Supplementary Materials: Reduction of Volatile Organic Compounds (VOCs) Emissions from Laundry Dry-Cleaning by an Integrated Treatment Process of Condensation and Adsorption

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S1. Process simulation

We conducted the process simulation to check the robustness of our integrated VOCs treatment process in a continuous operation. For this, we used a pore and surface diffusion model (PSDM) included in an Adsorption Design Software (AdDesignS™, Michigan Technological University, United Sates). According to the manual of Adsorption Design Software, the PSDM incorporates the following assumptions:

- Constant flow rate
- Plug-flow conditions exist in the bed
- Linear driving force describes the local bulk phase mass flux at the exterior surface of the adsorbent particle
- Local adsorption equilibrium exists between the solute adsorbed onto the granular activated carbon particle and the solute in the intra-aggregate stagnant fluid
- Intraparticle mass flux is described by surface and pore diffusion
- Adsorption equilibrium of individual compounds can be represented by the Freundlich isotherm equation and ideal adsorbed solution theory (IAST) describes the competition between the compounds
- There are no interactions between adsorbing compounds during the diffusion process

S2. Repetitive operation of VOCs reduction process with open-circuit flow process

To examine the time trend of TVOCs removal efficiency, we repeated 5 cycles (1 cycle = 2 condensation/adsorption + 1 desorption/condensation) with open-circuit flow process (Figure S4). During the 5 cycles of operation for condensation/adsorption, the average TVOCs concentrations for each cycle were as follows: 140.8 ± 39.0 ppmv (1st cycle), 151.5 ± 39.4 ppmv (2nd cycle), 182.0 ± 40.2 ppmv (3rd cycle), 179.4 ± 48.5 ppmv (4th cycle), and 198.5 ± 46.2 ppmv (5th cycle). The TVOCs removal efficiency was correspondingly calculated as follows: 98.0 ± 0.7 % (1st cycle), 97.8 ± 0.7 % (2nd cycle), 97.6 ± 0.6 % (3rd cycle), 97.5 ± 0.7 % (4th cycle), and 97.4 ± 0.6 % (5th cycle). The TVOCs removal efficiency declined slightly across the 5 cycles because desorption may not be fulfilled completely. We observed that the removal efficiency of the open-circuit flow process was lower than that of the closed-loop flow process throughout the 5 cycles.

S3. Adsorption/desorption experiment in a laboratory scale

To verify the process simulation results (Figure 4) incorporating adsorption and desorption, we conducted an adsorption/desorption experiment in a laboratory scale. We used toluene, instead of decane, as a representative compound in the adsorption/desorption experiment because quantifying toluene is more accurate than quantifying decane. Conditions in the adsorption/desorption experiment were as followings; toluene inlet concentration (2050 ppmv), adsorption (40 minutes)/desorption (40 minutes), and adsorbent material (activated alumina 100%). Figure S5 shows the toluene concentrations during the adsorption/desorption experiment (total 80 minutes; adsorption 40 minutes and desorption 40 minutes). With the toluene inlet concentration of 2050 ppmv, the toluene outlet concentration was approximately 246 ppmv at the end of the desorption stage. The overall

trend in the toluene concentration was almost consistent with the process simulation results (decane inlet concentration 300 ppmv and outlet concentration 51 ppmv).

Table S1. Input parameters for adsorption/desorption model simulation.

Parameters	Value	Unit
Fixed Bed Properties		
Bed Length	25.5 [a]	cm
Bed Diameter	20 [a]	cm
Bed Mass	5120 [b]	g
Flowrate	0.0273 [a]	m^3/s
Adsorbent Properties		
Name	Activated alumina	
Apparent Density	0.64 [c]	g/cm^3
Particle Radius	0.5 [c]	cm
Porosity	0.641 [c]	
Particle Shape Factor	0.72 [c]	
Component Properties: Decane		
Freundlich Isotherm Parameters		
K	339 [d]	$(mg/g)(L/mg)^{1/n}$
1/n	0.314 [d]	
Kinetic Parameters		
Film Diffusion	1.02 [e]	cm/s
Surface Diffusion	3.58×10^{-6} [f]	cm^2/s
Pore Diffusion	8.08×10^{-2} [f]	cm^2/s
Surface to pore diffusion flux ratio	16 [e]	
Tortuosity	1 [e]	
Air Properties		
Pressure	1 [a]	atm
Temperature (for adsorption)	6.5 [g]	^oC

