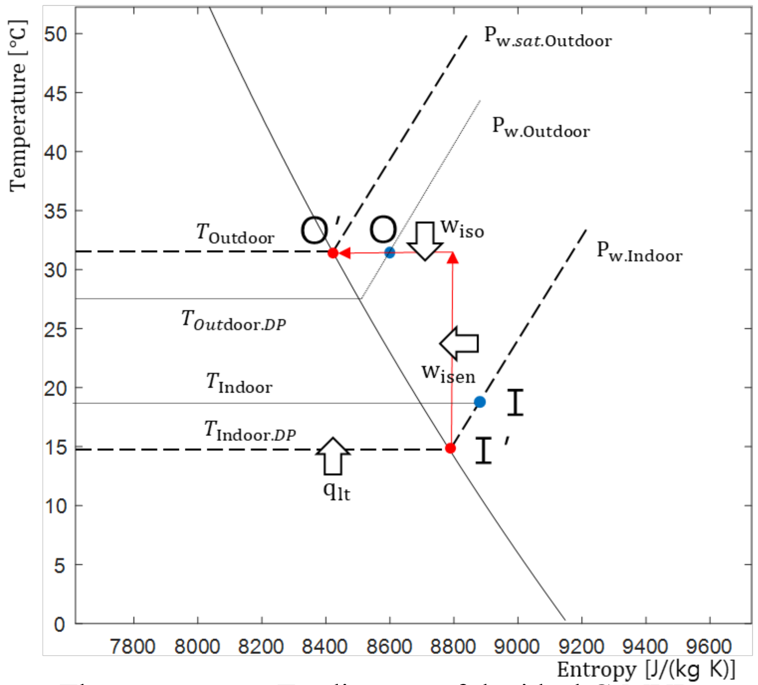
- **The internal pressure of the membrane unit** is equal to **the vapor partial pressure** of the air in contact
- Dependent to the indoor and outdoor **temperature** and **humidity**

$$COP_{W-MVD.ideal} \approx \frac{T_{DP.I}}{T_{DP.O} - T_{DP.I}}$$

## ➢Ideal Dehumidification COP of C-MVD




< C-MVD structure >




< The water vapor T-s diagram of the ideal C-MVD >

$RH_{Indoor}, RH_{Outdoor} \neq 100\%$

- **The exit pressure of the compressor** is equal to **the saturation pressure** at the outdoor temperature.
- Independent to the outdoor **humidity**

$$COP_{C-MVD.ideal} \approx \frac{T_{DP.I}}{T_O - T_{DP.I}}$$

# Ideal performance analysis



## ➢Compressor Modeling

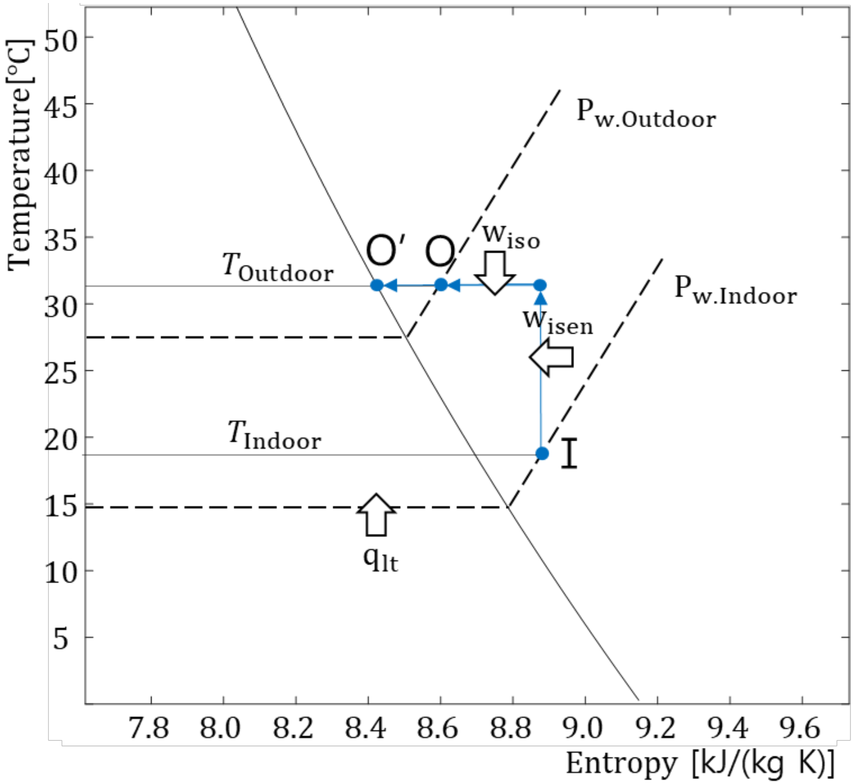
- Isentropic compression followed by isothermal compression at **ambient temperature**
- W-MVD :
  Compressed to **the outdoor air conditions** Point O
- C-MVD :
  Compressed to **the saturation condition** Point O'

