# Biofiltration of Ethanol Emissions from Bakery Operations

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## ABSTRACT

The management of volatile organic compounds in bakery exhaust gases was identified as a high priority problem by the American Bakers Association in conjunction with their member companies. Biotrickling filter technology was evaluated among other approaches and was selected for a pilot study to control ethanol emissions from a bakery oven exhaust gas stream. Biofilters and biotrickling filters use microbial populations in biofilms that grow on support media to degrade or transform contaminants in the air. The biotrickling filter employed in the pilot study used a synthetic fibrous support media to immobilize the biofilm. A pilot study was conducted from September 1997 to February 1998, to assess the performance of biotrickling filter technology in treating organic emissions from bakery ovens. Bench-scale studies were conducted to determine the effectiveness of the support media and develop initial estimates of biotrickling filter performance. Pilot studies were performed with USEPA's trailer mounted two-stage biotrickling filter system, at flowrates in the range of 1.8-3.0 standard cubic meters per minute (65-104 standard cubic feet per minute). Removal efficiencies in the range of 80% to 100% were measured experimentally, and averaged 91% over the duration of the study. The pilot-scale biofilter produced removal efficiencies exceeding 80% for about 99.6% of its operating time. The pressure drop across the bed was less than 6.4 millimeters (0.25 inches) of water. The test further revealed that the biotrickling filter was quite robust; it responded quickly to changes in inlet concentration and exhibited a recovery time of less than 150 minutes after a nine day shutdown period. Preliminary economic analysis of the biotrickling filter system, from a Reasonably Available Control Technology (RACT) perspective, showed that the tested biotrickling filter technology is cost-effective for treating ethanol emissions from a bakery oven.

## INTRODUCTION

The primary volatile organic compound (VOC) emitted from bakery operations is ethanol. In yeast-leavened breads, yeast metabolizes sugars during anaerobic fermentation, producing ethanol and carbon dioxide that is largely responsible for causing the bread to rise. Ethanol is about 98% of the VOC emitted. The primary emission source at the bakery is the oven. Ethanol volatilization occurs when product temperatures exceed 77$^{o}$C (170$^{o}$F) in the oven. Ovens are designed to operate under slightly negative pressure, thereby capturing bakery emissions. The capture efficiency of the oven is generally assumed to be 100%. For regulatory purposes, some states assume 90% capture efficiency. For bakery ovens, current USEPA guidance suggests that RACT should result in VOC emission reductions of 80 to 95 percent for large bakery operations. Most states require an overall reduction efficiency of 81 percent (90 percent capture efficiency and 90 percent destruction efficiency). The majority of the control devices on bakery ovens are catalytic oxidizers.

Biofiltration is not a physical filtration process, but rather involves bioreactions, specifically biodegradation of the contaminant VOCs. In this paper, the terms biofiltration and bioreaction are used interchangeably. Biofilters and biotrickling filters use microbial populations in biofilms to degrade or transform contaminants in the air. A biotrickling filter uses synthetic support media and employs a water/nutrient recycle stream to keep the biofilms moist and distribute needed nutrients (nitrogen, phosphorus, etc.). A biofilter uses natural support media, such as soil, peat, compost, and relies on indigenous microorganisms and nutrients present in the media.

Previous studies have shown that biotrickling filters can effectively treat ethanol with removal efficiencies exceeding 95%. This makes biotrickling filters viable as a control technology for meeting or exceeding current regulatory requirements. In addition, biofiltration may offer potential cost advantages when compared to other control technologies, including catalytic oxidation. The major potential cost savings are operational, specifically no supplemental fuel requirements or catalyst replacement (associated with plugging and/or fouling of catalytic oxidizers). Biofiltration does not produce secondary by-products, such as nitrogen oxides and particulates. Further, emission of carbon dioxide, a greenhouse gas, is substantially less for biofilters when compared with thermal and catalytic oxidation technologies.

The objective of this project was to demonstrate that the biotrickling filter technology is a viable alternative for control of ethanol emission from bakery ovens. The synthetic support media employed for this biotrickling filter pilot study utilized a mat of randomly arranged, 0.2 mm (0.008 inches) diameter, solid polypropylene fibers. This pilot-scale study was conducted in three stages: (1) Determine the kinetics and maximum rate of ethanol biodegradation using the fibrous support media; (2) Use the pilot-scale, trailer-mounted biotrickling filter system, with the fibrous support media to collect experimental data on the performance of biofiltration in controlling ethanol emissions from a bakery oven; and (3) Analyze the experimental data obtained during the pilot study to assess performance and evaluate preliminary cost of a full-scale biotrickling filter system.

