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Spray Towers Can Perform Better than Packed Towers in Capturing CO2

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Capture Performance versus Cost

1. chemical absorption using liquid absorbent
   - $1 - \eta \sim \exp(-\alpha h_m A_L/Q_g) \sim \exp[-\alpha (h_m A'')(Q_L/Q_g)(L/V_f)]$
   - factors affecting η ; h_m and $A_L[= A'L \sim A''Q_L(L/V_f)]$

2. common practice
   - increase $Q_L L/V_f$ → easy and direct → cost more money
   - Q_L (solvent flow) → energy for flow and regeneration
   - L (tower height) → construction for structure and packing
   - V_f (falling speed) → construction + maintenance for internal packing

3. η enhancement via $h_m A''$?
   - A" (specific surface area per liquid volume); film → drop
   - efforts to enhance h_m have not been very successful

Possibility of Enhancing h_m

1. h_m ; gas-interface-liquid
   - h_m in the gas phase ; fast enough → no/little additional benefit
   - overall h_m dominated by the internal dispersion within the liquid phase

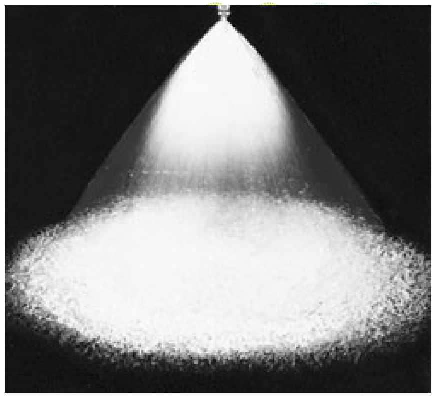
2. h_m for a single liquid drop or film
   - saturation($\Delta\Phi$) or effectiveness → $\tau_f/\tau_d \sim d^{-(2\sim2.5)}$

     τ_d, time for internal diffusion; τ_f ,contact/falling time
   - smaller drops or thinner films always advantageous ; $\Phi \sim d^{-(2-2.5)}$
   - liquid size difficult to change ; $l \sim V_g^{1/2}$, $V_t \sim d_p^{1-1.5}$

3. mass-averaged $\underline{h}_m$
   - every non-uniformity always deteriorates performance
   - highly non-uniform ; drop-size, spatial distribution

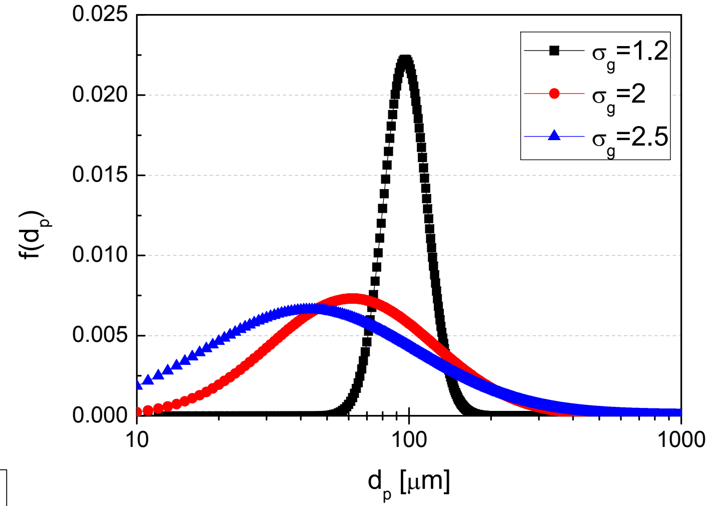
   * reduced non-uniformities → enhanced $\underline{h}_m$

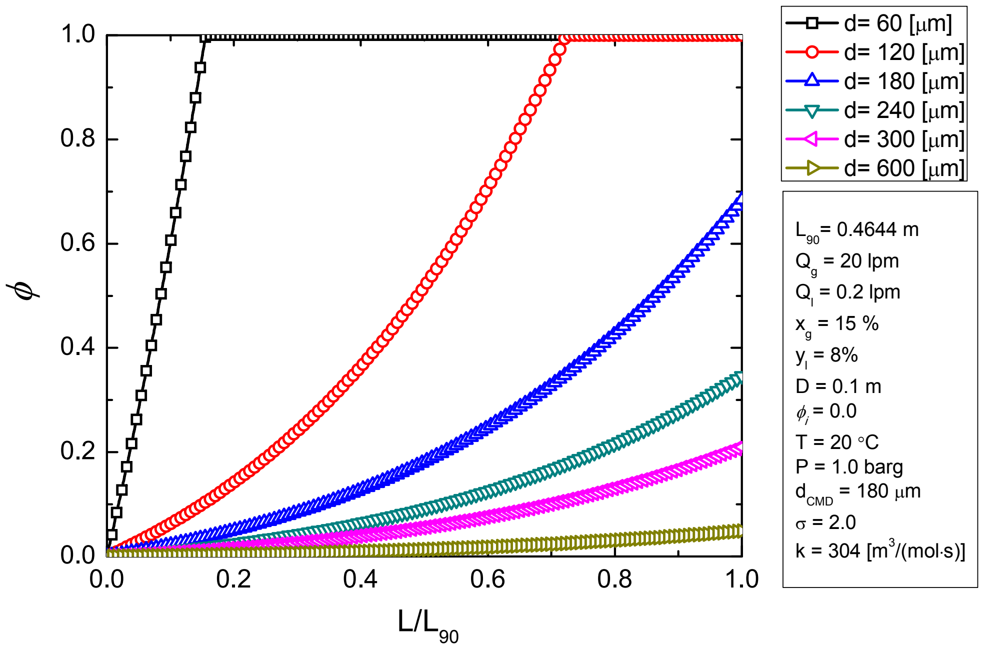
   → even without any change on the single-drop level

