Control of Vaporous Naphthalene by Scrubbing with Surfactants

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Abstract: This study investigates the effects of adding anionic and nonionic surfactants to the scrubbing liquid during the absorption of naphthalene (Nap) using a wet scrubber. Both batch and continuous experiments were performed on a laboratory-scale packed tower scrubber by adding surfactants to the scrubbing liquid. An anionic surfactant sodium dodecyl sulfate (SDS) and two nonionic polyoxyethylene surfactants C₁₀E₄ [tetraethylene glycol mono(decyl ether)] and C₁₄E₈ [octaethylene glycol mono(tetradecyl ether)] were used. The concentrations of the surfactant solutions all exceeded the critical micelle concentration. The results of continuous experiments indicate that the efficiencies of removal of naphthalene by C₁₀E₄ and C₁₄E₈ were 75.0 and 71.9%, respectively, at a concentration of 1.0×10^{-2} M. The removal efficiency of naphthalene by SDS ranged from 6 to 39% at concentrations from 1.0×10^{-2} to 1.0×10^{-1} M under continuous scrubbing. In the batch experiments, the batch naphthalene absorption capacities were estimated to be 31.8 $\mu\text{g Nap/g C}_{10}\text{E}_4$, 12.9 $\mu\text{g Nap/g C}_{14}\text{E}_8$, and 2.4 $\mu\text{g Nap/g SDS}$. A comparison was also made among SDS, C₁₀E₄, and C₁₄E₈ in terms of cost, foaming, impact of wastewater, removal efficiency, and absorption capacity.

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Introduction

Municipal and hazardous waste incinerators are extensively used to dispose of solid waste. However, the combustion of waste generates toxic air pollutants, including polycyclic aromatic hydrocarbons (PAHs). Some PAHs are known to be carcinogenic and mutagenic (You et al. 1994). Therefore, the emission of PAHs from incinerators has received considerable attention over recent years. The predominant PAH compound in the gas phase of flue gas is naphthalene (Nap), which represents over 60% of all the PAHs in the gas phase of the flue gas from municipal waste incinerators and industrial stacks (Yang et al. 1998). Consequently, naphthalene was selected as the representative PAH compound experimentally examined herein. Polycyclic aromatic hydrocarbons are semivolatile hydrophobic organic compounds (HOCs). Current technologies for controlling PAHs include activated carbon absorption, catalytic combustion, and thermal oxidation. However, the equipment for performing these processes is often ancillary control equipment installed in municipal waste and other incinerators. Only a few studies have addressed the development of technology based on existing equipment for controlling PAHs, to reduce cost and simplify the control system, facilitating its operation and maintenance.

Surfactants are composed of hydrophobic and hydrophilic segments. When a surfactant solution is at low concentration, some surfactant molecules disperse in solution and some are present at the interface between the gas and liquid phases. Micelles are formed when the surfactant concentration reaches a threshold. The threshold concentration is called the critical micelle concentration (CMC) (Rosen 1989). In aqueous solutions, the hydrophobic ends of the surfactant molecules are concentrated at the micelles' inner cores while the hydrophilic ends are at the surface. The inner cores of the micelles can dissolve HOCs (Doong et al. 1996; Butler and Hayes 1998).

The application of surfactants to increase the solubility of PAHs has been comprehensively investigated in recent years. However, the removal of vaporous PAHs in flue gas from municipal waste incinerators has not yet been studied. Liu et al. (1991) and Zheng and Obbard (2002) determined that the solubility of PAHs increases with surfactant concentration at a contaminated soil site when the concentration of surfactant exceeds the CMC. Shiau et al. (2000) and Zheng and Obbard (2000) employed food grade nonionic surfactants to remove chlorinated solvents and PAHs from soil. Bai et al. (2001) developed a process to extract PAHs in aqueous solution using the nonionic surfactant Tergitol 15-S-7, in a process called cloud point extraction. Tiehm et al. (1997) showed that surfactants can alter partitioning and that adding nonionic surfactants increases the amount of PAHs in the liquid phase (Arkopal N-300 and Sapogenat T-300). Edwards et al. (1991, 1992) used four polyoxyethylene nonionic surfactants (Brij 30, Igepal CA-720, Tergitol NP-10, and Triton X-100) to elucidate the solubility of PAHs in soil experiments at surfactant concentrations above and below the CMC. They reported that nonionic surfactants increase the solubility of PAHs above the CMC. Paterson et al. (1999) and Yeom et al. (1995) used an anionic surfactant at a concentration above the CMC to improve extraction from coal-tar-permeated land. Link (2000) claimed that partition coefficients increased with the number of rings in the PAH structure in a nonionic surfactant solution. Huang and Lee