## BACKGROUND

Biofiltration has been applied to remediate air contaminated with volatile organic compounds (VOCs) and other gases since the early sixties[1,2,3]. Detailed studies of literature findings reveal that soil biofilters are relatively large compared to filters using other media, since soil pores are smaller and compounds have low permeability in soil[1,2]. Soil biofilters also have limited depths due to problems associated with maintaining humidity in soil and minimizing pressure drop. Furthermore, soil sorption capacity is limited and residual contaminants are vented immediately to the atmosphere[4].

Peat/compost biofilters are suitable for treating large volumes of air containing easily biodegradable VOCs at low concentrations[5,6,7]. However, both soil and peat/compost biofilters are susceptible to channeling and maldistribution of the air stream. This leads to uneven biogrowth as well as drying of the bed. Both of these effects adversely impact biofilter performance. In soil and peat/compost biofilters, products of biomass decay cannot be washed out of the filters. Media replacement is required and the replacement interval has not been well established as a function of VOC loading. When VOCs contain organic chlorine, sulfur or nitrogen, the support media with solid buffers neutralize acidic degradation products.

Demonstrations of biofiltration technology ("BIOTON" system) for controlling ethanol emissions have shown effective treatment of more than 90% of ethanol from bakery off-gases containing up to 4g/m3 of ethanol. Typical elimination rates of 150 g/m$^3$-h were demonstrated[8], and removal efficiencies declined at loads exceeding 150 g/m$^3$-h. Major problems encountered with the use of biofiltration ("BIOTON" system) were as follows: (1) emission of acetic acid and acetaldehyde from incomplete biodegradation of ethanol at high off-gas concentrations; (2) acidification of support media, resulting in lowered degradation rates; and (3) release of condensate from off-gas coolers containing high concentration of ethanol and other organics.

## BENCH-SCALE KINETIC STUDY

A microbiofilter system, shown in Figure 1, was designed and assembled to obtain the biokinetics of ethanol biodegradation in biotrickling filters. A bench-scale biotrickling filter was also operated with the same fibrous mat support media used in the microbiofilter. The bench-scale biofilter system consisted of a short biofilter bed, 5.72 cm (2.25 inches) diameter with 10.2 cm (4 inches) height of support media. The nutrients flow downwards at a rate of 0.1 ml per hour. After the bench-scale biotrickling filter had been operated for some time and steady removal of ethanol had been achieved, a small section of the synthetic support media mat was removed from the bench-scale biotrickling filter and inserted into the microbiofilter bed to create a small support media height. A 5 liter (0.18 cubic feet) reservoir was used to circulate air through the microbiofilter. The reservoir was equipped with a septa, through which gas samples were withdrawn periodically, and analyzed using a gas chromatograph. Since the reservoir volume was substantially greater than the volume of air in the microbiofilter and connecting tubing, the concentration of contaminant in the air was obtained accurately by withdrawing gas samples from the reservoir. Air was circulated through the microbiofilter bed after passing through a coil immersed in a constant temperature bath. As the air at constant temperature flowed through the microbiofilter bed, ethanol that was adsorbed in the biofilms and support media gradually desorbed into the gas phase. The concentration of ethanol in the air, as measured by gas samples withdrawn from the reservoir, initially increased due to ethanol desorption, and then decreased due to biodegradation of ethanol by the active microorganisms in the biofilms on the support media. Eventually, the ethanol concentration decreased to below its detection limit.

In a series of microbiofilter tests, a fresh sample of the support media was withdrawn from a bench-scale biotrickling filter for each test. Ten separate experiments, with varying amounts of ethanol adsorbed in the biofilms and support media, were conducted using the microbiofilter with a constant temperature maintained at 25 $^{o}$C $\pm$ 0.2 $^{o}$C (77 $^{o}$F $\pm$ 0.36 $^{o}$F).

The following equations model the transport and biodegradation of ethanol in the microbiofilter:

$$\frac{dC}{dt} = -\frac{kA_B}{V_R}(C - HS)$$

$$\frac{dS}{dt} - \frac{rw_B}{w_L} + \frac{k}{w_L}(C - HS)$$

$$t = 0 : C = 0; S = S_o$$

C is the concentration of ethanol in the gas phase (mol/m$^3$), k is the mass transfer coefficient (cm/s), $A_B$ is the biofilm surface area per unit height of biofilter (cm$^2$), $V_R$ is volume of reservoir (cm$^3$), H is the dimensionless vapor/liquid equilibrium constant for ethanol, S is ethanol concentration in the liquid phase (mol/m$^3$), r is the rate of biodegradation of ethanol, $w_B$, and $w_L$ are the biofilm and liquid film thicknesses (cm), The initial (t=0) concentration of ethanol in the gas phase is zero and $S_o$ is the initial concentration of ethanol in the liquid film.