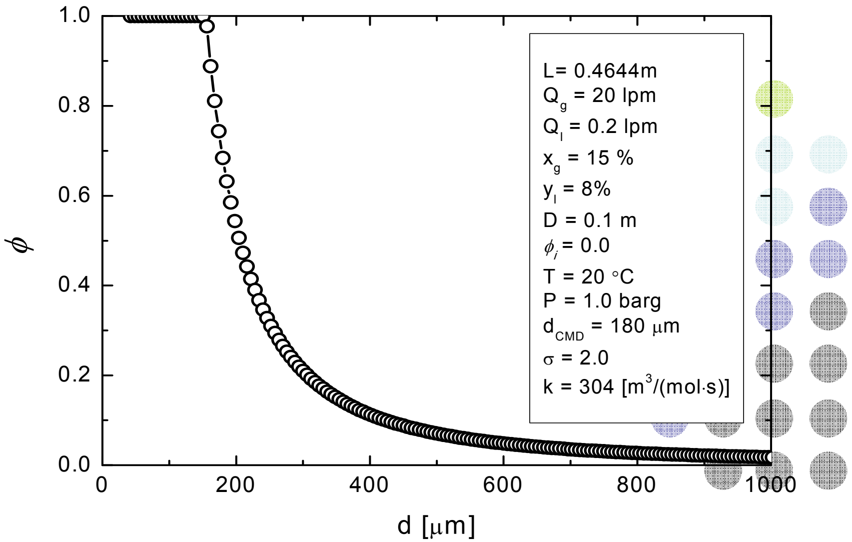


Effect of Drop-Size Non-uniformity

- example ; saturation(Φ) for σ_g = 2.0
  - drop size ; log-normal distribution
  - Φ(d) ~ 70%
  - Φ ~ 11% ~ Φ(2d)
  - * Φ(σ_g = 1.0) = Φ(d) ~ 70%







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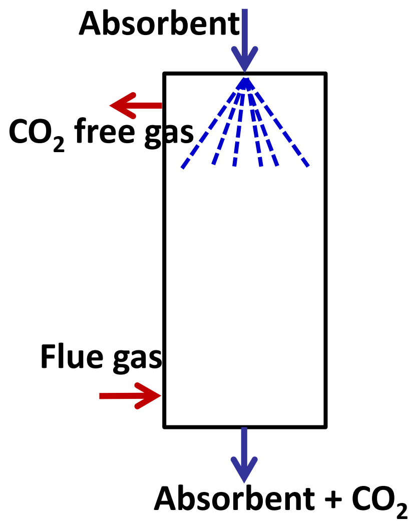
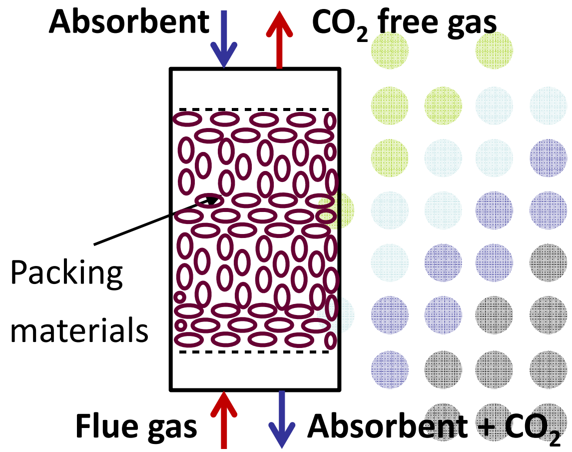
Spray Tower against Packed Tower

1. strong points
   - surface area (A”) ; large and easy to control
   - diffusion in 3-D → shorter diffusion time
   - internal circulation → enhanced mixing
   * theoretical performance → much better
   - simple structure and low cost ; no packing



