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An odor predictive model for rendering applications[☆]

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Abstract

The rendering process consists of crushing and heating animal remains to produce by-products. The U.S. produces approximately 30 billion pounds of inedible animal by-products annually, exporting a market value of US$ 1.5 billion. Benefits of the rendering process include reducing total waste material, and helping the livestock industry stay competitive over vegetable protein manufacturers. However, the rendering process can have a negative effect on the environment through the emission of nuisance odorous compounds such as hydrogen sulfide, reduced sulfur compounds, ammonia, various fatty acids, ketones and aldehydes. Several strategies are currently used to combat odor in rendering facilities. In recent years, rendering facilities are increasingly selecting biofiltration for combating nuisance odor. This work describes modeling and design strategies used in building large-scale biofilter systems of up to 250,000 cfm (cubic feet per minute) capacity. The models facilitated in the design and evaluation of operating conditions and capital investment. This work demonstrates that models play an important role in the design of large-scale odor control systems that deliver predicted performance.

Keywords: Rendering process; Odor control; Biofilter; Predictive model

1. Introduction

The rendering process consists of crushing and heating animal remains to remove moisture, thereby allowing the fat to be separated from the high-protein greaves. These greaves are then ground into bone meal, a livestock feed with good market value and high nutritional value. Fat, a major by-product, is used in cooking, frying, soap, detergent, candles, deodorants, paints, cosmetics, shaving cream and caulking compounds [1–2]. Other by-products of the rendering process are used in pharmaceuticals, leather, glue and fertilizer. The rendering market is large and according to Ockerman and Hansen [1], the U.S. produces approximately 30 billion pounds of inedible animal by-products annually, exporting a market value of US$ 1.5 billion. Benefits of the rendering process include reducing total waste materials and helping the livestock industry to stay competitive over vegetable protein manufacturers [1]. However, rendering can have a negative effect on the environment through the emission of nuisance odorous compounds into the atmosphere from the process facilities. The most odorous section of a rendering plant is the blood storage area. Odors from this area result from amino acids and peptides present in blood. Other foul-smelling areas are the singeing ovens, the gut department and the wastewater treatment facility [2]. The combustion of fossil fuels in ovens during the heating process also creates air pollution in the form of SO_x, NO_x and carbon dioxide. Additionally, at high temperatures, by-products of fat and protein breakdown become volatile and are typically odorous. Chemical by-products include hydrogen sulfide, ammonia, various fatty acids, ketones and aldehydes (refer Table 1).

Government regulations on odor emissions and air quality standards help monitor and control excessive emissions from plant facilities. In the United States, there are no federal odor regulations approved by the Environmental Protection Agency (EPA). Instead, odor emissions are monitored at the

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Nomenclature

A_s	biofilm surface area
$C_{\text{odor inlet}}$	concentration at the inlet of the biofilter
$C_{\text{odor outlet}}$	concentration at the discharge of the biofilter
D_e	effective diffusion coefficient in the biofilm
EBRT	empty bed residence time equals to media volume/volumetric flow rate
k_0	zero-order rate constant
K	first-order rate constant

Greek letters

m	air/biofilm distribution coefficient
α	lumped kinetic parameter
δ	biofilm thickness
ϕ	defined in Equation (3)

state and municipal levels [3]. In Canada, odor issues are dealt with at the provincial level, and odor is quantified based on emission rates and off-property boundary odor levels. Several strategies are currently used to combat odor in rendering facilities. The first step is to reduce odor at its source. This involves limiting the storage of raw materials (i.e. animal remains), maintaining cool temperatures, pasteurization to retard decomposition and general plant cleanliness. However, the above techniques are limited in their effectiveness, a secondary treatment must often follow, conventionally being adsorption, incineration or chemical scrubbing. Adsorption using carbon filtration is effective for low concentrations of contaminants, but problems arise when the adsorption bed reaches its adsorption capacity and must be disposed of at significant expense. Thermal and catalytic incineration are commonly used methods that involve combustion of odorous compounds at high temperatures; these processes are only feasible at moderate to high pollutant concentrations, and use a non-renewable petroleum-based fuel source. Chemical scrubbing uses the principle of pollutant oxidation to produce relatively odorless and harmless products. However, complex operational controls and intrusive chemicals requirements make operating costs very high.