The rate of ethanol biodegradation (r) is expressed as a first order reaction:

$$r = k_R S$$

Where $k_R$ is the first-order reaction rate constant.

## PILOT-SCALE BIOTRICKLING FILTER

A trailer mounted pilot-scale biotrickling filter system was operated at the bakery from September 1997 to February 1998. The system was modified to handle increased gas flow rates and the original support media was replaced by the fibrous mat used for the bench-scale and microbiofilter studies. The final system configuration, shown in Figure 2, was connected to the bakery oven stack by a 76.2 m (250 feet) long, 15.24 cm (6 inch) diameter duct, insulated with fiber glass insulation enclosed in a metal jacket. A water cooled plate heat exchanger was installed before the biofilter to provide additional cooling of the stack gases. Water condensing from the stack gases was collected in a condensate tank installed at the entrance of the biofilter. This tank protected the blower from liquid water droplets. The biotrickling filter consisted of two identical sections connected in series. Each section was equipped with a separate nutrient tank and pumps in order to pump the liquid nutrient from the bottom of each section tank to the nutrient tank, and from the nutrient tank to the spray head installed above the support media. The support media mats, 5.08 cm (2.0 inches) thick, were composed of randomly arranged solid polypropylene 0.2 mm (0.008 inches) diameter fibers. The mats were cut in 61.3 cm (24.12 inches) diameter circles, and stacked on top of each other to achieve a total support media height of 152.4 cm (60 inches) in each section.

The liquid level in each nutrient tank was maintained by a level controller, which added additional nutrients from a nutrient supply tank. The pH in each nutrient tank was maintained at 7.2 by a pH controller. The pump system supplied 2N sodium hydroxide solution from a tank, when needed. Each nutrient tank was aerated to ensure complete biodegradation of any ethanol dissolved in the liquid nutrients.

Industry experience suggests that the exhaust gas from the baking oven has the following general characteristics : Stack Gas Flow: 85 m$^3$/min (3,000 scfm); Range: 28-170 m$^3$/min (1,000-5,000 scfm); Exit Stack Gas Temperature: 121$^o$C; Range: 65.6$^o$C - 148.9$^o$C (250$^o$F; Range: 150 $^o$F - 300 $^o$F); Stack Gas Relative Humidity: 15%; Range: 10% - 35%; Oxygen Concentration:

10%; Range: 6% - 14%; Average VOC Concentration: 2,000 ppmv; Range: 0-3,500 ppmv.

Further details on each important component (refer to the alphanumeric designation in Figures 2 of the final pilot-scale biotrickling filter configuration are given below:

**A.** A 0.1 $m^3$ (30-gallon) condensate tank was employed to remove any condensate (water, dissolved ethanol) which collected in the ductwork. This was necessary to avoid short-circuiting of ethanol in the first section of the biotrickling filter.

**B.** A 7 horsepower (HP) blower moved the oven exhaust gases through the biotrickling filter system. The oven exhaust gas flow rate through the biofilter was maintained initially at 1.8 $m^3$/min (65 scfm) from 9/18/97 to 1/24/98. Subsequently, the flow rate was increased and maintained at 2.88 $m^3$/min (104 scfm) through the completion of the pilot study.

**C.** Two biotrickling filter sections (each 61 cm (2 feet) in diameter and 183 cm (6 feet) in height with 152 cm (5 feet) of support media height), were connected in series. The sump at the bottom of each biotrickling filter section collected the nutrients and a level controller operated a liquid pump, which periodically pumped the nutrients from the sump into the nutrient recirculation tank. A pump, operated on a timer, pumped the nutrients from the nutrient recirculation tank to a spray nozzle located at the top of the biotrickling filter bed.

**D.** An impinger plate was used at the exit of each biofilter to prevent entrainment of liquid droplets with the gas flow.

**E.** Exhaust air, residual VOCs, and products of biological decomposition (mainly carbon dioxide and water) exited from the second biofilter into the atmosphere.

**F.** Both nutrients and buffering solution were added to each of the two 0.08 $m^3$ (25 gallon) recirculation tanks. The tank was also aerated to prevent anaerobic conditions from developing.

**G.** 2 HP recirculation pump, capable of recirculating nutrient solution at a rate of 1 $m^3$ per hour (4.4 gallons per minute).