[a] Defined by user, [b] Measured by user, [c] Obtained from M&E Tech (the manufacturer of activated alumina), [d] Experimentally measured for toluene in an adsorption isotherm study [Kim, D. and G.A. Sorial, *Comparative study of gas phase adsorption of volatile organic compounds on two types of activated carbon.* Abstracts of Papers of the American Chemical Society, 2004. 227: p. U811-U811].[e] Based on the study performed by Moe and Li [W.M. Moe, C.N. Li, A design method for activated carbon load dampening systems for biofilters treating intermittent VOC concentrations, Proceeding of USC-CSC-TRG Conference on Biofiltration for Air Pollution Control (2004) 89-96].[f] Calculated by AdDesignS™, [g] Temperature for desorption process was 40 ^{o}C.

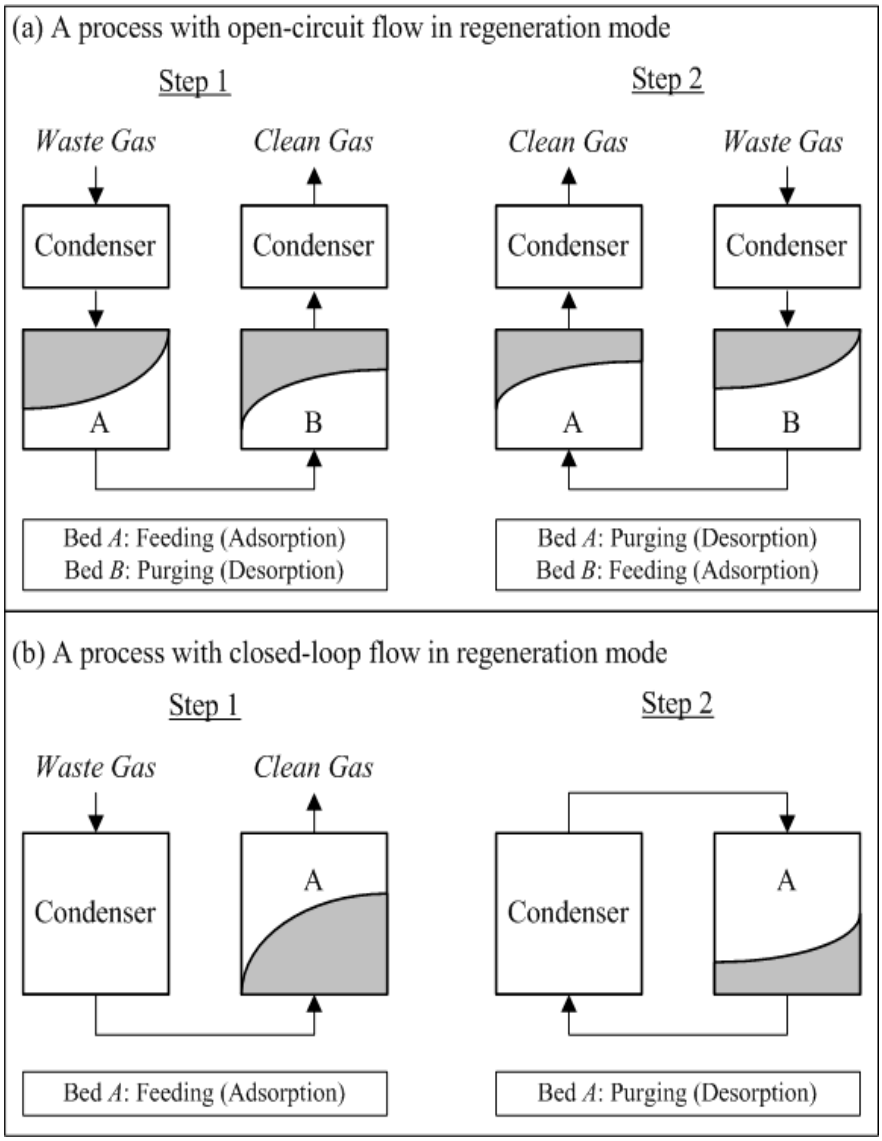
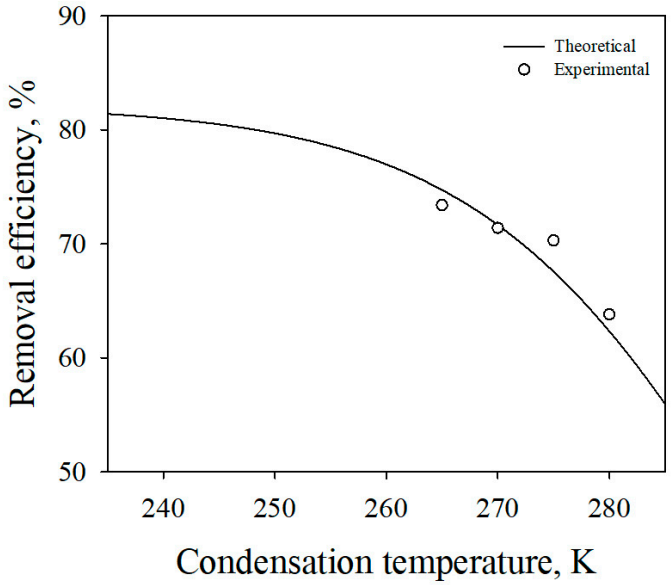