- **Compressor work**

$$w_{isen} = \frac{k}{k-1} R_w T_I \left(r_{p.isen}^{\frac{k-1}{k}} - 1\right) \text{ [kJ/kg]}$$
$$w_{iso} = R_w T_O \ln(r_{p.iso}) \text{ [kJ/kg]}$$

- **Dehumidification COP**

$$COP_{DH} = \frac{h_{lt}}{w_{isen} + w_{iso}} \text{ [-]}$$




< T-s diagram >

$RH_{Indoor}, RH_{Outdoor} \neq 100\%$

# Ideal performance analysis

## ➢Exergy Analysis

- **The minimum work** calculation based on the **exergy change** with reference to the ambient air conditions

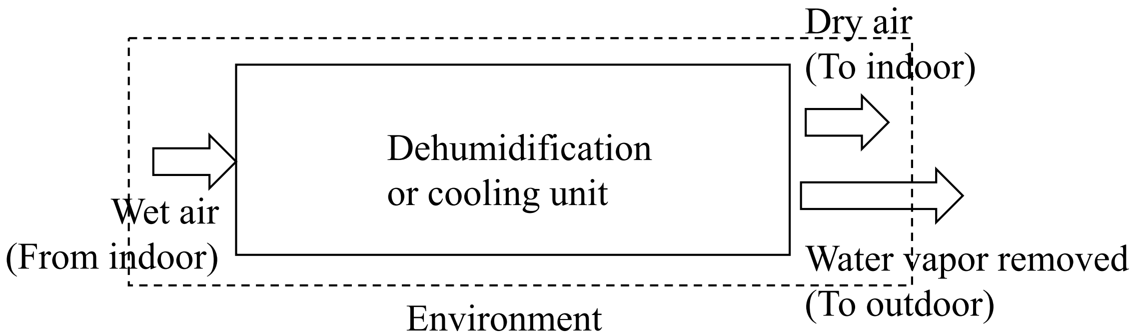
- **Total exergy of humid air**

$$\xi = (c_{p,a}+\omega c_{p.w})T_0\left(\frac{T}{T_0}-1-ln\frac{T}{T_0}\right)+(1+\tilde{\omega})R_aT_0 ln\frac{P}{P_0}$$
$$+R_aT_0\left((1+\tilde{\omega})ln\frac{1+\tilde{\omega}_0}{1+\tilde{\omega}}+\tilde{\omega}ln\frac{\tilde{\omega}}{\tilde{\omega}_0}\right)$$

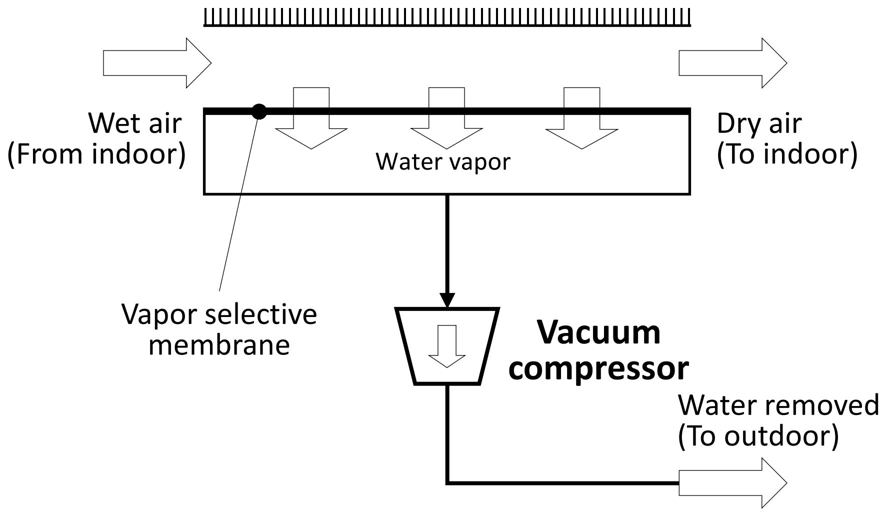
$\xi$: Exergy [kJ/kg]