2. weak points
   - high falling speed → short capture time
   - spatial distribution ; highly non-uniform
   - drop-size non-uniform ; σ_g > 2.0
     → residence/reaction time
     → big drops lost to the wall
     → small droplets lost by fly-back
     * the bigger drops are the more ineffective



Room for Performance Improvement

1. packed tower
   - better capture ; mainly due to the slow fall
   - little room for further improvement ; film thickness ~ $f(Q_L, V_g)$
   - packing materials, heavy structure

2. spray tower
   - larger surface area + 3-directional diffusion + internal circulation
   - poorer capture ; wall loss + fly-back + various high non-uniformities
     → spatial distribution, drop-size, gas velocity (higher porosity)
   - large room for performance improvement

3. chance for performance enhancement
   - via reducing the drop-size non-uniformity
   - negligible additional cost

Performance Simulation of Spray Tower

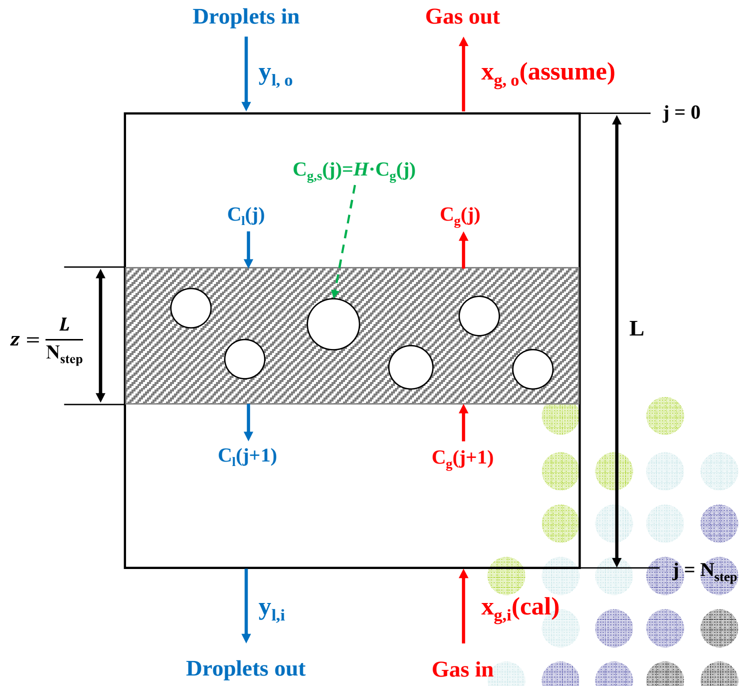
1. Non-uniform gas velocity, drop size and droplet spatial distribution

2. Poly-disperse drop size distribution ; log-normal

$$f(i) = \frac{1}{\sqrt{2\pi} \cdot d(i) \cdot \ln\sigma} \cdot \exp\left(- \frac{\left[\ln\left({d(i)}/{d_{CMD}} \right) \right]^2}{2[\ln\sigma]^2} \right)$$

$$N(i) = N_{tot} \cdot f(i) \cdot \Delta d(i) = \frac{Q_l \cdot [f(i) \cdot \Delta d(i)]}{\sum_1^{i_{\max}} [q(i) \cdot f(i) \cdot \Delta d(i)]}$$