**H.** A Varian gas chromatograph with flame ionization detector (FID), automatic sampler, and a digital data recorder were used to measure ethanol concentrations at various points in the system. The three sampling points have been noted as S1, S2 and S3, respectively, in the schematic (Figure 2).

## GAS SAMPLING AND ANALYSIS OF ETHANOL CONCENTRATION

Ethanol concentrations were monitored at three locations: (1) the gas inlet to the first biotrickling filter section (S1 in Figure 2); (2) the gas outlet from the first biotrickling filter section and at the entrance to the second section (S2 in Figure 2); and (3) exit gas from the second section of the biotrickling filter (S3 in Figure 2). The ethanol concentrations were measured using a Varian Gas Chromatograph (EPA Method 8015). The Gas Chromatograph was connected to the three sampling points, S1, S2, and S3, using a computer-controlled heated rotary valve. Heated lines and three computer-controlled on-line solenoid valves were used to direct the flow of gas samples from the appropriate locations in the biotrickling filter to the rotary valve. Sampling was achieved automatically using the computer software. The samples were withdrawn sequentially from the three sampling points, S1, S2, and S3, each for a period of five minutes. The analysis required 10 minutes and the system required a five-minute air purge between samples. Hence, gas samples were withdrawn automatically (sample size of 10 μL) and analyzed from the three sampling points, S1, S2 and S3, once during a 1 hour time period.

The gas chromatograph was equipped with a 2.44 m (8 ft) x 2.54 mm (0.1 in) internal diameter, stainless steel column packed with 1% SP-1000 on Carbopack-B 60/80 mesh. Detection was achieved by a flame ionization detector (FID). Peak areas were used to calibrate the gas chromatograph using six standard samples with ethanol concentrations of 100 ppmv, 500 ppmv, 1,000 ppmv, 2,000 ppmv, 3,000 ppmv and 6,000 ppmv. Gas standards were injected using a 10 μL syringe directly into the gas chromatograph, which was operated under the following conditions: helium gas flow rate at 40 mL/min, column temperature at 45 $^{o}$C (113 $^{o}$F) for 3 minutes and then programmed at 8 $^{o}$C/min (14.4 $^{o}$F/min) temperature ramp to 220 $^{o}$C (428 $^{o}$F) with a final temperature hold for 15 minutes.

# RESULTS AND DISCUSSION

## Bench-Scale Kinetic Test

Biokinetic parameters obtained from the microbiofilter experimental data and the mathematical model were as follows: First-order kinetic constant, $k_R = 0.004\ s^{-1}$ and mass transfer coefficient, k =0.0167 cm/s.

## Pilot-Scale Test

The performance of the biotrickling filter was quantified by the Percent Removal Efficiency, which was defined as follows:

Percent Removal Efficiency = [(Inlet Conc. - Outlet Conc.)/(Inlet Conc.)] x 100

It should be noted that when the inlet ethanol concentration was low, small variations in the inlet concentration caused the percent removal efficiency to vary considerably. The percent removal efficiency was determined using the inlet ethanol concentration entering the first section of the biotrickling filter and the ethanol concentration in the gas leaving the second section of the biotrickling filter. Hence the removal efficiency represented the overall performance of the biotrickling filter system including both biotrickling filters.

The daily average inlet concentration of ethanol and the daily average % removal efficiency versus time are shown in Figure 3. The system achieved at least 80% ethanol removal efficiency for 99.6% of the operating time. The system achieved greater than 90% efficiency for about 54% of the operating time with an overall average removal efficiency of 91%. A detailed breakdown of the biotrickling filter performance is shown in Table 1. High removal efficiencies were attained even though the inlet concentration of ethanol varied from 0 ppmv to 3,500 ppmv. Variations in inlet ethanol concentration were due to changes in the type of bakery product made, production capacity, and weekend shutdowns. Due to the long duct connecting the bakery oven to the biotrickling filter, changes in the ethanol concentration at the bakery stack were delayed in affecting the inlet of the biotrickling filter. Further, when there was liquid condensate in the condensate tank, fluctuations in ethanol concentration in the stack gas were modified by the ethanol concentration in the liquid condensate

The nutrient liquid levels in the two recirculation tanks were manually monitored during the pilot study. Fresh nutrients were added periodically to maintain the desired levels in the two tanks. However, in the large-scale design, the nutrient supply system will be automated. The capability for direct and continuous measurement of ammonium and phosphorus concentrations will be included, in order to maintain and control the desired nutrient concentration in the nutrient supply tank. The biotrickling filter performance can be significantly improved by controlling this variable.