In recent years, rendering facilities are increasingly selecting biofiltration to combat odor. Biofiltration uses microorganisms to metabolize pollutants at ambient temperatures without the need for expensive adsorbents, fuels or chemicals. Biofiltration is more energy efficient, making it the more economical and environmentally friendly alternative. By passing a humidified polluted air stream through media bed particles covered with biofilm, odorous compounds are metabolized by a variety of microorganisms into harmless and odorless products [4].

Table 1
Sources of odors in rendering process

Process/department	Odorous compounds
Blood storage	Amino acids, peptides
Wastewater treatment	Ammonia (NH_3), hydrogen sulfide (H_2S)
Evaporation	H_2S, NH_3, amines, aldehydes
Animal waste product storage	H_2S, mercaptans, NH_3, acetic acid, indole, skatole, butyric acid, amines, aldehydes
Smokehouse emissions	Acetaldehyde, formic acid, furfural, cresol, acrolein

This work describes modeling and design strategies used in building large-scale biofilter systems of upto 250,000 cfm (cubic feet per minute) capacity for rendering plants.

2. Design methods

2.1. Mixture of odor components and modeling

As described above, rendering odors are due to multiple compound mixtures consisting of many volatile organic compounds (VOCs, i.e. aldehydes), reduced sulfur compounds (i.e. dimethyl disulfide), nitrogen based compounds (i.e. amines) and others. Recently, Ramesh and Devinny [5] have presented a review of most biofilter models. In general, biofilter models are limited to single compounds or mixtures with only a few compounds [6]. When a mixture of pollutants is present in the air-stream, bio-degradation kinetics can become complex due to interference or inhibition effects of compounds [7]. It is time-consuming and often not feasible to fully determine kinetic properties and cross interference effects of all the compounds involved in the rendering process. Due to lack of parameters and simplicity, in this work, odor concentration is treated as a single VOC compound, and subsequently a single VOC [8] model is used to describe odor destruction in a biofilter. To our knowledge, this work is the first attempt to model odor destruction through the use of a VOC modeling approach and the application of the model in full-scale designing of large (∼250,000 cfm capacity) biofilters.

2.2. Limitations of on-site pilot test data

Often biofilters are scaled-up from pilot scale tests that are carried out at plant sites. Although, continuous concentration measurement of volatile organic compounds and some reduced sulfur compounds are possible using portable or hand-held instruments, continuous monitoring of odor concentration is not possible and also expensive. In most cases, pilot test results are based on several spot odor readings, which do not accurately represent the actual fluctuations of process conditions. The probability of variations in flow and concentration levels, process changes and future expansion plans make these tests alone inadequate for accurate designs that are risk-free. In a large-scale biofilter project, 5% error in estimation of media volume can cause significant variation in the capital cost. Furthermore, customers demand a guarantee that the installed system will perform as specified. Designing large-scale biofilter systems requires minimal or preferably no risk, thus predictive models that are validated with pilot test data have become valuable tools in the accurate design of equipment and control systems.