- **Ideal dehumidification COP**

$$COP_{DH} = \frac{m_{wet}h_{wet}-m_{dry}h_{dry}}{m_w\xi_w+m_{dry}\xi_{dry}-m_{wet}\xi_{wet}} \text{ [-]}$$



< Control volume for exergy analysis (Labban, 2017) >



< Basic structure of MVD >

# Ideal performance analysis

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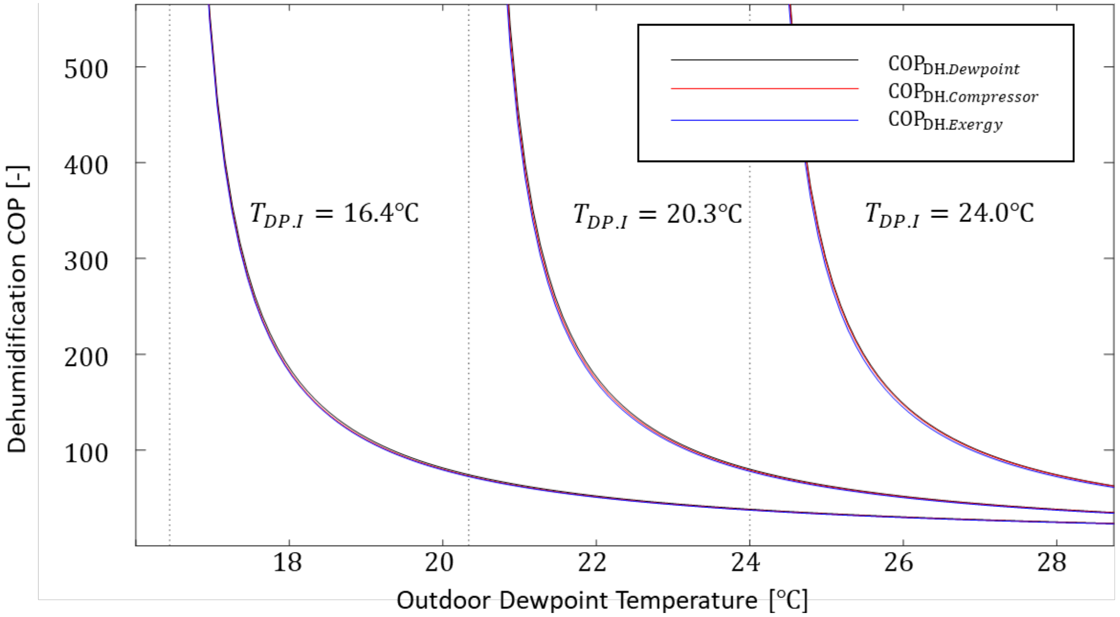
## ➤COP Calculation

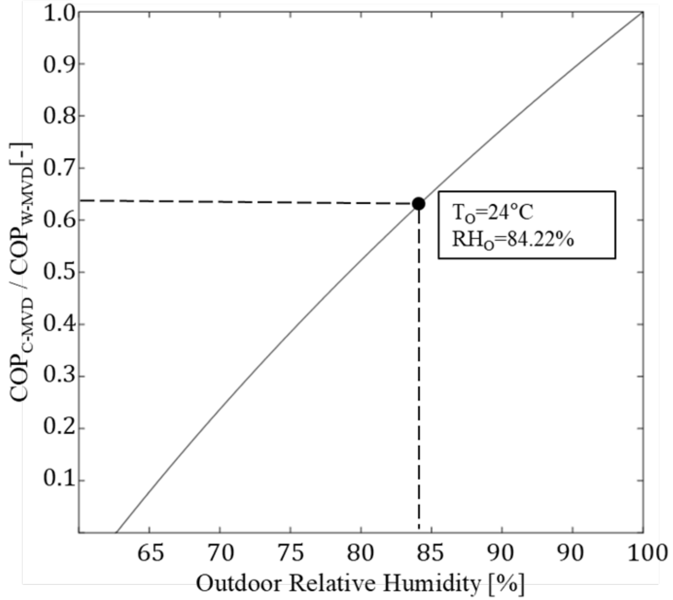
- COP of W-MVD calculated at indoor temperature of 24℃ and relative humidity of 62.66~100%, with outdoor relative humidity of 84.22%
- **Overlapped results** calculated by three ways. (dewpoint temperature, compressor modeling and exergy analysis)
- **Maximum performance** of dehumidification through **gas separation** achieved by **W-MVD**