$$n'''(i) = \frac{N(i)}{A_C \cdot V_f(i)} \qquad N_{tot} = Q_l / \bar{q}$$



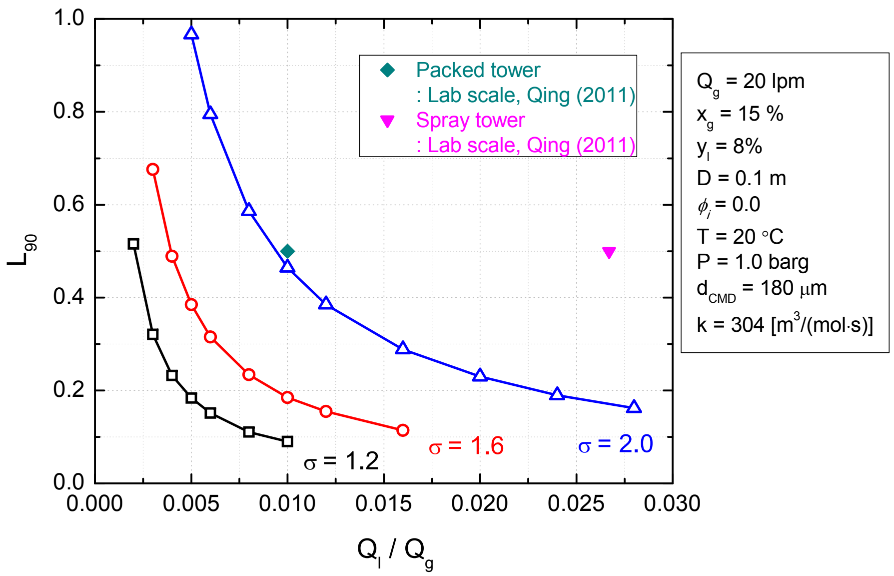
3. Mass balance equations

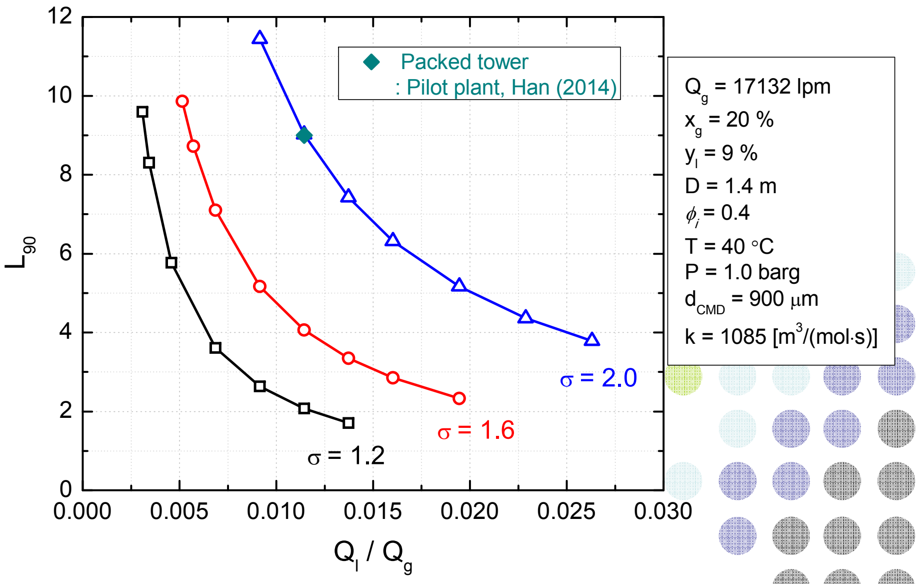
$$dM(i,j) = m_g''(i,j) \cdot A(i) \cdot [n'''(i) \cdot z \cdot A_C]$$

$$dM(j) = \sum_1^i dM(i,j) = \sum_1^i m_g''(i,j) \cdot \{\pi \cdot [d(i)]^2\} \cdot [n'''(i) \cdot z \cdot A_C]$$

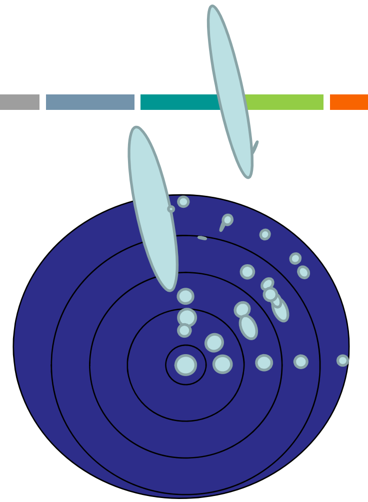
Effect of Drop-size Uniformity

- reduced size variation (σ_g) → (Q_L/Q_g)L reduced (same η condition)
  - → 1/2 with σ_g = 1.6 and 1/3 with σ_g = 1.2 (relative to σ_g = 2.0)
  - → system size (L) reduced ; same ratio (same Q_L/Q_g condition)
- enhanced capture for any type of solvent
- enhancement factor ; independent of the system size L and V_g (~ 1:10)

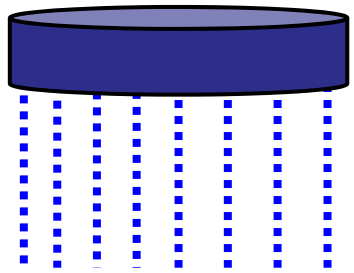




Ideal Spray Tower



1. target performance
   - maximum capture per solvent mass
   - every droplet follows the same capture/saturation history
2. basic structure
   - uniform vertical injection of mono-disperse droplets
   - spatial distribution of droplets optimized ; radial + axial
3. implementation
   - nozzle plate with multiple micro-nozzles
   - optimized nozzle array pattern and nozzle hole size
4. other characteristics
   - wall loss and fly-back minimized
   - coagulation minimized ; small relative velocity between drops
   - similar conditions along the axial position → scale-up easy