2.3. Pilot test

The pilot biofilter was packed with 2.7 m^3 proprietary inorganic BIOSORBENS^{TM} media [Biorem Technologies Inc., Ont.] and operated over a period of 2 months from the start-up. BIOSORBENS^{TM} media particles are pre-inoculated; thus, biofilters take only 1–2 days for acclimation. Since pilot data were taken after several days of operation, the data represent long-term operation of the full-scale biofilters. The main air streams to the pilot biofilter consisted of airstreams from blood, mucosa and hard material processing facilities. Biofilter inlet and discharge air samples were collected from the pilot unit installed at the rendering plant site, and odor concentrations were measured by the Olfactometric method. In this method, a descending series of known dilutions from collected air samples are introduced simultaneously to all participants of an odor panel. The results for each sample are processed to determine the odor threshold value (OTV) for the sample. First, logarithmic values of dilution levels are plotted against panel responses. From the regression line between dilution levels and panel responses, OTV values are determined. The point at which 50% of the panel can just detect the odor is recorded as the OTV or effective dilution to 50% response (ED_{50}). Since OTV is a dilution factor, it has no units but is often expressed in odor units (OU) [9]. Air samples were analyzed for odor concentrations under various process conditions including varying empty bed residence times to develop the model parameters. Odor concentrations were determined by Pinchin Environmental Laboratory (Ont., Canada), which uses the AC'SCENT® International Olfactometer and the data are within the confidence level of 95%. AC'SCENT® International Olfactometer complies with ASTM E679-91 standard as well as prEN 13725 "Air quality-determination of odor concentration by dynamic olfactometry" (http://www.pinchin.net). Odor panelists were presented with samples at the 20 l/min rate typical of the prEN standard. McGinley and Mann [10] report comparison of two standards in more details. A summary of the pilot data (average values of at least three samples for each case) is listed in Table 2.

2.4. Model equations

Because of simplicity, the Ottengraf and van den Oever [8] model has been used by a number of researchers [5,7,11–14] to predict VOC removal performance in biofilters. In this work, the model is extended to describe the prediction of odor removal performance in a biofilter. In Ottengraf and van den Oever's [8] model, which is based on number of simplified assumptions, two limiting cases of first- and zero-order biodegradation kinetics are considered. For the details of all model equations, refer to Ottengraf and van den Oever [8]. The simplified forms of the model equations for the gas phase are given below:

zero-order reaction-limited model

$$\frac{C_{\text{odor outlet}}}{C_{\text{odor inlet}}} = 1 - \alpha_{\text{lump}}\left(\frac{\text{EBRT}}{C_{\text{odor inlet}}}\right) \tag{1}$$

where $\alpha_{\text{lump}} = A_s \delta k_0$

zero-order diffusion-limited model

$$\sqrt{\frac{C_{\text{odor outlet}}}{C_{\text{odor inlet}}}} = \left\{1 - \alpha_{\text{lump}}\text{EBRT}\sqrt{\frac{1}{C_{\text{odor inlet}}}}\right\} \tag{2}$$

where $\alpha_{\text{lump}} = \left\{A_s\sqrt{\frac{k_0 D_e}{2m}}\right\}$

first-order model

$$\frac{C_{\text{odor outlet}}}{C_{\text{odor inlet}}} = \exp(-\alpha_{\text{lump}}\text{EBRT}) \tag{3}$$

where $\alpha = \frac{A_s D_e}{m\delta}\phi\tanh\phi$, and $\phi = \delta\sqrt{\frac{K}{D_e}}$

In the above equations, units of concentration for odor and EBRT are in odor units (OU)/m^3 and minutes, respectively.

3. Results and discussion

3.1. Model parameter estimation

When pilot data given in Table 2 were compared with the three models (zero-order diffusion limited, zero-order reaction limited and first-order models) of Ottengraf and van den Oever [8], the first-order model fit the pilot data most accurately. In Table 3, estimated parameter values and correlation coefficients of these three models are listed. The first-order

Table 2
Odor data from the pilot plant at the rendering facility

Flow rate (m^3/s)	Residence time (s)	Odor threshold value (OU/m^3)		Removal efficiency (%)
		Inlet	Outlet	
0.095	28.3	4150	990	76
0.088	30.6	3350	507	85
0.074	36.2	8706	796	91
0.065	41.7	6300	750	88
0.061	44.1	14283	1220	91
0.057	47.2	8483	660	92