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Table 1. Molecular Weight and Critical Micelle Concentration of Surfactants

Surfactant	Molecular weight (g)	Critical micelle concentration (M)
Anionic surfactant		
Sodium dodecyl sulfate	288.4	8.2×10^{-3} (25°C) (Rosen 1989) 8.6×10^{-3} (40°C) (Rosen 1989) 8.01×10^{-3} (25°C) (Clarke et al. 1993) 7.98×10^{-3} (25°C) (Doong et al. 1996)
Nonionic surfactant		
Tetraethylene glycol mono(decyl ether) (C ₁₀ E ₄)	334.5	4.9×10^{-4} (50°C) (Chen et al. 1998)
Octaethylene glycol mono(tetradecyl ether) (C ₁₄ E ₈)	566.8	7.3×10^{-6} (50°C) (Chen et al. 1998)

(2002) considered the enrichment factor in performing enhanced removal of vaporous naphthalene by the anionic surfactant sodium dodecyl sulfate (SDS). Vipulanandan and Ren (2000) described the enhanced solubility and biodegradation of naphthalene using anionic and nonionic surfactants. Yeom et al. (1996) posited that micelles have an enhanced effect on the solubility of PAHs. Liu and Roy (2000) presented a model to determine a surfactant's micelle-water distribution coefficients of aromatic hydrocarbons. Guha et al. (1998a, b) and An et al. (2002) considered three PAHs (naphthalene, phenanthrene, and pyrene) that were partitioned between surfactant solution and micelles. According to their results, hydrophobic PAHs dissolve in the core of micelles such that the volume of the core changes, increasing the solubility of the more hydrophobic PAHs.

Currently, packed scrubbers are often used to control acidic gases, such as HCl, in the flue gas from municipal incinerators. However, little work has been conducted on the removal of vaporous PAHs using wet scrubbers. This study investigates the efficiency of removal of vaporous naphthalene using a wet scrubber, by adding anionic and nonionic surfactants to the scrubbing liquid. The wet scrubber used herein is a laboratory-scale packed tower, designed and made with the characteristics of the packed tower operated at a municipal incinerator in Taiwan. Huang (2001) conducted batch experiments on the enhancement of the solubility of naphthalene, using three surfactants, including the anionic surfactant SDS and the nonionic surfactants C₁₀E₄ and C₁₄E₈. Several useful data on these three surfactants were obtained. Therefore, three surfactants (SDS, C₁₀E₄, and C₁₄E₈) were selected to clarify the effects of adding surfactants on the removal of vaporous naphthalene using a wet scrubber.

Materials and Method

Chemicals

Naphthalene was purchased from Merck (minimum purity 99%). Sodium dodecyl sulfate was the anionic surfactant (Merck, purity >99%). Tetraethylene glycol mono(decyl ether) [CH₃(CH₂)₉(OCH₂CH₂)₄OH] (C₁₀E₄) and octaethylene glycol mono(tetradecyl ether) [CH₃(CH₂)₁₃(OCH₂CH₂)₈OH] (C₁₄E₈) were selected as the nonionic surfactants. They were purchased from Nikko Chemical Co. and were at least 99% pure. Table 1 presents the properties of the above surfactants, including their molecular weights and CMCs.