< Dehumidification COP of W-MVD as a function of outdoor temperature >
$T_{indoor}$ = 24℃, $RH_{outdoor}$ = 84.22%

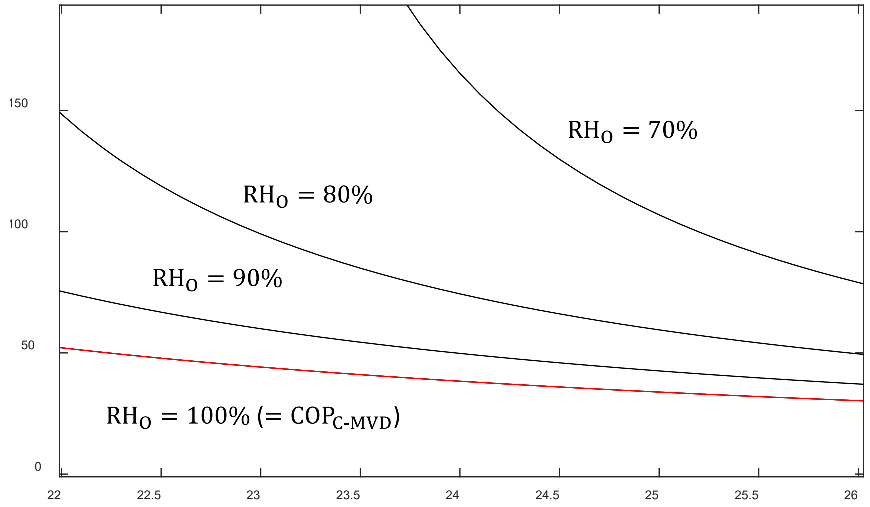
# Ideal performance analysis

## ➢Performance Comparison




< Ideal COP ratio of C-MVD and W-MVD >

$T_I$ = 24℃, $RH_I$ = 62.66%, $T_O$= 24℃ (ISO 5151)




< Ideal COP W-MVD >

$T_I$ = 24℃, $RH_I$ = 62.66% (ISO 5151)

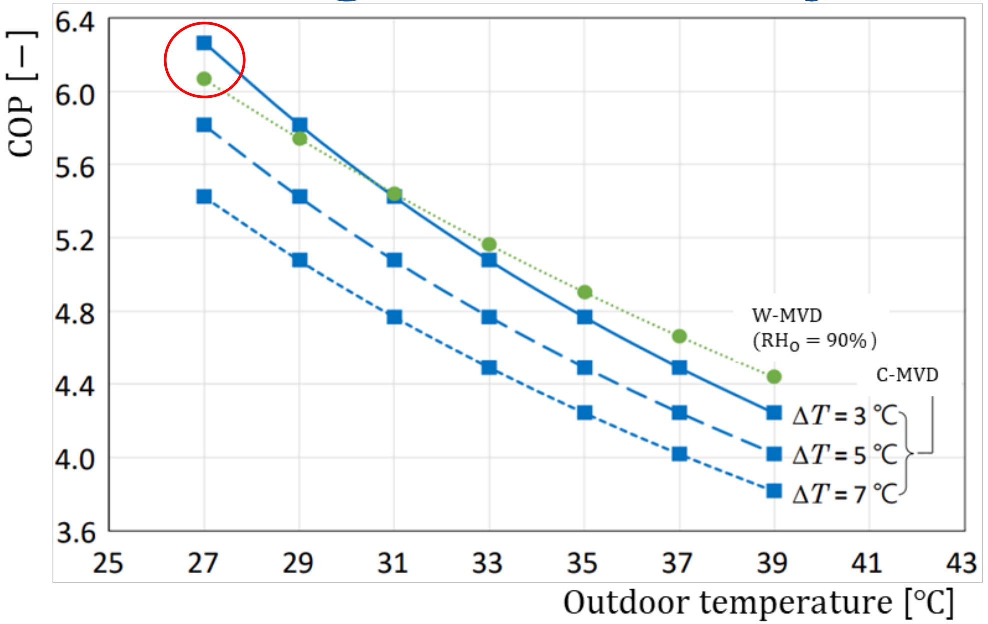
$$COP_{W-MVD.ideal} \approx \frac{T_{DP.I}}{T_{DP.O} - T_{DP.I}}$$

$$COP_{C-MVD.ideal} \approx \frac{T_{DP.I}}{T_O - T_{DP.I}}$$

- Ideal performance of **C-MVD** equivalent to that of **W-MVD** under conditions of **saturated outside air**
- **Ideal W-MVD** always outperforms C-MVD **below 100%** of outdoor relative humidity.