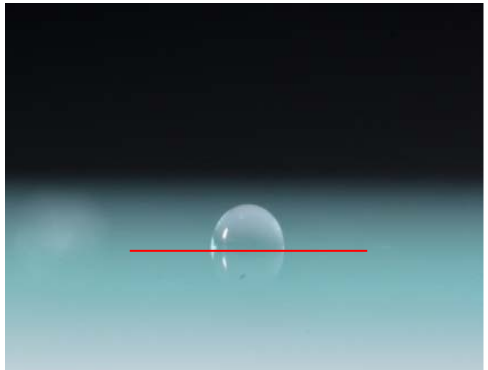
Generation of Mono-disperse Droplets

1. single nozzle
   - breakup of liquid column
   - hydrodynamic instability + proper control mechanism
   - f = F(do, V_j, liquid properties)
   - d_p = F'(do, V_j, liquid properties)
   - $\sigma_g \sim 1.2$

2. nozzle plate
   - micro nozzles of variable shape and size
   - optimum arrangement of nozzle holes
   - vertical injection
   - $\sigma_g \sim 1.2$

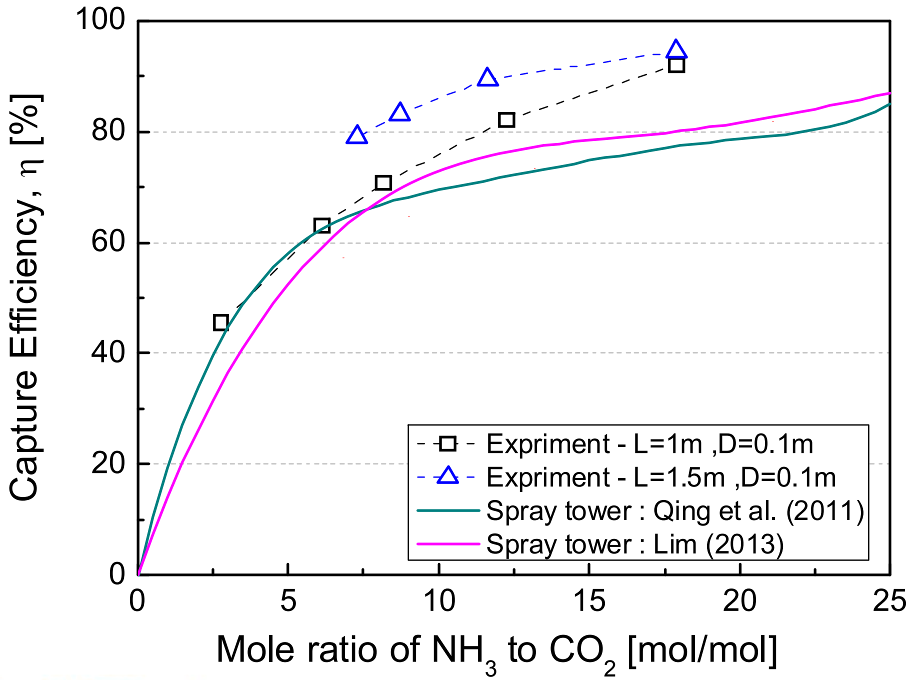
Experimentation of CO2 Capture

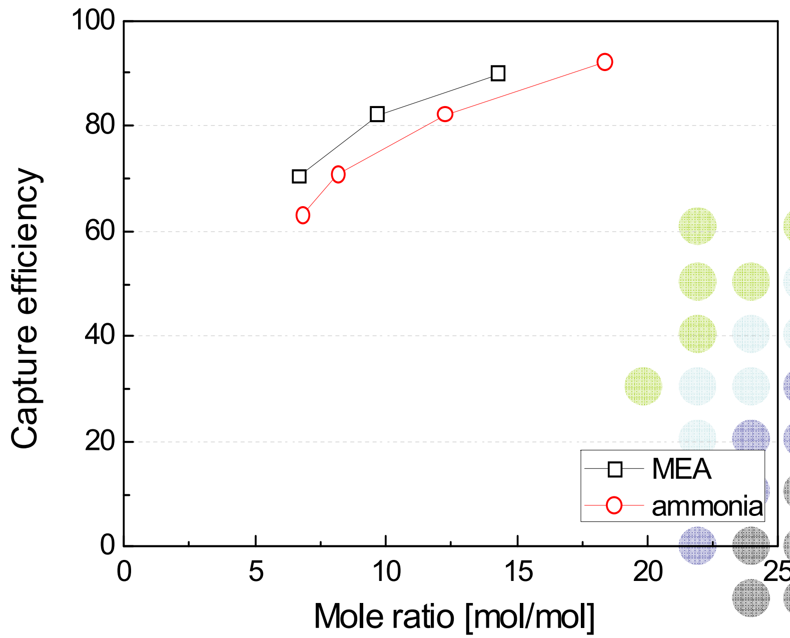
1. spray tower
   - D = 100mm
   - L = 0.5, 1.0 and1.5m → L/D = 5, 10 and 15
2. gas mixture
   - 15% CO2 in N2
   - V_g = 2~4 cm/s
   - gas distributor ; uniform, non-uniform
3. solvent
   - 8% NH3 and 30% MEA
   - d_{CMD} ~ 300μm, σ_g = 1.2
4. nozzle plate
   - variety of designs ; do, thickness, contour
   - support
5. temperature ; 25°C