The capacity of the biotrickling filter to biodegrade ethanol is defined as the Elimination Capacity, which is given as follows:

$$\text{Elimination Capacity} = F_{gas} \text{ x } (C^{in} - C^{out})/V_{media}$$

where $F_{gas}$ is the stack gas flow rate into the biofilter (scfm), $C^{in}$ and $C^{out}$ are the inlet and outlet ethanol concentrations (g/ft$^3$), respectively, and $V_{media}$ is the volume of support media (ft$^3$) in the biofilter. The elimination capacity represents the rate of ethanol biodegradation (removal) per unit volume of support media, and this capacity varies with ethanol loading. The ethanol loading is defined as the rate at which ethanol enters the biotrickling filter, and can be calculated as follows:

$$\text{Ethanol Loading} = F_{gas} \text{ x } C^{in}$$

As the ethanol loading entering the biotrickling filter increases, the elimination capacity initially increases, until a plateau value is achieved. This plateau represents the maximum elimination capacity of the system, i.e., the maximum rate at which the ethanol can be biodegraded for the specific volume of support media in the biotrickling filter. In the pilot-scale study, the elimination capacity did not attain a plateau value, indicating that the system was capable of treating higher ethanol loadings.

Liquid condensate ethanol concentration was expected to vary depending on the stack gas temperature and ethanol concentration in the stack gases. As different bakery products were produced, the amount of ethanol emitted in the stack gas varied. Based on the average liquid condensate volume that was collected and ethanol concentration in the condensate, the percent of ethanol removed by the liquid condensate varied between 0.5% and 22%.

The liquid condensate pH was acidic mainly due to fermentation of ethanol in the liquid condensate tank. Ethanol fermentation results in the formation of acetic acid. The high values of liquid condensate COD compared with lower $BOD_5$ values, indicates that high molecular weight oils were condensed or entrained from the bakery oven gas into the condensate tank. The oils and grease method used for analysis was not able to measure the oil concentration, which had a method detection limit of 5 mg/L.

The stack gas velocity was expected to decrease along the duct, as the gas temperature decreased due to heat losses from the duct to the ambient air. However, the stack gas velocity varied also due to changes in ambient pressure and variations in blower speed due to fluctuations in the line voltage. The stack gas temperature varied along the duct due to heat transfer losses and also due to changes in oven operating conditions.

One of the major concerns with the use of biofiltration is its robustness, i.e, ability to respond to changes in inlet ethanol concentration or stack gas flow rate (ethanol loading) and the viability of the microorganisms after no ethanol had been supplied to the biofilter for some time. These issues were addressed in this study by measuring the biofilter performance after severe changes had occurred in ethanol loading and after the gas blower had been shutdown for a few days.

The dynamics of the biotrickling filter showed that after the inlet ethanol concentration had changed abruptly from an inlet value of 200 ppmv (Loading of 50 g/m$^3$ of support media/h) to 3,000 ppmv (Loading of 750 g/m$^3$ of support media/h) over a period of 3 hours, the biotrickling filter maintained a removal efficiency exceeding 90%. This was consistent with the earlier observation that the pilot-scale biotrickling filter was capable of handling higher ethanol loadings. Further, the active microorganisms were able to quickly adapt to increased ethanol concentrations, since ethanol is an easily biodegradable chemical.

The start-up response of the biotrickling filter was obtained after the blower had been shut down for various time periods ( 3 - 9 days). During the shutdown period, the blower was not operating and the liquid nutrients were being recirculated through the two biofilter sections. The only ethanol load available to the biofilter microorganisms was the ethanol dissolved in the liquid nutrients and this ethanol load was expected to decrease over the shut down time period due to biodegradation of the ethanol. The experimental data for the percent ethanol removal efficiency of the biofilter after the various shut down periods showed that the microorganisms decay rate is very slow and the biofilter is able to achieve over 95% removal efficiency in a few hours.

## PRELIMINARY COST ANALYSIS

The objective of the cost calculations was to provide a ± 30% estimate of the biotrickling filter capital and operating costs. Improved cost estimates can only be obtained after a detailed biofilter design has been conducted for a specific bakery location. Economic data presented in this paper are intended to provide a reasonable first-cut estimate of biotrickling filter costs as applied for treating ethanol emissions from bakeries. The capital and operating costs have been calculated for only the biotrickling filter . The costs of connecting the biotrickling filter to a bakery oven have not been included, since such costs will be site specific.