Experimental System

As depicted in Fig. 1, the experimental system comprises three parts—a standard naphthalene gas generation subsystem, a packed tower scrubber, and a naphthalene sampling analysis sub-

system. Pure compressed nitrogen was the carrier gas used to generate a standard concentration of vaporous naphthalene, and its flow was controlled using a mass flow controller (Sierra, Side-Trak Mode 860). The flow rate of nitrogen was maintained at 10 L/min and standard temperature and pressure STP. A diffusion tube (VICI Metronics Co.) was filled with solid naphthalene and immersed in a water bath (Deng-Yng Co., ZC-4000, $\pm 0.1^\circ\text{C}$) with a temperature controller. The concentration of gaseous naphthalene was regulated by the nitrogen flow rate and the temperature of the water bath. The temperature of the gas stream was 45.0°C . A switch valve was operated to enable the flow of standard naphthalene gas through the scrubber or gas sampling bulbs (Supelco, 1,000 mL). When the flow of standard naphthalene approached the steady state, the Teflon stopcock plug of the gas-sampling bulb was closed to check the concentration of standard vaporous naphthalene. The generation of naphthalene takes approximately two hours to stabilize. The vaporous naphthalene in the sampling bulb was adsorbed almost instantly by the solid phase microextraction (SPME) device (Supelco, PDMS [polydimethylsiloxane] coating), which remained exposed for 15 min. The SPME combines the sampling and preconcentration of organic compounds in a single procedure. Naphthalene was directly desorbed into a gas chromatograph (GC) in a heated GC inlet. The SPME device has a structure like a modified syringe that contains a fused silica fiber, which is coated with a 7- μm polydimethylsiloxane film as the stationary phase. Naphthalene is analyzed by GC-PID (photon ionization detector, HP 5890 series II). The chromatographic column was a Supelco SPB-5 fused

Fig. 1. Illustration of experimental system: (a) pure nitrogen cylinder; (b) mass flow controller; (c) water bath; (d) diffusion tube; (e) switch valve; (f),(g) storage tanks of nonionic surfactant solution; (h) pump; (i) flow meter; (j) packed tower; (k) gas sampling bulb; (l) solid phase microextraction (m) hood

Fig. 2. Illustration of packed tower scrubber

silica capillary column (30 m long, 0.53 mm internal diameter, 1.5 μm film thickness). The switch valve was operated to lead the standard vaporous naphthalene into the scrubber after the inlet naphthalene concentration was verified. Nonionic or anionic surfactant solution was stored in a tank and pumped into the scrubber spray apparatus. The flow of the scrubber liquid was controlled using the flow meter. The gas that flowed out of the packed scrubber was sampled using a gas-sampling bulb and analyzed by SPME and GC-PID to determine the concentration of naphthalene.

Design of Packed Tower Scrubber

The scrubber (Fig. 2) was 80 cm high and had a diameter of 13 cm; it was made of polymethacrylate resin. The scrubbing liquid was pumped through an inlet and spray apparatus. Gas that included a specified concentration of naphthalene flowed through the gas inlet and the gas dispersion plate. The packed material was of the 1.6 cm diameter plastic Pall ring type and was made of polyethylene. The surface area was 360 m^2/m^3 and the free volume percentage was 83%. The material was packed to a height of 10 cm. The scrubbing liquid and the naphthalene gas were well mixed in the packed material with a liquid/gas ratio of 2.65 (L/Nm^3). The mixing time was 7.5 s and the residence time of the gas was 64.8 s in the scrubber with the packing material. Two stainless steel meshes were installed to eliminate fog and foam. Whenever too much foaming occurred, an alcoholic defoaming agent was sprayed to suppress it.