Capture Efficiency

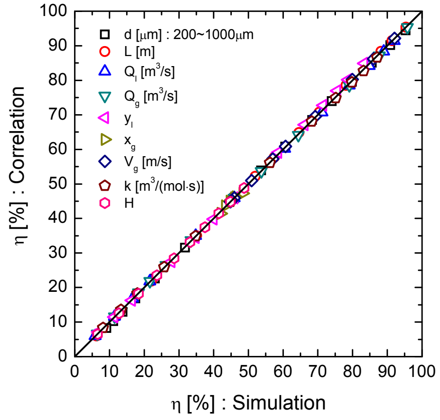
1. general shape of the η-curve
   - close to the theoretical or exponential curve up to very high $(Q_L/Q_g)L$ ~ 25
   - not flattened at high η conditions, unlike in most existing systems
2. very high efficiency of 95% attained at 25(mol/mol)m condition
   - mass transfer coefficient ($h_m A$) ; twice as high as in other spray towers
   - similar between NH3 and MEA ; 25% smaller Q_L with MEA

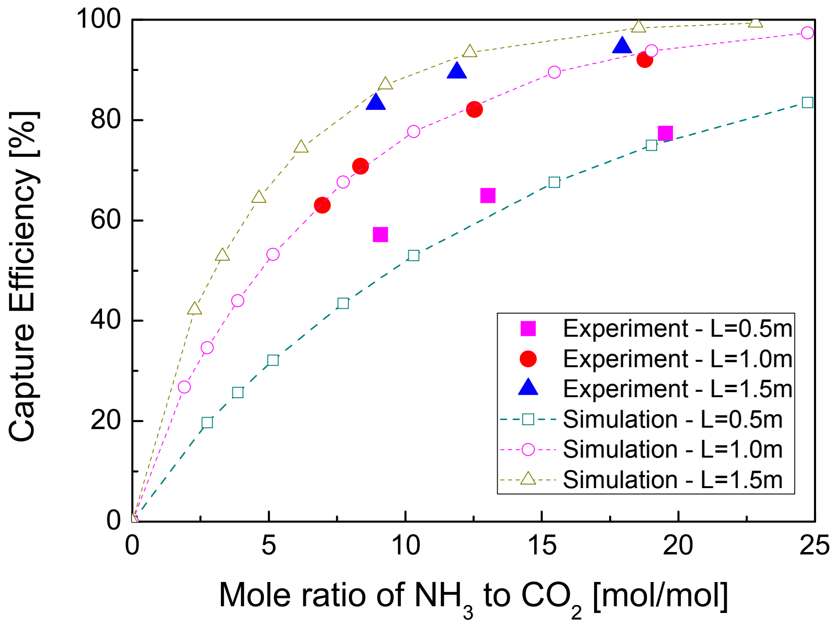


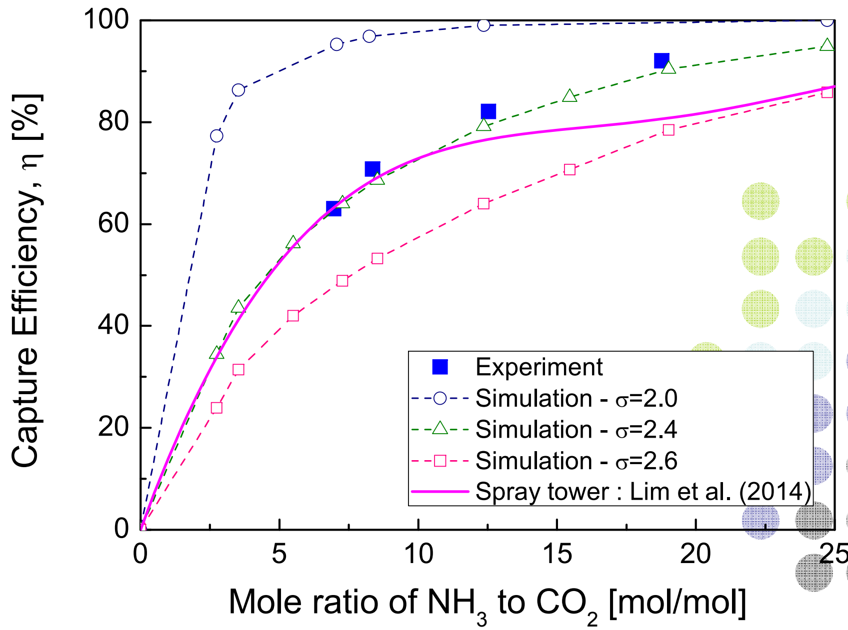


Comparison with Numerical Simulation

- numerical results → universal efficiency formula
  (formula not shown here)
- excellent agreement