The types of equipment involved in a typical biotrickling filter system include liquid pumps, for achieving nutrient flow, spray heads to distribute the nutrients evenly on the support media, and level, pH and temperature controllers for the nutrient recirculation tanks. Flow control is required to maintain a specified nutrient flow rate. A gas blower is required to move the gases through the biotrickling filter and the gas-phase pressure drop across the support media is measured. Temperature of the incoming gas is controlled in the desired temperature range of 24$^{o}$C (75$^{o}$F) to 38$^{o}$C (100$^{o}$F). The performance of the biotrickling filter system can be monitored continuously by a total hydrocarbon analyzer, which measures the change in the total hydrocarbon concentration between the inlet and outlet gases. The support media is a very critical component of the biotrickling filter and performance of the system (percent removal efficiency) can change dramatically by altering the design of the support media.

Capital and annualized costs of VOC abatement technologies are fundamental to their selection. Regulatory development of emission standards often include a cost impact analysis for the proposed treatment options.

The total capital investment typically includes the direct and indirect costs. Direct capital cost includes: Biofilter system, auxiliary equipment, instrumentation and controls, taxes, freight charges, and support media. Indirect capital cost includes: Engineering and Supervision, Construction and Field Expenses, Contracts Fee, Start-Up (Training and Operating and Maintenance Manuals), Performance Test and Contingencies (contingency represents expected expenditures, but due to the level of the estimate, the exact nature of these expenditures cannot be defined). Direct Installation costs includes: Site preparation, foundation and supports, erection and handling, electrical, piping, insulation, and painting. The annual operating costs consist of the following direct and indirect costs. Direct operating costs includes: consumable nutrients, and utility costs (electricity and water). Operating labor and maintenance includes operating labor, supervisory labor, maintenance labor, replacement parts and replacement labor. Indirect operating cost includes: Overhead, Property Tax, Insurance, Administrative charges, and Capital Recovery.

The cost parameters used in the cost analysis were derived from the personal computer software package, developed by the EPA Control Technology Center (CTC), a technology transfer and assistance program within the EPA Offices of Research and Development (ORD) and Air Quality Planning and Standards (OAQPS). The computer package, known as HAP-PRO (for Hazardous Air Pollutant Program), provides easy access to cost algorithms that EPA frequently uses in its development of capital and annualized costs of abatement technologies. The EPA cost factors used in the cost analysis have been presented in the final report[9]. HAP-PRO does not include a cost estimation methodology for biofiltration systems.

The biotrickling filter volumes required for the various stack gas flow rates were calculated using the biodegradation kinetics and mass transfer parameters determined from the microbiofilter tests. The capital cost of the biofilter system, using the monolith fibrous packing material as the support media, was calculated based on the dimensions of the biofilter vessel and construction costs.

The following assumptions were made in the cost analysis: (1) The average ethanol concentration is 2,000 ppmv (4.11 g/m$^3$ at 0$^o$C or 32$^o$F) in the inlet stack gas; (2) Maximum stack gas flow rates in the range of 28-140 m$^3$/min (1,000-5,000 scfm) are used in the cost calculations. The units of m$^3$/min or scfm refer to standard conditions of temperature and pressure, which is defined for engineering applications as 25$^o$C (77$^o$F) and 1.0 atmosphere; (3) Operating labor requirements are one-half hour per shift; (4) Maintenance labor requirements are one-half hour per shift; (5) Maintenance materials are 2% of the total capital cost; (6) Electricity requirements to operate a blower to transport the waste gases through the biofilter bed are 0.306 kilowatt-hour (kWh) per 1,000 m$^3$ of stack gas flow rate; Electrical power costs $0.059 /kWh; (7) The filter material has a five-year lifetime, and the rest of the system has a 10-year lifetime; (8) The equipment operates 8,000 hours per year; (9) Capital is borrowed at 7% interest rate; and (10) Site Preparation and building costs are assumed to be 10% of Purchased Equipment Cost.

Figure 4 shows the variations in Total Capital Cost and Total Annual Cost for various stack gas flow rates treated in the biofilter system. Both costs increase in a non-linear fashion with stack gas flow rate. Further, the Total Capital Cost per scfm ranges from $80/scfm to $180/cfm. This compares well with capital costs given in the literature. The ($/year/scfm) ratio decreases as the gas flow rate increases and ranges from $22/year/scfm to $61/year/scfm. The Total Annual Cost per ton of ethanol treated ($/ton) as a function of stack gas flow rate and ranges from $391/ton to $1083/ton.