Naphthalene Analysis

Naphthalene was analyzed by GC-PID and SPME. The standard naphthalene concentration was 1,064 $\mu\text{g}/\text{nm}^3$, generated by a diffusion tube. The coefficient of correlation R^2 for the calibration curve was 0.998 and the method detection limit (MDL) was 198 $\mu\text{g}/\text{N}\cdot\text{m}^3$. The rate of recovery was 92.6–105%. The desorption time for SPME was 2 min in the GC inlet. The GCPID operation parameters were as follows: inlet temperature of 280°C; detector temperature of 220°C; oven initial temperature of 80°C; heating at 15°C/min to 110°C, at 2.5°C/min to 150°C, and finally at 20°C/min to 200°C. The GC was run for 26.50 min per sample.

Table 2. Enrichment Factors for Four Surfactants at Different Concentrations

Concentration (M)	Enrichment factor		
	Sodium dodecyl sulfate	C_{10}E_4	C_{14}E_8
1.0×10^{-6}	—	—	1.18
1.0×10^{-5}	1.01	1.13	1.59
1.0×10^{-4}	1.03	1.37	1.67
1.0×10^{-3}	1.08	1.75	2.11
5.0×10^{-3}	—	8.10	6.24
1.0×10^{-2}	1.44	14.20	12.86
5.0×10^{-2}	4.68	—	—
1.0×10^{-1}	9.20	—	—

Note: Taken from Huang 2001.

The experiments involved C_{10}E_4 and C_{14}E_8 surfactant solutions at concentrations of 1.0×10^{-3} , 5.0×10^{-3} , and 1.0×10^{-2} M. The anionic surfactant SDS was used at concentrations of 1.0×10^{-2} , 5.0×10^{-2} , and 1.0×10^{-1} M. All concentrations exceeded the CMC. The scrubber was operated under both continuous and batch conditions. In continuous experiments, the scrubber achieved an approximately steady state after 5 min of operation. The concentration of naphthalene in the flue gas was analyzed in the steady state. In batch experiments, the nonionic surfactant solutions were maintained at a scrubbing liquid volume of 500 mL without recirculation, and a concentration of 1.0×10^{-2} M. The anionic surfactant was present at a scrubbing liquid volume of 500 mL and a concentration of 1.0×10^{-1} M. The concentration of naphthalene in the flue gas was determined at 2, 5, 8, 11, and 14 min in the C_{10}E_4 batch experiments. The naphthalene concentration in the flue gas was analyzed at 5, 8, 11, and 14 min in the C_{14}E_8 batch experiments. The temperature of the scrubbing liquid was about 25°C. The efficiencies of removal of naphthalene in all reported cases were corrected for the absorption of pure water.

Results and Discussion

Table 2 summarizes the enrichment factors (EFs) at various concentrations of surfactants (Huang 2001). Our previous studies involved an anionic surfactant (SDS) and two nonionic surfactants (C_{10}E_4 and C_{14}E_8) to examine the enhanced solubility of naphthalene in the presence of surfactants (Huang 2001). Experiments on the solubility of vaporous naphthalene at equilibrium in the presence of surfactants were performed to obtain the enrichment factors. The enrichment factor represents the ratio of solubility in the surfactant solution to that in pure water. As the results in Table 2 show, when the concentration of surfactants exceeded the CMC, the enrichment factor was high, and increased with the concentration of surfactants. The CMCs of the two nonionic surfactants are below that of SDS. Consequently, the EFs of the two nonionic surfactants are higher than the EFs of SDS at a given concentration. The data reveal that EFs increase with surfactant concentration, especially in excess of the CMC. Accordingly, the concentrations of the surfactants in the scrubbing liquid in the experiments all exceeded the CMC because the solubility of naphthalene was enhanced mainly at concentrations of surfactants above the CMC.