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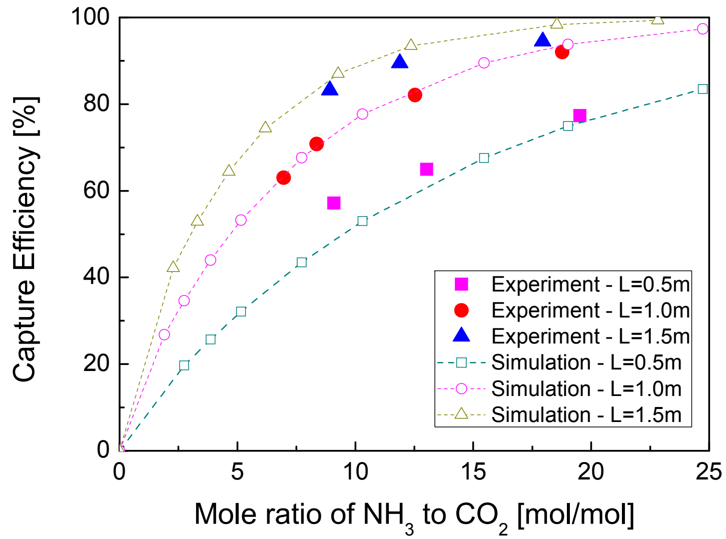
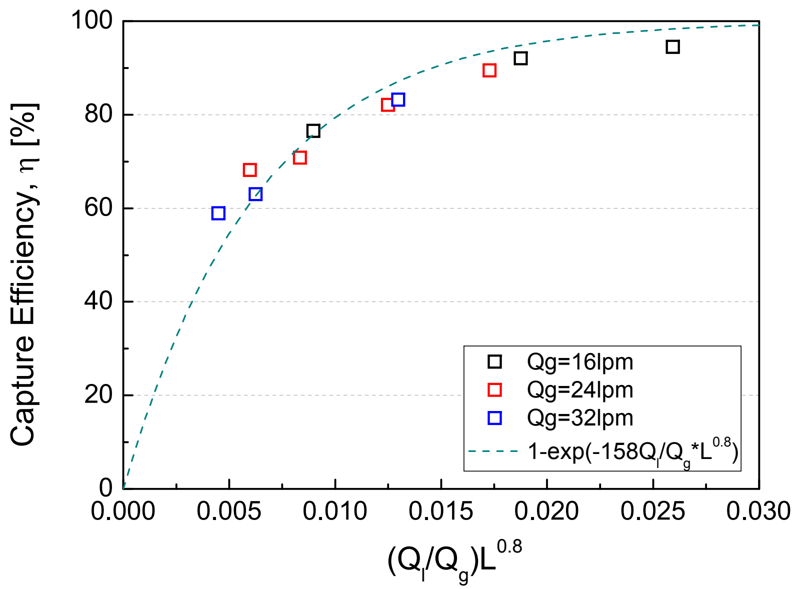
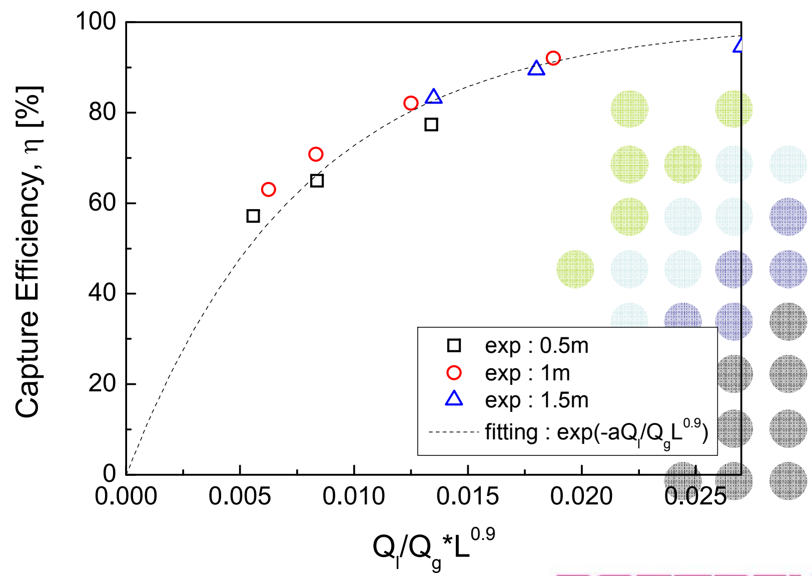
Effect of Tower Length