Figure S1. Conceptual layouts of two different integrated treatment processes: (a) a process with open-circuit flow in regeneration mode and (b) a process with closed-loop flow in regeneration mode.

(a) Theoretical removal efficiency



(b) Effect of condensation temperature and inlet TVOCs concentration

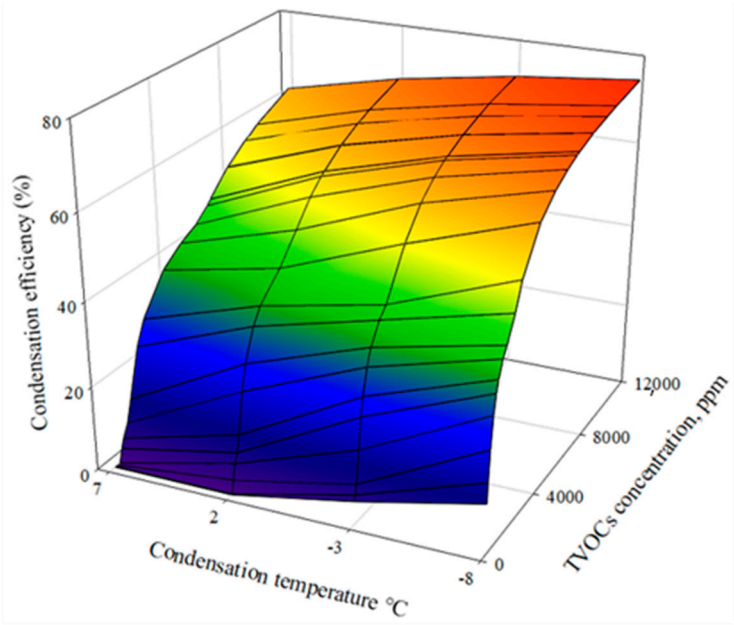
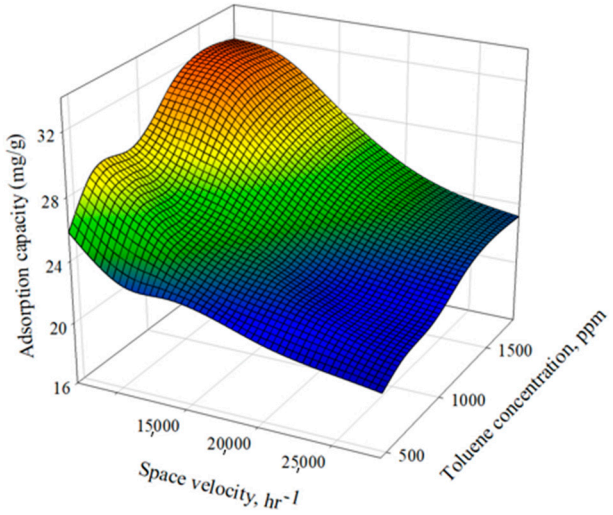


Figure S2. Condensation efficiency of vaporized dry-cleaning solvents from dry-cleaning process as a function of applied temperature and inlet TVOCs concentration. Theoretical efficiency was estimated from Antoine equation and experimental one was practically obtained from the condenser designed in this study.

