Desorption of Odor-Active Compounds by Microwaves, Ultrasound, and Water

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The tolerance against malodors in industrialized societies decreases. Thus, it is necessary to develop new and more powerful technologies for exhaust air purification. To reduce concentrations below the odor threshold, selective adsorption processes with on-site regeneration of the adsorbents are very promising. To regenerate adsorbents new and more cost sensitive methods are needed. The development of four innovative methods based on microwave, ultrasound, ultrasound with water, and water desorption for the regeneration of adsorbents is reported. Different odorous lead compounds such as acetic acid and triethylamine were desorbed. The investigations were performed with various adsorbents such as activated carbon, silica gel, aluminum oxide, and a modified bentonite, covering a wide range of typical materials used in industry. The examination by microwave desorption was successful. After 20 min of microwave radiation bentonite had a residual load of less than 10% of the original load. Desorption by ultrasound gave satisfactory results only when using water as a transmitter. Moreover, the results with water strongly depend on the odor compound to be desorbed. In the case of a highly soluble adsorptive in water the results are promising but, because odor compounds are often sparingly soluble in water, the yields decrease. Among the four examined desorption methods microwave desorption and ultrasonic–water desorption offer the best results. From among the adsorbents the modified bentonite provides the best adsorption properties with the best regeneration performance. © 2005 American Institute of Chemical Engineers *AIChE J,* 51: 502–510, 2005
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Introduction

Odorous emissions of agricultural or industrial origin are discussed as environmental stressors. Complaints from the public are increasing as the tolerance against malodors from the food industry and livestock farming is decreasing. Therefore it is necessary to find solutions to reduce odor emissions that are technologically powerful and cost-effective. The biological waste gas purification, often used in this context, is not sufficient for the reduction of malodors below the odor threshold.[1] Different innovative methods are examined to find the best solution for odor reduction in the food industry and agriculture.[2] One focus is the development of selective adsorption methods for odor depletion. To be economically competitive against other purification methods, it is necessary to include a regeneration step. This will minimize operational expenditures

for the adsorbent and consequently reduce waste production (loaded adsorbent) contributing to an in-line material recycling process. Because pollution control is a cost intensive part of food production there is a need for new and cost-sensitive regeneration methods for adsorption materials.[3-7]

Fundamentals of regeneration

Currently, regeneration methods are used for such processes as solvent recovery and gas separation. The techniques can be divided into three main groups, the most important of which is the *temperature-swing process*. The loaded adsorbent is heated with steam or inert gas at temperatures up to 500°C. At the same time, the steam or inert gas serves as a transport medium for the desorbed components and reduces the concentration of adsorptives in the gas phase.[8] The disadvantage of this process is the need for a steam generator or inert gas supply.[9,10] Moreover, a purge gas flow with low concentrations is produced. If the bonding forces between adsorbent and adsorptive are very high, it is necessary to increase the desorption temperature. For activated carbon, this leads to gasification of the adsorptives at temperatures up to 900°C. Thereby, the adsorptive will be oxidized and released from the adsorbent, a process known as reactivation.[11] It is also possible to heat the adsorbent by electric heating, such as with graphite or metallic fabric inserted in the fixed bed, which causes the risk of hot spots in the fixed bed.[12] The second regeneration method is the *pressure-swing process*.[13] By decreasing the pressure in the fixed bed, the desorption rate is forced. However, because the effect is generally low it is suitable only for gases such as oxygen, nitrogen, hydrogen, and methane.[14] Finally, *regeneration by extraction* is available. This is the elution of adsorbed compounds from the fixed phase into the liquid phase with an extracting agent. Normally, it is used only if there is a risk of ignition or decomposition of the adsorptive. After the desorption step it is necessary to remove the extraction agent, resulting in extra effort to regenerate the adsorbent.

In environmental engineering, exhaust air systems based on adsorption techniques especially for odor removal, which are small in size, are mostly used without a regeneration step. The loaded adsorbent (such as activated carbon, charcoal) will either be disposed of or reactivated by the manufacturer. Therefore at regular intervals a service has to be provided causing operational costs. Consequently, there is a need to develop cost-effective regeneration methods that can be fully integrated in the sorption process and which are applicable on-site. Thus four innovative methods of microwave desorption, ultrasonic desorption, ultrasonic–water desorption, and extraction with water were investigated.