## CONCLUSIONS

From the experimental data obtained using the pilot-scale biotrickling filter system, it can be concluded that this system is capable of biotreating ethanol emissions from bakeries, achieving average ethanol removal efficiencies of 91%. The pilot-scale biotrickling filter produced removal efficiencies of at least 80% for 99.6% of its operating time, and exceeded 90% for about 54% of its operating time. The gas-phase pressure drop across the bed remained less than 6.4 mm (0.25 inches) of water throughout the testing period. The pilot-scale system was subjected to inlet ethanol loadings in the range of 0-3,500 ppmv, while producing ethanol removal efficiencies in the range of 80% to 100%. Even with the large ethanol loading at the inlet (maximum inlet ethanol concentration of 3,500 ppmv), the biotrickling filter system was capable of handling higher loads.

The biotrickling filter system exhibited fast dynamics and responded very rapidly to changes in inlet ethanol loadings. This was mainly due to the short gas-phase residence time and inherent biodegradability of ethanol. The biotrickling filter also exhibited quick recoveries (duration of a few hours) even after a nine-day shutdown period. Only liquid nutrients were recycled through the support media during shutdown, and no ethanol was present in the stack gases.

Preliminary economic analysis of the biotrickling filter system, from an available control technology perspective, indicated that biofiltration is a cost-effective technology for treating ethanol emission from bakery ovens. Other advantages of the biotrickling filter technology includes no emission of nitrogen oxides, less release of carbon dioxide gas, near ambient temperature and pressure operation, and substantially less weight of equipment compared to catalytic oxidizers, which may result in lower installation cost. In summary, the technology provides an environmentally-friendly treatment system. Results presented in this report can be used for full-scale development of a biotrickling filter using the fibrous support media for treating ethanol emissions from bakery ovens.

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**Table 1. Summary of Removal Efficiency of Pilot-Scale Biotrickling Filter.**

| **Percent Ethanol Removal Efficiency** | **Percent of Total Operating Time*** |
|---|---|
| < 80% | 0.4% |
| > 80% | 99.6% |
| >90 % | 54.4% |
| **Average** | **91%** |

* Does not include downtime of the biotrickling filter

Figure 1. Schematic of the Microbiofilter System for Measuring Biokinetics.

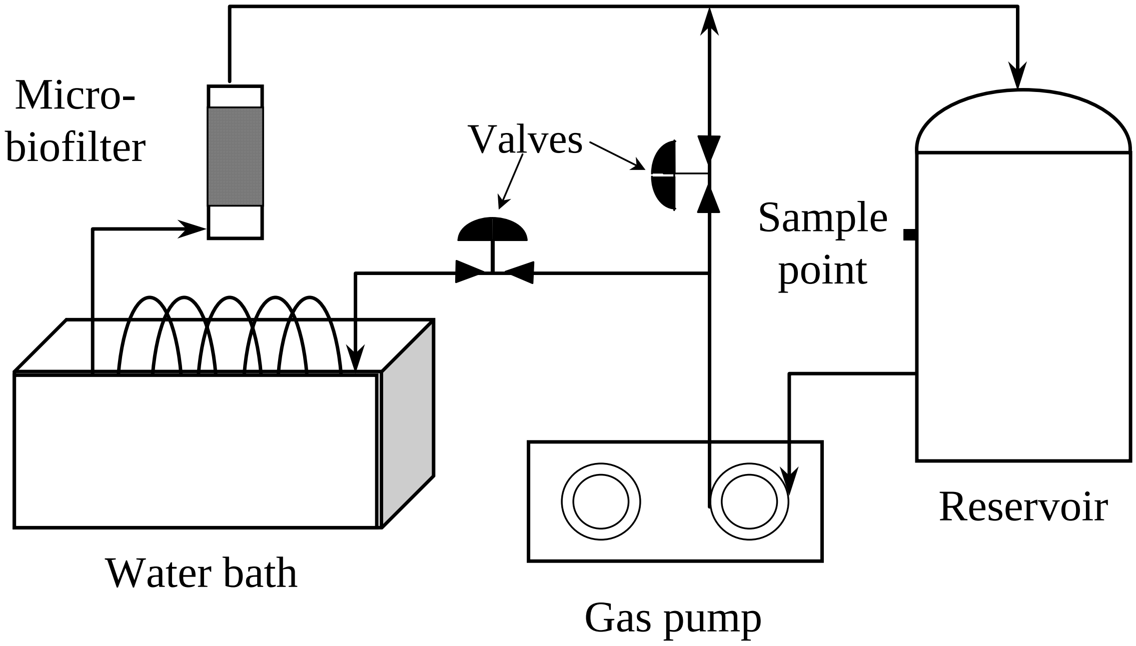

Figure 2. Schematic of the Pilot-Scale Biotrickling Filter System.