Table 3
Model parameter estimation

Model	Parameter α_{lump}	Parameter value	Correlation coefficient
Zero-order reaction-limited	$\alpha_{\text{lump}} = A_s \delta k_0$	7930.0	0.02
Zero-order diffusion limited	$\alpha_{\text{lump}} = \left\{ A_s \sqrt{\frac{k_0 D_e}{2m}} \right\}$	83.9	0.68
First-order (case 1)	$\alpha = \frac{A_s D_e}{m\delta} \phi \tanh\phi$	3.4	0.94
First-order (case 2)	$\alpha = \frac{A_s D_e}{m\delta} \phi \tanh\phi$	6.4	0.83

model fit the pilot data more closely with a correlation coefficient of 0.94 and a lumped parameter (α_{lump}) value of 3.4 min^{-1}. Estimation of a lumped parameter value α_{lump} from individual parameters such as biofilm surface area (A_s), kinetic constants (K), film thickness (δ), effective diffusion coefficient (D_e) or distribution coefficient (m) is not possible because of the complex characteristics of the airstreams and unknowns involved. As discussed above, in addition to reduced sulfur compounds, nitrogen-based compounds such as amines, ammonia and several VOCs also contribute to the odor makeup. Thus, a model developed for hydrogen sulfide or other reduced sulfur compounds cannot be applied to a rendering process. The model Equation (3) is used for predicting various conditions required by the design specifications as described in the next section.

3.2. Model validation and pilot data comparison

In Fig. 1, odor destruction efficiency as predicted by the model is compared with the pilot data. The agreement between the pilot data and model-predicted values is excellent. It confirms that odor removal in the biofilter follows first-order kinetics for the rendering waste air. When the same approach was used in another pilot study at a rendering application, of all the three models tested, again the first-order model fit the data best with the lumped parameter value (α_{lump}) of 6.4 min^{-1} with a correlation coefficient of 0.83. The main difference between the two rendering applications is the type of waste materials processed. Since the compounds in the airstreams are different, parameter values vary.

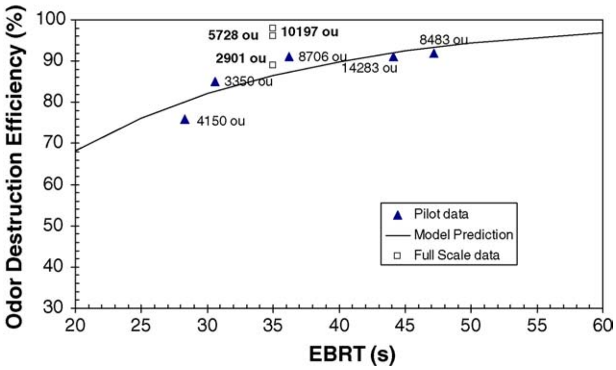

Fig. 1. Comparison of model prediction and field data.

Since odor characteristics depend on the types of waste materials processed at a rendering facility, a single model with the same parameter values is not expected to predict odor removal performance in every rendering process application. Regardless, as for VOC applications, the modeling of odor removal is feasible. In Fig. 1, data collected from the full-scale system depicted in Fig. 2 is also compared with the predicted values. This is discussed in detail in the next section.

3.3. Application of the model in full-scale design

The model described above has been used in designing one of the world's largest synthetic media biofilter systems (Fig. 2). This system consists of six biofilter cells. The rendering plant customer had requested a biofilter that

Fig. 2. A 250,000 cfm biofilter system at a rendering facility, Ontario (courtesy of Biorem Technologies Inc., Ont., Canada).

guarantees average odor removal efficiency of 85% or higher for inlet maximum odor concentration of 17,000 OU/m^3. The customer also specified that the outlet concentration was not to exceed 500 OU/m^3 to ensure that the concentration at the nearest sensitive receptor did not exceed 5 OU/m^3. With 85% removal in a biofilter, discharge concentration will be about 2550 OU/m^3. The remaining reduction in concentration is accomplished via a stack and dispersion. With this level of odor, dispersion model calculations confirmed that the odor concentrations at the property boundary were meeting conditions set in the air permit of 5 OU/m^3.

In Fig. 3, predicted performance curves are presented as a function of inlet concentration and EBRT. Two regions (with and without a stack) are identified in Fig. 3. Fig. 3 shows that a biofilter without a stack needs to be designed for at least 60 s EBRT. Although this leads to a very large footprint, such a design will meet a design specification of 500 OU/m^3 at the discharge. The figure also shows that a 30 s EBRT does not meet the specified condition of 85% removal, but a 35 s EBRT biofilter with a stack will guarantee customer specified conditions of 500 OU/m^3. This also points out that pilot data (refer to Table 2) alone are not adequate to determine EBRT accurately. Based on the model, 35 s EBRT was selected to meet all performance specifications. Based on this design approach, a 250,000 cfm capacity biofilter system, as shown in Fig. 2, has been built and was commissioned in August 2003.