Microwaves

Microwaves are electromagnetic waves with a frequency between 300 MHz and 300 GHz. For a standard microwave device, a frequency of 2450 MHz is regulated by law. Microwaves can create vibrations and rotations in different molecules such as water and fat, and thus heat is produced. The effect of microwaves is described as polarization. In the case of a standard microwave generator the dominating effect is dipole polarization, depending on the electromagnetic properties of the adsorptive/adsorbent combination.[15] A more detailed analysis of the mechanism can be found in Bathen.[16]

Ultrasound

Frequencies above the human auditory threshold of approximately 20 kHz are described as ultrasonic waves. For technical applications, ultrasound is used because of the intensive acoustic energy, the reflection in cracks or pores inside of particles, the agitation of liquids, and cavitation effects.[17]

Experimental

All chemicals, obtained from Merck (Darmstadt, Germany), were of analytical grade. All adsorbents were dried before use and were commercially available materials used for various applications.

Adsorbents

For the investigations adsorbents with different material properties such as aluminum oxide, silica, and carbon were used. Out of these groups adsorbents that showed promising results in the adsorption profile analysis, such as high capacity, favorable kinetic behavior, and high selectivity toward odorous compounds, were selected.[18,19] The following adsorbents were chosen: activated carbon LUWA R10 (Pleisch, Bäretswil, Switzerland), silica gel K60 (Merck, Darmstadt, Germany), modified bentonite GP-S-1 (S&B Industrial Minerals, Marl, Germany), and aluminum oxide KBS (Sasol, Brunsbüttel, Germany). For tests with native multicompound mixtures the activated carbon, Siralox, an aluminum mixed oxide (Sasol, Brunsbüttel, Germany) and OC-SG-01, a material based on a siliceous structure (S&B Industrial Minerals, Marl, Germany), were used.

Adsorptives

For the adsorption profile analysis, six different adsorptives were applied: *n*-heptane, acetone, triethylamine, acetic acid, water, and toluene.[19] For the desorption experiments, the adsorbents were loaded with triethylamine and acetic acid as odor-active substances. Triethylamine is a typical odor component in the fish-processing industry, whereas acetic acid is a typical component from the chocolate-producing industry.[2] Moreover, desorption examinations with native multicompound mixtures were performed. Thus, samples of activated carbon, OC-SG-01, and Siralox, loaded at a chocolate-producing company, as well as OC-SG-01, loaded at a fat-processing plant, were applied to remove the odorous compounds and, consequently, to release the adsorbed substances by different regeneration methods.

Experimental setup

For the adsorption profile analysis the adsorption was carried out at room temperature under the vapor pressure of the adsorptive over a period of 23 h. The following desorption step was performed in a vacuum cabinet at 65°C for 18 h. The weight changes after the adsorption and desorption step were measured and compared in radar plots. For all studies the weight change between loaded and desorbed adsorbent was carried out by use of a Mettler PM 200 (Mettler Toledo, Greifensee, Switzerland) balance. In addition to the adsorption
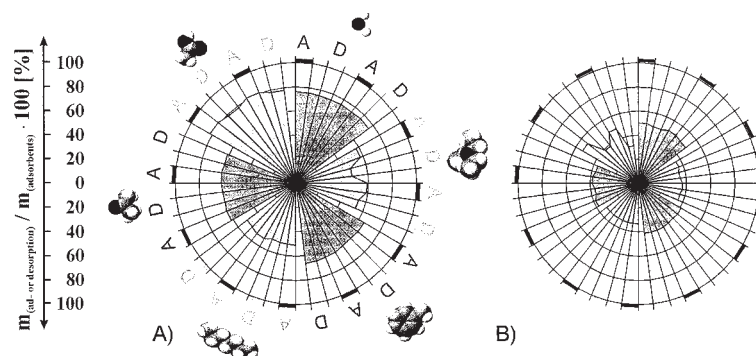
Figure 1. Adsorption profile of silica gel K60 (A) and KBS (Al$_2$O$_3$) (B) with the six adsorptives: water, triethylamine, toluene, *n*-heptane, acetone, and acetic acid.

A: adsorption values; D: desorption values.

profile analysis the loaded adsorbents were desorbed at 65°C over a period of 24 h in a vacuum cabinet, to define a reference to the maximum desorption values in technical processes.

For the microwave experiments, a commercially available microwave device MWT 1720 Rapid (Bauknecht, Schorndorf, Germany) was used. For industrial applications microwaves are limited to five industrial/scientific/medical (ISM) used frequencies. The microwave generator MWT 1720 Rapid worked at the usual frequency of 2450 MHz (Europe). All investigations were performed with the maximum power of 750 W. For the investigations a sample quantity of 0.1 to 0.5 g adsorbent was used. The weighed samples were placed in the device for a period of 0.5 to 20 min. After microwave radiation the weight loss was measured. Immediately after the microwave exposure the sample temperature was monitored with an extremely fast thermocouple (Testo, Lenzkirch, Germany). Concentrations of desorbed compounds during microwave radiation were detected by means of a flame ionization detector (FID; Amluk, Oberaudorf, Germany).