Table 3 presents the removal efficiency of naphthalene and the absorption capacity in micrograms of naphthalene per gram of surfactant at three concentrations of SDS, C_{10}E_4 , and C_{14}E_8 . The

Table 3. Naphthalene Removal Efficiency and Absorption Capacity at Different Concentrations of Surfactants in Continuous Experiments

Surfactant	Concentration (M)	Naphthalene removal efficiency (%) (corrected for pure water)	Absorption capacity (μg naphthalene/g surfactant)
Sodium dodecyl sulfate	1.0×10^{-2}	-6.0 ± 2.6	8.4
	5.0×10^{-2}	28.4 ± 2.7	7.9
	1.0×10^{-1}	39.0 ± 1.4	5.4
C_{10}E_4	1.0×10^{-3}	52.6 ± 1.6	631
	5.0×10^{-3}	66.8 ± 2.0	160
	1.0×10^{-2}	75.0 ± 2.8	90.0
C_{14}E_8	1.0×10^{-3}	59.1 ± 0.9	419
	5.0×10^{-3}	64.2 ± 1.2	91.0
	1.0×10^{-2}	71.9 ± 1.1	51.0

Note: Inlet concentration of naphthalene; $1,064 \mu\text{g}/\text{Nm}^3$.

removal efficiency of naphthalene from pure water was $4.3 \pm 1.9\%$ under continuous scrubbing. The removal efficiency of naphthalene discussed here is corrected for the value in pure water. Experimental results indicate that the naphthalene removal efficiency increased with the surfactant concentrations over the CMC. The absorption capacity decreased as the concentration of surfactants increased. The efficiencies of removal of naphthalene by C_{10}E_4 and C_{14}E_8 were 75.0 and 71.9% at a concentration of 1.0×10^{-2} M. The removal efficiency of naphthalene by SDS ranged from 6.0 to 39.0% at a SDS concentration from 1.0×10^{-2} to 1.0×10^{-1} M. However, the concentrations of SDS were larger than those of C_{10}E_4 and C_{14}E_8 ; the removal efficiency of naphthalene by SDS was lower than the removal efficiencies by C_{10}E_4 and C_{14}E_8 .

Fig. 3 depicts the relationship between the removal efficiency of naphthalene and the surfactant concentration under continuous scrubbing. The results indicate that the removal efficiencies of naphthalene by C_{10}E_4 and C_{14}E_8 were very similar to each other. The removal efficiency of naphthalene by SDS was lower than those by C_{10}E_4 and C_{14}E_8 , even though the concentration of SDS exceeded those of C_{10}E_4 and C_{14}E_8 . The CMC of SDS exceeded that of C_{10}E_4 and C_{14}E_8 , as shown in Table 1. When these three surfactants were at the same concentration, higher than the CMC, more micelles of C_{10}E_4 and C_{14}E_8 were formed than of SDS. Accordingly, more micelle cores were available to capture the naphthalene in the C_{10}E_4 and C_{14}E_8 scrubbing liquid than in the

SDS scrubbing liquid. As Table 3 states, the absorption capacity was negatively correlated with the concentration of surfactants and with the removal efficiency of naphthalene. The SDS had the lowest absorption capacity. The absorption capacity declined as the concentration of surfactant increased, because the enhanced dosage of surfactant exceeded the enhanced efficiency of removal of naphthalene. Therefore, the absorption capacity at high efficiency can be enhanced if the scrubbing liquid can be recycled, reducing the removal efficiency of naphthalene.

Table 4 presents the concentrations of effluent naphthalene and the removal efficiencies at various absorption times in batch experiments. The time to breakthrough was approximately 14–17 min in batch experiments that involved SDS, C_{10}E_4 , and C_{14}E_8 . The batch experiments involved 500 mL of scrubbing liquid without recirculation, and a SDS concentration of 1.0×10^{-1} M, a C_{14}E_8 concentration of 1.0×10^{-2} M, and a C_{10}E_4 concentration of 1.0×10^{-2} M. The batch absorption capacity of naphthalene was $2.4 \mu\text{g}$ Nap/g SDS, $31.8 \mu\text{g}$ Nap/g C_{10}E_4 , and $12.9 \mu\text{g}$ Nap/g C_{14}E_8 , as determined from the total amount of naphthalene trapped during the period of absorption.