(a) Effect of space velocity and inlet toluene concentration on adsorption capacity



(b) Effect of gas temperature on adsorption and desorption of toluene

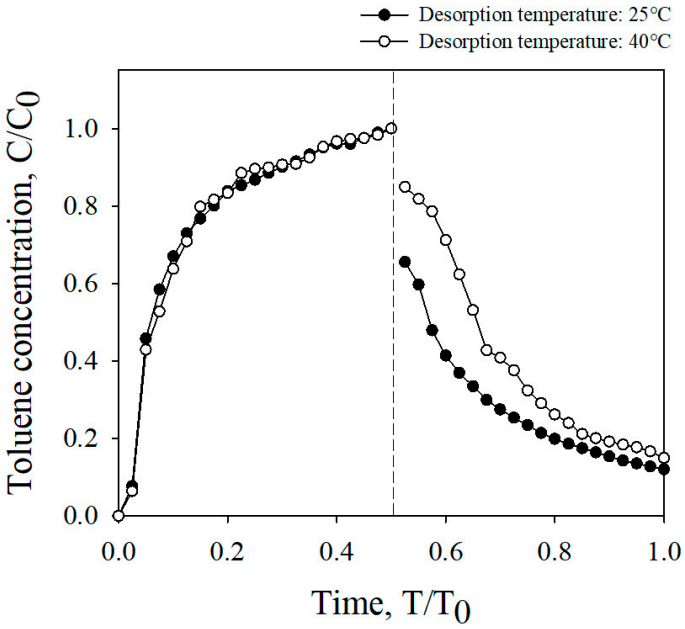


Figure S3. Effect of process parameters on adsorption and desorption on activated alumina as an adsorbent. Each experiment for adsorption and desorption was conducted for 40 minutes.

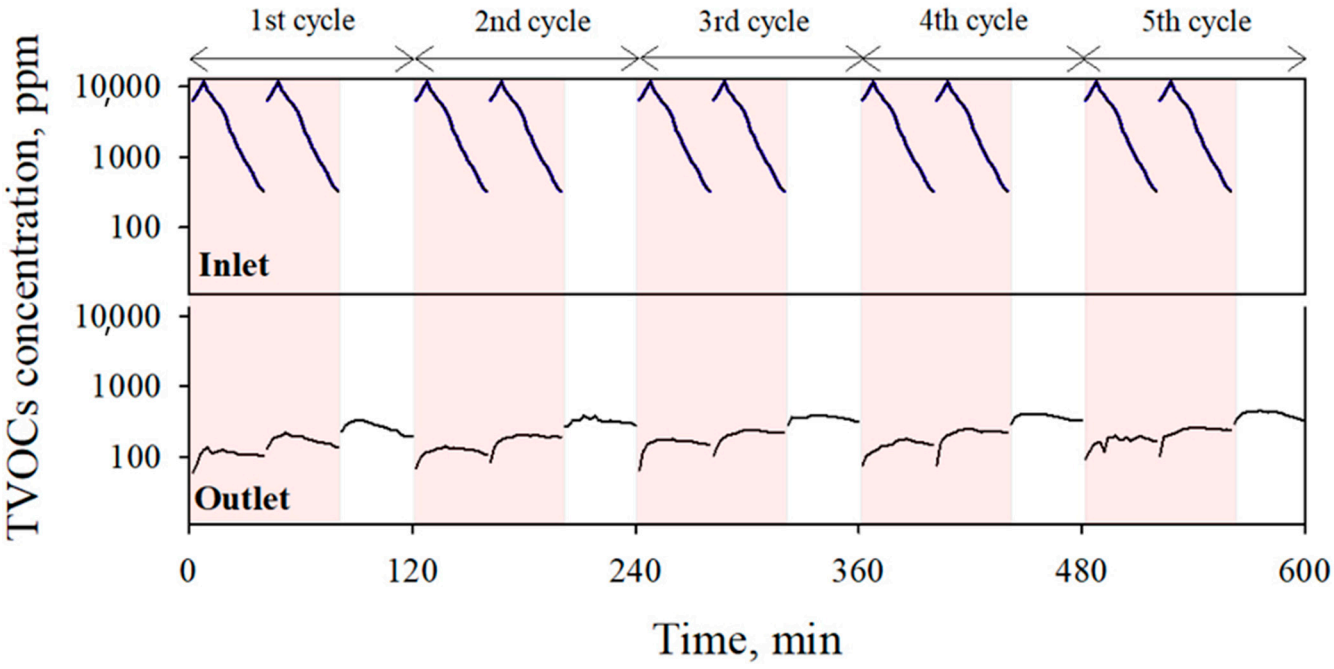


Figure S4. TVOCs concentrations of 5 cycles (1 cycle = 2 condensation/adsorption + 1 desorption/condensation) with the open-circuit flow process applied.