For the desorption with water, sample quantities of 0.2 to 0.7 g adsorbent were used. The loaded material was placed in a Buechner funnel covered with a filter and rinsed with deionized water. Different amounts (50 to 500 mL) of deionized water were used. The quantity of desorbed adsorptive was measured by titration with a Titrator LD 67 (Mettler Toledo, Greifensee, Switzerland). The titration of triethylamine with 0.01 M HCl and of acetic acid with 0.1 M NaOH allowed the determination of the released adsorptives.

For ultrasonic investigations, a SONOREX ultrasonic bath (Bandelin Electronic, Berlin, Germany) was used. The device operated at a frequency of 35 kHz and a maximum power of 2 × 250 W. The sample weight varied from 0.3 to 0.7 g adsorbent. The specimens were placed in the ultrasonic setup for a period of 5 to 20 min. After the ultrasonic exposure the weight loss was measured. During ultrasonic exposure the temperature was monitored with a thermocouple.

During the desorption by the ultrasonic–water method the sample weight varied between 0.3 and 1.2 g, depending on the adsorbent. Deionized water (100 mL) and the loaded material were placed in a vessel and put into the SONOREX ultrasonic bath. After the ultrasonic treatment the samples were filtrated over the Buechner funnel and analyzed as described in the water-desorption experiments.

After the desorption of multicompounds from industry, additional investigations for the identification of single compounds by gas chromatography and mass spectrometry were performed. For the sampling, Tenax tubes for microwave desorption and SPME fibers for ultrasonic–water desorption were used.[6]

Results

Figure 1 shows adsorption profiles of silica gel K60 and KBS (Al$_2$O$_3$). The higher values for the adsorption of the six different adsorptives were reached with the silica gel. For most of the adsorptives it is possible to desorb nearly 100% from silica gel and KBS under the conditions applied. Only for silica gel with triethylamine and KBS with acetic acid is there a noticeable decrease in the adsorption profile.[18,19]

The maximum desorption value in the vacuum cabinet was almost 100% for bentonite. In the case of aluminum oxide the desorption was not quantitative. Only about 40% of acetic acid could be desorbed again. This may be attributable to a reaction of acetic acid with aluminum oxide, which would be in accordance with the results presented in Figure 1. The same effect was observed for silica gel with triethylamine as well as activated carbon with acetic acid and triethylamine. In these cases the results will be discussed separately.

Microwave desorption

For the evaluation of the influence of microwaves on the adsorbent adsorption–desorption experiments were carried out. The adsorption with odorous compounds and the desorption with microwaves were repeated several times in which the same sample was always used. No decrease for the removal of odorous compounds for regenerated adsorbents was observed, even after several adsorption/regeneration cycles, except for the results discussed in the adsorption profile analysis. These results are in accordance with investigations by other authors.[20,21]

Figure 2 shows the desorption kinetics of two adsorption–desorption cycles of triethylamine from the modified bentonite GP-S-1. The load was monitored for a time period of 10 min. The first treatment demonstrates a high desorption rate initially, which decreases after about 5 min. The kinetic in the second
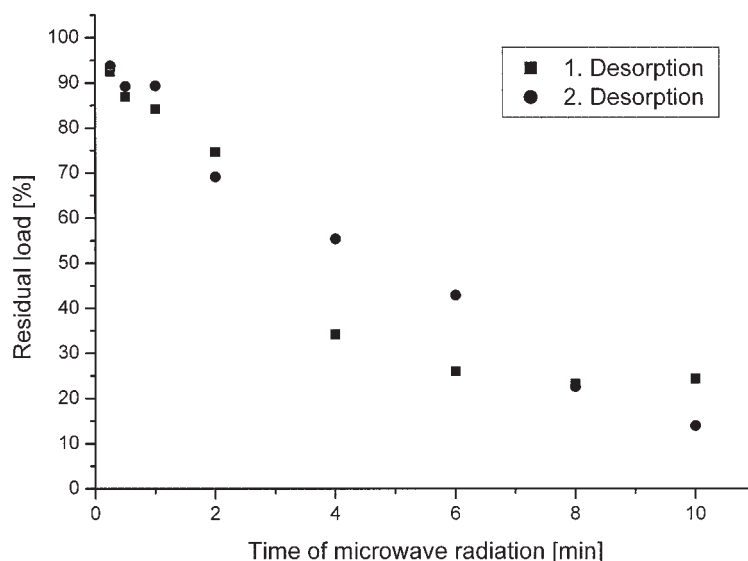
Figure 2. Microwave desorption of triethylamine from bentonite (GP-S-1) in a two-cycle adsorption–desorption experiment.