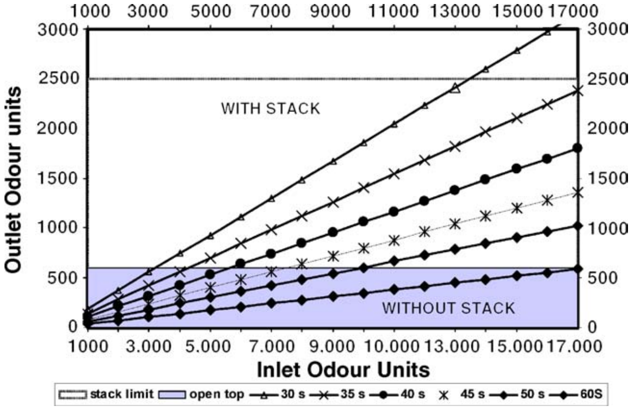

Fig. 3. Model predicted design curves.

After the full-scale system had reached steady state, odor measurements were taken from the inlet and outlet airstreams of the biofilter system, and compared with the model-predicted data. The full-scale system exceeded predicted performance (refer to Fig. 1). In the full-scale system, an efficient three-stage humidification unit that humidifies inlet process air and removes particulates was also installed. No odor data were taken at the inlet and outlet of the humidification unit; however, it will be interesting to evaluate odor removal efficiency of the humidification system. Furthermore, biofilters

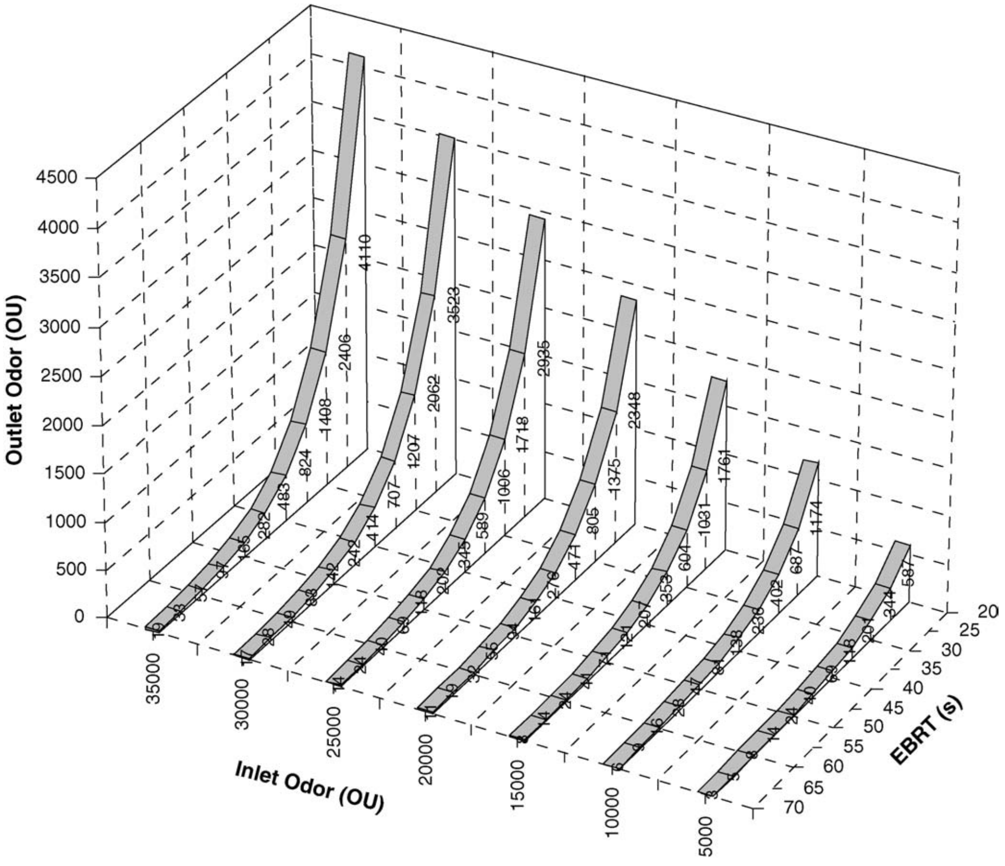

Fig. 4. Model predicted design curves for 230,000 cfm biofilter design.