The data provided here imply that the removal efficiency of naphthalene by C_{10}E_4 and C_{14}E_8 exceeded that of SDS. Furthermore, C_{10}E_4 and C_{14}E_8 yielded similar removal efficiencies. The efficiency was over 70% for C_{10}E_4 and C_{14}E_8 at 1.0×10^{-2} M in continuous experiments. The capacity of C_{10}E_4 to absorb naphthalene was approximately 2.5 times greater than that of C_{14}E_8 in batch scrubbing. The chemical structure of molecular C_{10}E_4 consists of a ten-carbon chain and four polyoxyethylene groups. C_{14}E_8 is composed of a 14-carbon chain and eight polyoxyethylene groups. The carbon chain is the hydrophobic end and the polyoxyethylene is the hydrophilic end. A longer carbon chain corresponds to greater hydrophobicity. In contrast, more polyoxyethylene groups correspond to higher hydrophilicity. Both the carbon chain and polyoxyethylene groups in C_{14}E_8 are longer than those in C_{10}E_4 . Therefore, the strengths of the hydrophobic and hydrophilic properties of C_{10}E_4 and C_{14}E_8 are difficult to compare. The difference between the absorption capacities of C_{10}E_4 and that of C_{14}E_8 can be explained by the hydrophile-lipophile balance (HLB) value, as defined by Griffin (Rosen 1989), to represent the overall characteristics of the balance between the hydrophilic and lipophilic interactions. For nonionic surfactants, the HLB value is defined as

$$\text{HLB} = \frac{M_H}{M_H + M_L} \times 20$$

The term M_H represents the molecular weight of the hydrophilic segment and M_L is the molecular weight of the lipophilic segment in a nonionic surfactant molecule. The calculated HLB values of

Fig. 3. Removal efficiency of naphthalene as a function of concentrations of surfactants (sodium dodecyl sulfate, C_{10}E_4 , and C_{14}E_8) at 2.65 liquid/gas ratio

Table 4. Naphthalene Outflow Concentration and Removal Efficiency by Surfactants at Various Absorption Times in Batch Experiments

Surfactant	Absorption time (min)	Napthalene outflow concentration ($\mu\text{g}/\text{nm}^3$)	Removal efficiency (%)
Sodium dodecyl sulfate	5	677	36.4
	8	683	35.8
	11	719	32.5
	14	842	21.0
	17	1,060	0
Batch absorption capacity of naphthalene 2.4 μg Nap/g SDS			
C_{10}E_4	2	398	62.7
	5	554	48.0
	8	609	42.8
	11	616	42.2
	14	1,021	4.1
Batch absorption capacity of naphthalene 31.8 μg Nap/g C_{10}E_4			
C_{14}E_8	5	447	58.0
	8	678	36.3
	11	844	20.7
	14	1,063	0
Batch absorption capacity of naphthalene 12.9 μg Nap/g C_{14}E_8			

Notes: The inlet concentration of naphthalene was 1,064 $\mu\text{g}/\text{nm}^3$. The concentration of SDS was 1.0×10^{-1} M. The concentrations of C_{10}E_4 and C_{14}E_8 were 1.0×10^{-2} M.

C_{10}E_4 and C_{14}E_8 were 11.56 and 14.47, respectively. A higher HLB value implies a more hydrophilic nature. Accordingly, C_{10}E_4 is more hydrophobic than C_{14}E_8 . The C_{10}E_4 solution dissolves more of a hydrophobic organic compound, such as naphthalene, than does C_{14}E_8 .