treatment is nearly linear. After 10 min of microwave radiation in the second desorption step, there is a residual load of the adsorbent of 14%. The loading for the first cycle is higher as its kinetic rate decreases. There are no clear indications for these results, given that no visible changes of the adsorbent could be found. The results of the modified bentonite GP-S-1 are not transferable to activated carbon. An intense reaction of activated carbon during microwave exposure was observed. Because of the graphite structure, activated carbon acts as an electrical conductor. Moreover, activated carbon has a high dielectricity coefficient and dielectricity coefficients have been found to increase with the temperature.[8,16] Microwaves induce an electric current that leads to an inductive heating-up of activated carbon,[22] leading to a self-accelerating effect on the

dielectricity coefficients followed by characteristic phenomena such as spark discharge. Consequently, the measured values for microwave desorption with activated carbon could not be evaluated.

The experiments with the adsorbents silica gel and aluminum oxide proceeded without complications such as lightning. In comparison with triethylamine the desorption velocity of acetic acid is lower. After 20 min nearly all of the adsorptive on the modified bentonite is desorbed, whereas silica gel has a residual load of 24% and aluminum oxide of 40%, respectively (Figure 3). The results of the desorption of acetic acid and triethylamine from aluminum oxide demonstrate clear differences between the two adsorptives. The desorption rate of both is high within the first 5 min, after which the kinetic decreases.
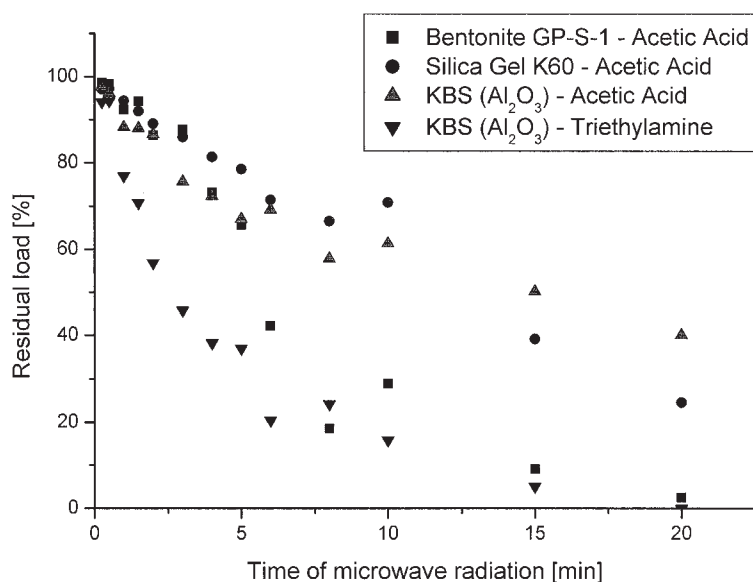

Figure 3. Microwave desorption of acetic acid from bentonite (GP-S-1), silica gel K60, and KBS (Al$_2$O$_3$) and triethylamine from KBS (Al$_2$O$_3$).
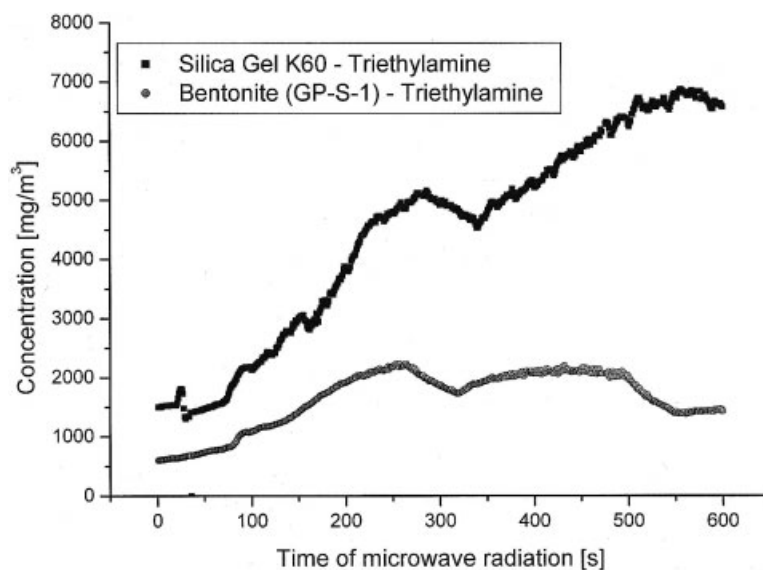
Figure 4. Microwave desorption of triethylamine from silica gel K60 and bentonite (GP-S-1) detected with a flame ionization detector (FID).