1. potential adverse secondary effects
   - coagulation + wall loss + crossing
2. universal η-curve
   - $\eta = \eta[(Q_L/Q_g)L_{eff}]$; $L_{eff} = L_O(L/L_O)^a$
   - experiment ; α = 0.8~0.9
   - simple theory ; α ~ 0.8







Possibility for Further Enhancement

1. longer tower (L)
   - residence time ~ 1 sec → 1/10 ~ 1/5 of other lab-scale towers
   - longer towers provide longer contact time ; $h_m \sim (Q_L/Q_g)L_{eff}/V_f$

2. high gas velocity (V_g)
   - $V_f = V_t - V_g$
   - residence/contact time increased

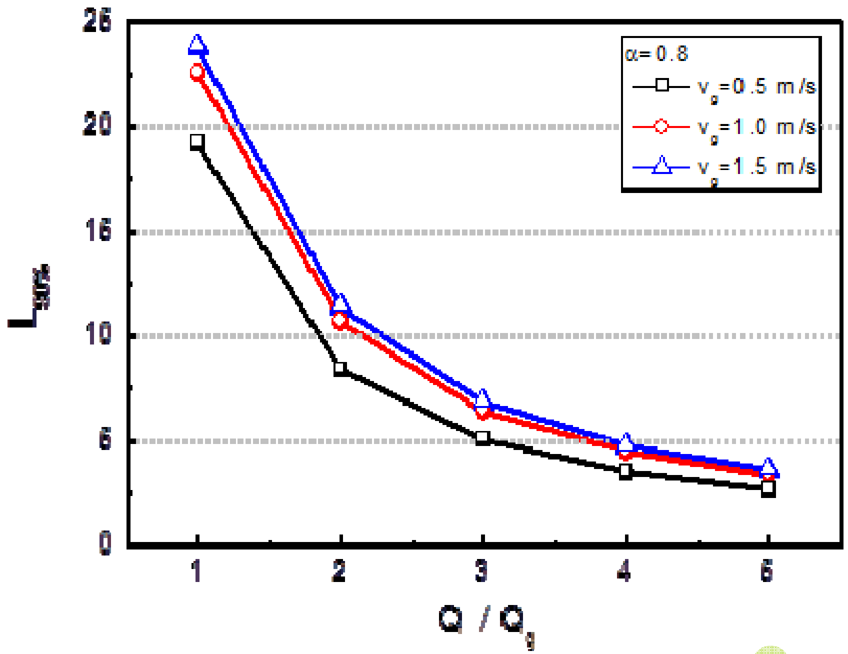
3. drop-size optimized to V_g
   - falling velocity optimized independently of V_g → additional d.o.f.
   - $V_t \sim d_P^{1\sim1.5}$

4. optimized nozzle array
   - non-uniform V_g
   - gas exit manifold

Prediction for Large-Scale Application

1. demo-scale pilot plant
   - V_g = 0.5~1.5 m/s
   - α = 0.8

2. sample solution for NH3
   1) drop-size optimized to V_g
   2) L_{90} ~ 10m with Q_L/Q_g = 2 liter/m^3
      → much shorter than any others
   3) L_{90} ~ 20m with Q_L/Q_g = 1 liter/m^3
   4) very short tower is sufficient for η = 90% at any gas velocity
      - irrespective of solvent type and gas velocity
      - further reduction in solvent flow possible in taller towers
   5) MEA/DEA ; 25% less absorbent or absorber length



Additional Advantages

1. design flexibility – single unit
   - shape of the cross-section flexible
   - (actively) controlled non-uniform size/position distribution possible
   - no viscosity-effect → multi-step liquid injection not needed

2. design flexibility – multi units of small cross-section
   - simultaneous multi-functions ; gas, absorbent, conditions
   - multi-step, recycling, variation of gas load, alternate maintenance

3. overall facility and operation
   - simple structure → low cost for construction and maintenance

4. applicable to regenerators
   - lower Q_L ← (effective mean internal dispersion) → lower T_r

Summary and Conclusions

1. Basic concept of the ideal spray tower developed
   - mono-disperse droplets + vertical injection
   - scale-up easy and straight-forward with little side effect

2. Capture performance verified ; lab-scale
   - performance curve close to that of an ideal reactor
   - best-ever performance of 95% observed with NH3
   - performance enhanced irrespective of the type of solvent

3. Feasibility of application to full-scale confirmed
   - very short tower is sufficient for η = 90% for any solvent gas velocity
     L_{90} ~ 10m with Q_L/Q_g = 2 liter/m^3 ; L_{90} ~ 20m with Q_L/Q_g = 1 liter/m^3
   - applicable to regenerators with similar benefit
   - substantial (< 1/2) cost reduction expected relative to packed towers thru much shorter tower and no packing material

For More Information or Discussion

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