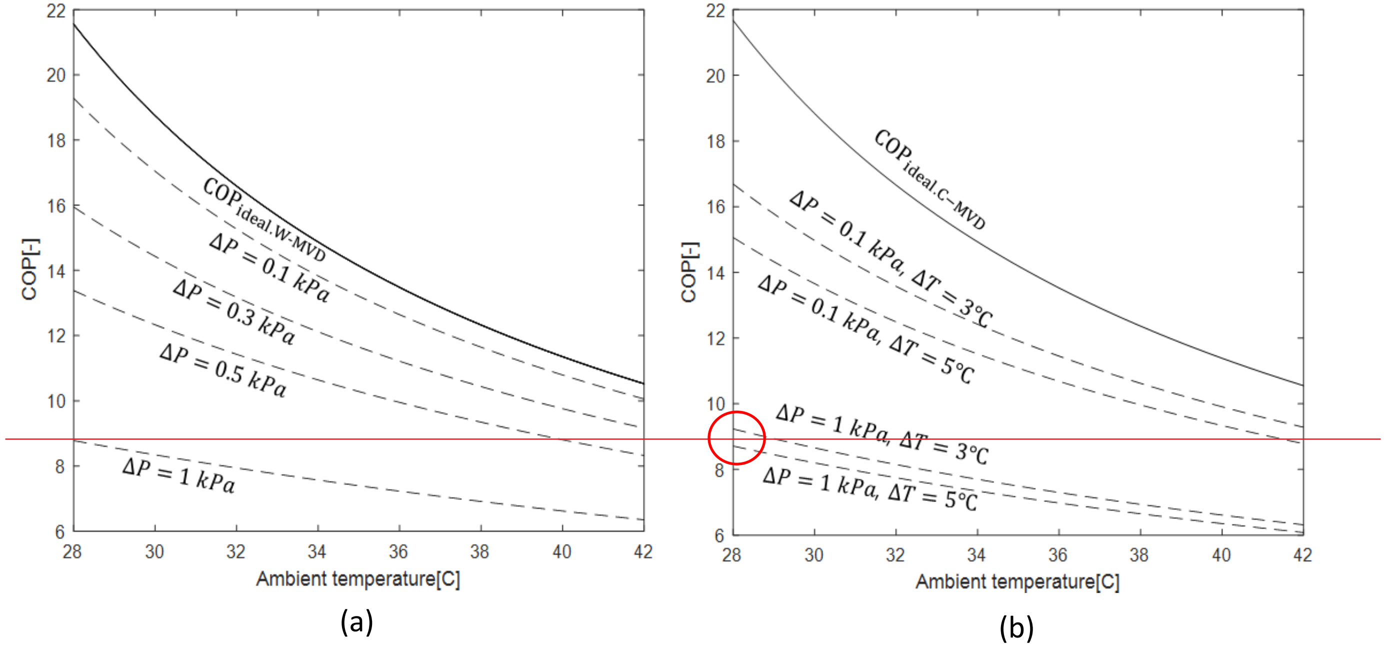
# Irreversibility analysis

## ➢COP Degradation by Irreversibility




< Dehumidification COP of C-MVD and W-MVD >

$\Delta P_{min}$ = 0.5 kPa (LMPD = 1.17kPa), $\eta_{isen}$ = 0.8, $T_I$ = 27℃, $RH_I$ = 46.94% (ISO 5151), Lim(2020)




< COP degradation of (a) W-MVD and (b) C-MVD due to irreversibility >

- **W-MVD** shows better performance under most conditions
- **C-MVD** may have an advantage in **cool and humid climates**

# Summary

- ✓ The ideal dehumidification COP of the MVDs can be simply defined using dewpoint temperature.
- ✓ The presented definition corresponds to exergy analysis and compressor modeling results.
- ✓ It can provide insight into system analysis and serve as a basis for system design.
- ✓ C-MVD may have an advantage in cool and humid climates, although W-MVD shows better performance under most conditions.

**"THANK YOU"**