After 20 min triethylamine is completely desorbed, whereas acetic acid shows a residual load of 40%. This is in accordance with the maximum desorption value investigated in the vacuum cabinet and verified the assumption of a chemical reaction between acetic acid and aluminum oxide.

The results of the desorption of triethylamine and acetic acid from silica gel K60 differ. In the initial 10 min of microwave radiation the desorption of triethylamine is slightly higher than that of acetic acid. Further on, the desorption rate of triethylamine decreases, whereas the desorption rate of acetic acid remains constant. This could be explained by the adsorption profile results from silica gel K60, which complies with the theory of a reaction between silica surfaces and different amines at higher temperatures.[23,24] The rising temperatures accelerate the reaction between silica gel and triethylamine, and thus the amount of desorbed molecules decreases. Because triethylamine has a lower vapor pressure than that of acetic acid, the higher desorption rate at the beginning may be explained as well.

The temperature course for the microwave desorption of acetic acid onto bentonite GP-S-1 after a short heat-up stage demonstrates a constant temperature at about 80°C. This is attributed to the high energy input compared with the small amount of adsorbent and the small heat of desorption required. Within 1 min an equilibrium between energy input by microwaves and energy loss by forced convection and heat conduction appears. A reduced energy input would result in a slower increase in temperature.[21]

The influence of dielectricity constants of different adsorptives is slight compared to the energy input. Thus the temperature courses for the microwave desorption of acetic acid and triethylamine from GP-S-1 are nearly the same; otherwise, more time is needed to reach the equilibrium with increasing dielectricity constants.[8,16]

Figure 4 presents the results of the microwave desorption of triethylamine from silica gel K60 and the modified bentonite

GP-S-1 quantified by the flame ionization detector (FID). The concentrations were monitored over a time period of 600 s. After a short heat-up stage with low concentrations, both curves are increasing up to a maximum level of about 6800 mg/m^3 for the desorption of triethylamine from silica gel K60 and nearly 2200 mg/m^3 for GP-S-1, respectively. The decrease in concentration after 250 and 500 s, respectively, is attributed to the pulsed microwave device; else the graph of silica gel continuously increases, whereas the course of the modified bentonite decreases after 500 s with the maximum value reached after about 250 s. The maximum concentrations from silica gel and the modified bentonite depend on the different amounts of adsorbents used, such as 0.91 g loaded silica gel and 0.32 g loaded GP-S-1, respectively. After 500 s GP-S-1 is nearly regenerated as the concentration decreases. The smaller particles and therefore smaller diffusion paths out of GP-S-1 ($dp_{50} = 34$ μm) accelerate their overall desorption of the adsorptives over silica gel K60 ($dp_{50} = 347$ μm).

Water desorption

A very cost sensitive method to desorb odors is to use water as an extracting agent. The loaded water could be discarded in the urban wastewater system because odors are easily biodegradable.[1] With an exhaust air scrubber it is complicated to reach concentrations below the odor threshold.[6] The combination of adsorption on surfaces and desorption with water is a promising solution. With adsorption techniques concentrations below the odor threshold are easily achievable.[7] The mass transfer of the adsorbed odors to the liquid phase during water extraction is much higher compared to the mass transfer from the gas to the liquid phase in an exhaust air scrubber. Thus, the efficiency of waste gas cleaning will be substantially increased. The results for acetic acid as an adsorptive are encouraging. The residual load of the adsorbent is less than 20% after water extraction. The amount of water used for desorption has only a
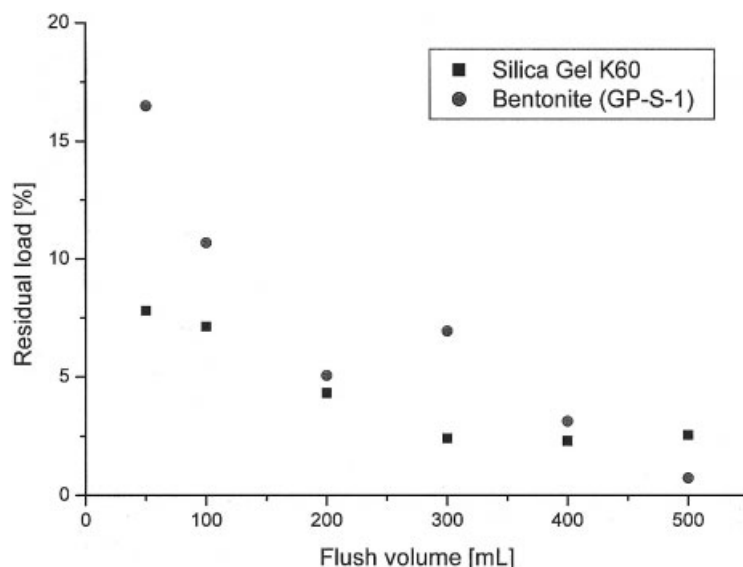
Figure 5. Desorption of acetic acid from silica gel and bentonite with water without ultrasonication.

slight influence on the results. An increase of the water flush volume from 50 to 500 mL results in a decrease of the residual load of <20% to <3% (Figure 5). The desorbed amount of triethylamine was below the limit of determination, independent of the water flush volume used.