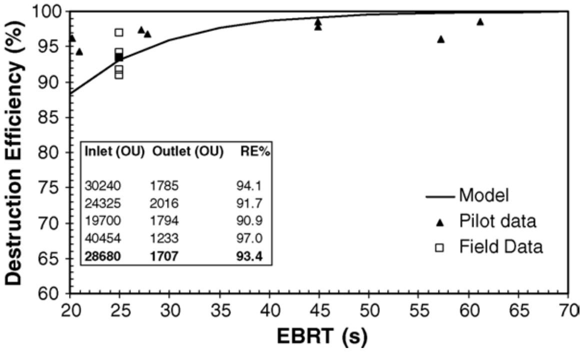

Fig. 5. Comparison of model prediction and field data for the 230,000 cfm biofilter.

perform better under varying loads as opposed to steady loads. The above reasons could account for better than predicted performance in the full-scale biofilter systems. After a year, the full-scale system continues to remove odorous air and keeps the plant environment free of nuisance odors.

After a successful application of the case study described, a second biofilter project of similar size (approximately 230,000 cfm) was awarded. Using the same modeling approach, a 25 s EBRT was selected for this system. Performance curves used in designing this system are presented in Fig. 4. The system has recently been built and was commissioned in September of 2004. In Fig. 5, performance data from this field unit is compared with model predictions. Average removal efficiency (93%, ■) calculated from four odor data points (Pinchin Environmental Laboratory, Ont., Canada) closely agree with the model. For this system, the odor emission claim in the certificate of approval (CofA) application is only 83%. Thus, the odor control system exceeded the design requirement. The model predictions given in Fig. 5, are based on the lumped parameter value of $\alpha = 6.4\,\mathrm{min}^{-1}$ (refer to Table 3). Fig. 6 shows odor destruction efficiency is very sensitive to the lumped parameter value, α. Presence of more water-soluble odorants in the rendering air and increased biomass (i.e. high biofilm surface area) can give a higher value for this parameter (α). Currently, research is underway to characterize airstreams and to identify dominant microbial species in different rendering applications.

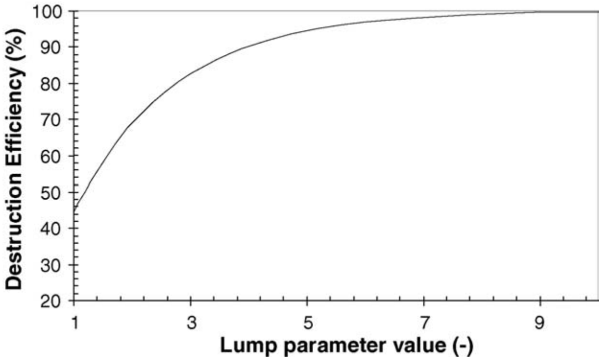

Fig. 6. Sensitivity of the lump parameter value (α).

4. Conclusion

Through pilot and field-scale verification, this modeling exercise has demonstrated that mathematical models that were developed originally for predicting VOCs can be extended to predict odor removal performance in biofilters. The empirical models facilitated the design and evaluation of operating conditions and determination of capital investment. In the past, modeling of biofilters has been a mere academic exercise; however, this work demonstrates that models play an important role in the design of large-scale odor control systems that deliver predicted performance. It will be interesting and challenging to develop realistic models that incorporate mass balances and mathematical correlations (odor concentration versus mass concentration) of all odor-causing compounds in the rendering process. Further research work is needed in verifying the model with the individual components making up the odor.

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