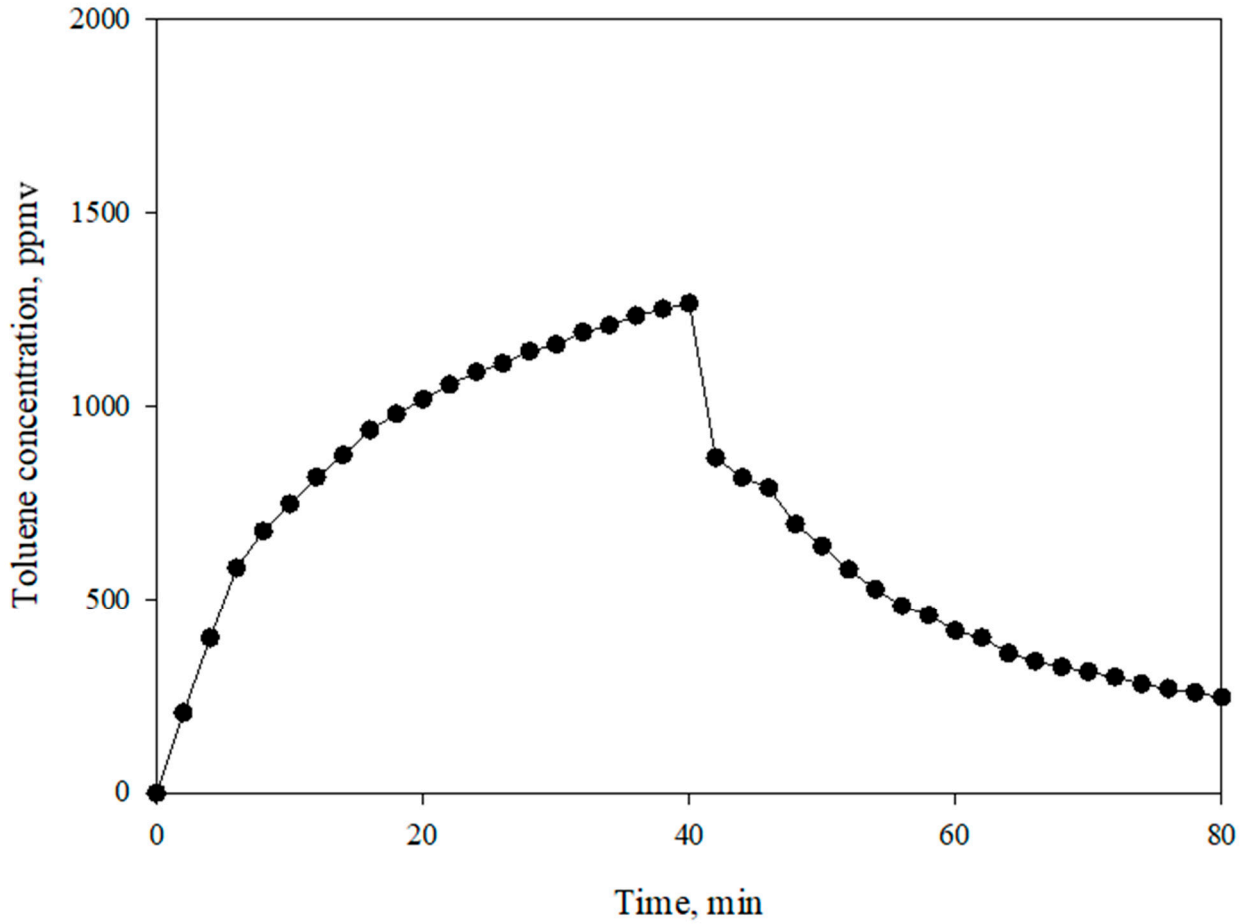


Figure S5. Toluene concentration during an adsorption/desorption experiment in a laboratory scale. The first 40 minutes was for adsorption stage and the next 40 minutes was for desorption stage.