Ultrasonic desorption

Compared to microwaves ultrasound is a mechanical wave. Thus, the propagation occurs through a medium such as liquid or gas. Effects of ultrasound are the local variation of pressure and density of the fluid, which leads to a medial local displacement of molecules and atoms.[25] In industrial applications cavitation effects are used for disintegration and emulsification. Other applications are cleaning of silicon wavers, activation of chemical reactions,[26] and soil decontamination.[27] To examine

the applicability of ultrasonic desorption of odors from selective adsorbents, different investigations were carried out.

Figure 6 shows the ultrasonic desorption of triethylamine and acetic acid from silica gel K60 and the modified bentonite GP-S-1. After 20 min a residual load of >80% remains for silica gel with acetic acid and triethylamine and for modified bentonite with acetic acid. The results for modified bentonite and triethylamine are slightly better because there is a residual load of about 70% after 20 min of ultrasonic exposure. In comparison the desorption rate of triethylamine is higher than that of acetic acid and the desorption rate of modified bentonite is higher than that of silica gel, attributed to the higher vapor pressure of triethylamine. Additionally the smaller particles of the modified bentonite result in a shorter diffusion path of the desorbed adsorptive and thus in a shorter diffusion time out of the adsorbent.
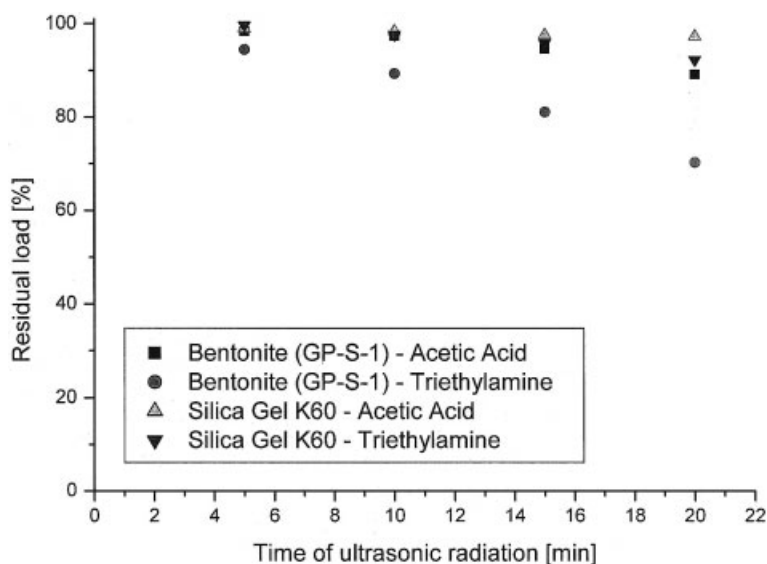

Figure 6. Ultrasonic desorption of acetic acid and triethylamine from bentonite (GP-S-1) and silica gel K60.
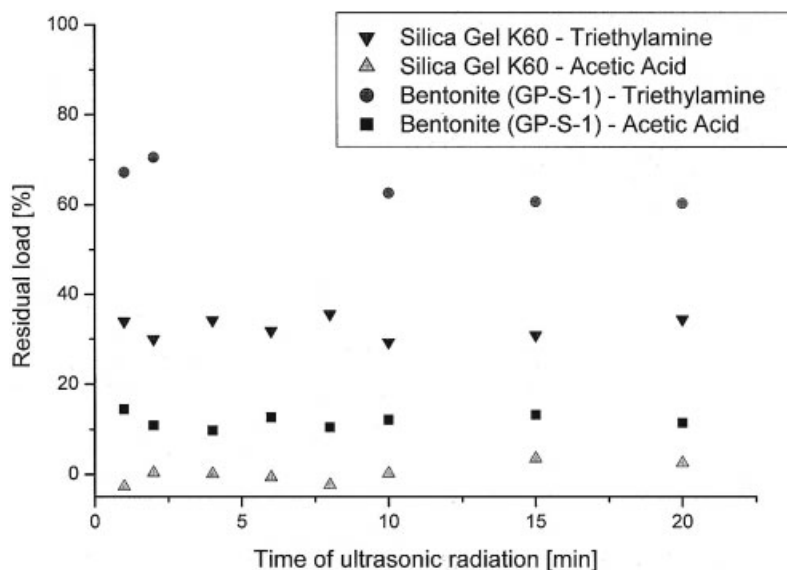
Figure 7. Desorption of triethylamine and acetic acid from bentonite and silica gel with ultrasonic–water desorption.