This study involved a laboratory-scale packed tower scrubber to explore a control technology that can be applied to remove vaporous PAHs from flue gases emitted from municipal incinerators. This work considered a municipal waste incinerator plant in Taiwan. The design and operating parameters of the laboratory-scale scrubber were based on the scrubber at this plant. The experimental removal efficiency and capacity were used to determine the amounts of surfactant required and the cost of the surfactant consumed. Some quotations for industrial-grade chemicals on the Taiwanese market were requested to estimate the costs of the surfactants for removing gram quantities of naphthalene. Pure nonionic surfactants were substituted for industrial-grade nonionic surfactants with the fatty alcohol polyethylene glycol ether group. Pannox 77 is similar to C_{10}E_4 , and the two substances have a very close HLB value. Pannox 79 is very similar to C_{14}E_8 . Pannox is a trademark of the Pan Asia Chemical Corporation. The surfactant prices were \$3.6 per kg for SDS, \$1.5 per kg for Pannox 77, and \$1.7 per kg for Pannox 79. The surfactant costs per gram of naphthalene removed were estimated from the absorption capacity and surfactant prices. The results reveal that

less C_{10}E_4 than SDS or C_{14}E_8 was consumed. Table 5 summarizes the assessed costs of the surfactants added to the scrubbing liquid. Other items examined were efficiency, absorption capacity, available concentration range, effect of foaming, and impact of wastewater. The impact of wastewater was determined from the dose of surfactant added, the amount of wastewater processed daily in a plant, and the biological oxygen demand (BOD) contribution of surfactants, to obtain the contribution to BOD by surfactants in the wastewater system of a plant. The contribution by surfactants to BOD was assumed to be completely biodegradable, and estimated as 1.61 g BOD/g SDS, 2.39 g BOD/g C_{10}E_4 , and 2.31 g BOD/g C_{14}E_8 . The results suggest that nonionic surfactants such as C_{10}E_4 and C_{14}E_8 are preferred over the anionic surfactant SDS, and that C_{10}E_4 is better than C_{14}E_8 for addition to the scrubbing liquid to remove vaporous PAHs from flue gas emitted from municipal waste incinerators.

Conclusions

This investigation considered the removal of a representative PAH, naphthalene, using a wet scrubber, by adding nonionic and anionic surfactants to the scrubbing liquid. Nonionic surfactants (C_{10}E_4 and C_{14}E_8) and the anionic surfactant SDS were added at concentrations higher than the CMC. The hydrophobic inner core

Table 5. Overall Assessment of Surfactants

Item	Sodium dodecyl sulfate	C_{10}E_4	C_{14}E_8
Removal efficiency (η)	6.0–39.0%	52.6–75.0%	59.1–71.9%
Absorption capacity (μg Nap/g surfactant) (at concentration 10^{-2} M)	8.4	90.0	51.0
Concentration	10^{-1} M	10^{-3} – 10^{-2} M	10^{-3} – 10^{-2} M
Cost (\$/g Nap)	428	16.7	33.3
(industrial grade chemical)	η (39%)	η (75%)	η (71%)
Foaming (by observation)	High	Low	Medium
Wastewater impact, BOD contribution	η (39%)	η (70%)	η (70%)
mg BOD/L	2.6	0.31	0.64
g BOD/mg Nap removed	193	18.0	37.9

of micelles formed above the CMC increases the solubility of naphthalene. The efficiency of removal of naphthalene by both nonionic surfactants $C_{10}E_4$ and $C_{14}E_8$ exceeds 70% at a surfactant concentration of 1.0×10^{-2} M with continuous scrubbing. The absorption capacity of $C_{10}E_4$ with continuous scrubbing was higher than that of $C_{14}E_8$ and SDS at a given concentration. In batch experiments, the total capacity of $C_{10}E_4$ to absorb naphthalene was 2.5 times higher than that of $C_{14}E_8$. The HLB values of $C_{10}E_4$ and $C_{14}E_8$ were determined to be 11.56 and 14.47, respectively, implying that $C_{10}E_4$ is more hydrophobic than $C_{14}E_8$. Overall, of the three surfactants considered here, $C_{10}E_4$ is the best surfactant to be added to scrubbing liquid for removing vaporous naphthalene. The data imply that control of the vaporous PAHs in flue gas from municipal waste incinerators using a wet scrubber is feasible if appropriate surfactants are added to the scrubbing liquid. However, future research should address the removal of other PAH compounds present at low concentrations, but which are more complex and toxic than naphthalene.

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