To evaluate the inverse exponential shape of the curves a model based on the Arrhenius equation is used

$$k = k_0 e^{-E_a/RT} \tag{1}$$

The reaction velocity with a stoichiometric coefficient of 1 is described as

$$r = \frac{dn_{os}}{dt} = k n_{os}^z \tag{2}$$

Desorption processes are described as reactions of the first order.[28] From this follows

$$\frac{dn_{os}}{dt} = k_0 e^{-E_a/RT} n_{os} \tag{3}$$

with

$$n_{os} = \frac{m_{os}}{M_{os}} \quad \text{and} \quad \frac{m_{os}}{m_{solid}} = q_{os} \tag{4}$$

Inserting Eq. 4 into Eq. 3 yields

$$\frac{dq_{os}}{dt} \cong \frac{\Delta q_{os}}{\Delta t} = k_0 q_{os} \exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

$$\Leftrightarrow \ln\left(\frac{\Delta q_{os}}{\Delta t}\right) = k_0' - \frac{E_a}{R}\frac{1}{T} \tag{6}$$

From this a value of 102 kJ/mol for E_a and a value of 5.24E13 s^{-1} for k_0 is obtained for the desorption of triethylamine from silica gel K60. The correlation coefficient for the linear fit is 0.9973 with a standard deviation of 0.07356. The value for the activation energy is in good agreement with reported values in the literature for the thermal desorption of triethylamine from silica.[29]

Ultrasonic–water desorption

For ultrasonic waves water is a much better transmitter than air. In general the desorption values for silica gel are higher than those for the modified bentonite. Additionally, the results for silica gel are significantly improved compared to those of water extraction without ultrasound. The influence of the time of ultrasonic radiation is negligible. No significant decrease of the residual load could be achieved within 1 to 20 min of ultrasonic exposure (Figure 7). Thus the desorption kinetic in ultrasonic water desorption is very fast. In combination with water as an extraction agent it is possible to desorb a substantial amount of triethylamine from the adsorbent's solid surfaces. For acetic acid the results are not significantly higher than water extraction without ultrasonic radiation, given that the results with water desorption already lead to highly satisfactory results. For triethylamine a residual load of about 60% is left on the modified bentonite GP-S-1 and for silica gel K60 a residual load of nearly 30% is analyzed. For acetic acid the residual load is nearly 10% for the modified bentonite and nearly 0% for silica gel K60.

Desorption of multicompound odors from industrial plants

The desorption of industrial multicompound mixtures was carried out by microwave desorption and ultrasonic–water desorption. Figure 8 presents a typical curve for the regeneration with microwaves detected with the FID. The concentration of released components increases after about 100 s and reaches a maximum value of nearly 350 mg/m^3 after 250 s. Afterward the concentration continuously decreases to 180 mg/m^3 after 10 min. During the first 100 s the sample was heated up and, consequently, the highly volatile compounds were released with a maximum concentration within 250 s. In the third stage the tighter adsorbed compounds were discharged.
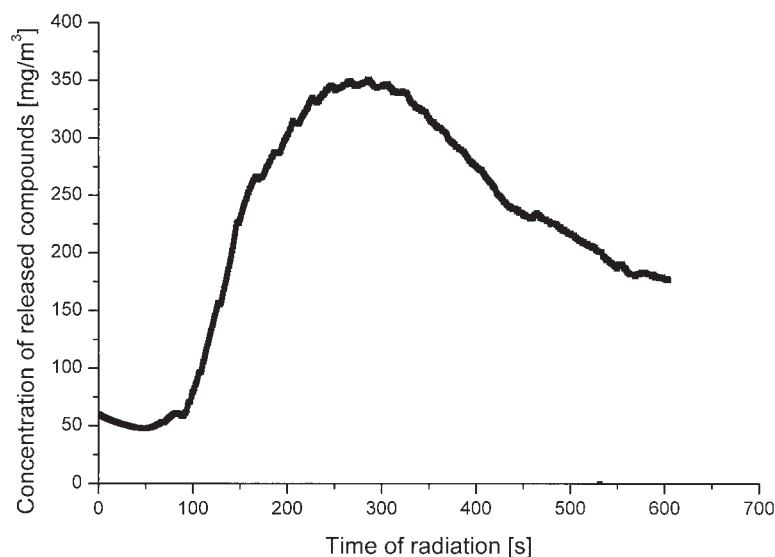
Figure 8. Desorption of industrial multicompound mixtures with microwaves.

Overall signal for different compounds detected with the FID.

For additional information different samples were analyzed with a gas chromatograph coupled to a mass spectrometry detector (GC-MS). Therefore samples of the applied multicompound mixtures were compared to the desorbed compounds. According to expectations the highly volatile components were detected shortly after microwave exposure. For example, in the exhaust air from the chocolate production the ratio of hexanal increased, whereas the ratio of acetic acid decreased during the adsorbent regeneration.

After desorption with ultrasonic waves in water fewer components were found in the mixture, which is attributed to the different sampling methods described in the experimental setup. Moreover, the released components identified in the extraction agent were different from those of the untreated exhaust air. For example, the exhaust air of the fat-processing company contained mainly alkanes and aldehydes. After ultrasonic–water desorption mainly alcohols and ketones were analyzed in the desorbed mixture. The chemical reactions that occur during this process as well as the influence of the ultrasonic waves could not be determined. Therefore more detailed investigations must be performed.

Discussion and Conclusions

With microwave radiation good results for the desorption of odors could be achieved. By introducing energy with high density the purge gas flow could be reduced, thus lowering the operating costs.[30,31] Additionally, capital costs may be minimized by a less complicated process control. In technical processes the small penetration depth of microwaves might be unfavorable, which could be solved, if electromagnetic waves with lower frequencies are used for desorption.[32] The penetration depth will increase up to several meters while the same effects such as dipole polarization are predominant. The application of microwaves to activated carbon in technical processes must be performed under an inert gas atmosphere to avoid the risk of spontaneous ignition.[3]

The results with water as an extracting agent depend strongly

on the chemical behavior of the odor compound to be desorbed. With highly water soluble adsorptives good results could be achieved but, because odor substances are often barely soluble in water, the results get worse. Using special additives in the water (such as different humic substances), better results could be achieved, although the additives have to separated from the wastewater after use.[2] After the desorption step the adsorbents have to be treated for the new cycle. Dry exhaust air has to be applied on-site, which results in a more sophisticated control system and additional costs. Furthermore, the adsorptives must be stable in the aqueous phase, which has to be considered in the design phase.

The results for ultrasonic waves are unsatisfactory because only a temperature effect could be observed. No direct interaction between adsorptive or adsorbent and ultrasonic waves could be established, which is in agreement with other published research results.[33]

A combination of water extraction and ultrasonic exposure seems to be promising.[34] The transmittance of the ultrasonic waves in water has substantial effects on the results, but extra efforts in investment and process control have to be provided. Besides this, the same conditions as those in water desorption (such as stability of the adsorbent in the aqueous phase) have to be considered.

Among the four examined desorption methods, microwave desorption and ultrasonic–water desorption demonstrated the best results. Whereas it is possible to completely regenerate different adsorbents by microwave independent from the odor compounds, ultrasonic–water desorption is suitable only for highly water soluble adsorptives. The choice which regeneration method will be the best solution for a special problem has to be decided by means of the conditions at the company on-site and the compounds to be separated. For all methods the demands on the adsorbents were high. In comparison the modified bentonite GP-S-1 showed the best adsorption properties with the best regeneration performance.

Acknowledgments

Notation

dp_{50} = medium particle size, μm
E_a = activation energy, J/mol
k = reaction rate constant, 1/s
k'_0 = arithmetic factor for determination of k_0
k_0 = factor of the Arrhenius equation, 1/s
m_{os} = mass of organic substance, g
m_{solid} = mass of loaded adsorbent, g
M_{os} = molar mass of organic substance, g/mol
n_{os} = amount of organic substance, mol
q_{os} = odor load at the adsorbent, kg/kg
R = general gas constant, J mol^{-1} K^{-1}
r = reaction velocity, mol/s
T = temperature, K
t = time, s
z = reaction order
GP-S-1 = modified bentonite (S&B Industrial Minerals, Marl, Germany)
K60 = silica gel (Merck, Darmstadt, Germany)
KBS (Al_2O_3) = aluminum oxide (Sasol, Brunsbüttel, Germany)
LUWA R10 = activated carbon (Pleisch, Bäretswil, Switzerland)
OC-SG-01 = silica-structured material (IKO-Minerals, Marl, Germany)
Siralox = aluminum mixed oxide (Sasol, Brunsbüttel, Germany)

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