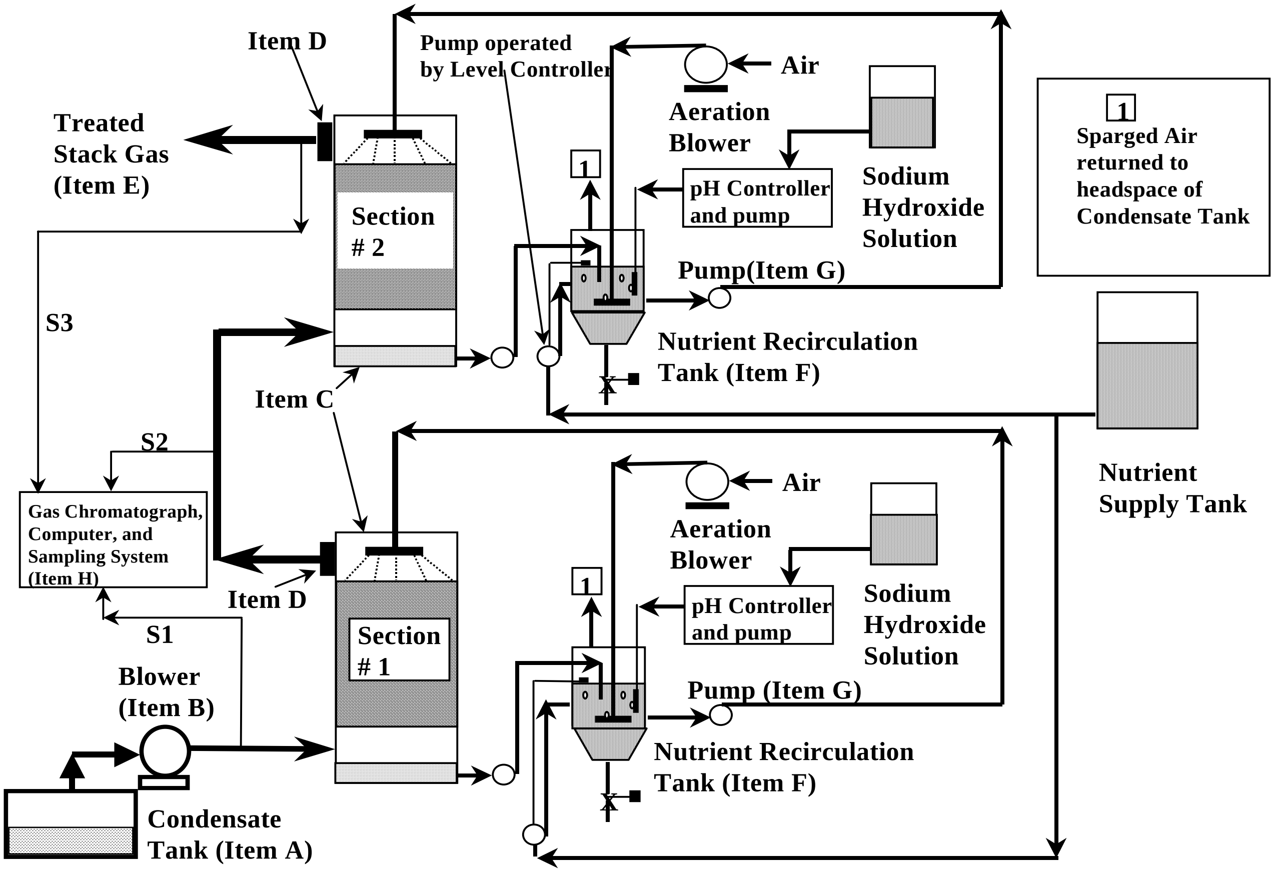
Item D
Pump operated by Level Controller
Air
Aeration Blower
Treated Stack Gas (Item E)
1
pH Controller and pump
Sodium Hydroxide Solution
1
Sparged Air returned to headspace of Condensate Tank
Section # 2
Pump(Item G)
S3
Nutrient Recirculation Tank (Item F)
Item C
S2
Nutrient Supply Tank
Air
Aeration Blower
Gas Chromatograph, Computer, and Sampling System (Item H)
1
pH Controller and pump
Sodium Hydroxide Solution
Item D
Section # 1
S1
Blower (Item B)
Pump (Item G)
Nutrient Recirculation Tank (Item F)
Condensate Tank (Item A)

**Figure 3. Plot of Inlet Ethanol Concentration and Daily Average % Removal Efficiency.**

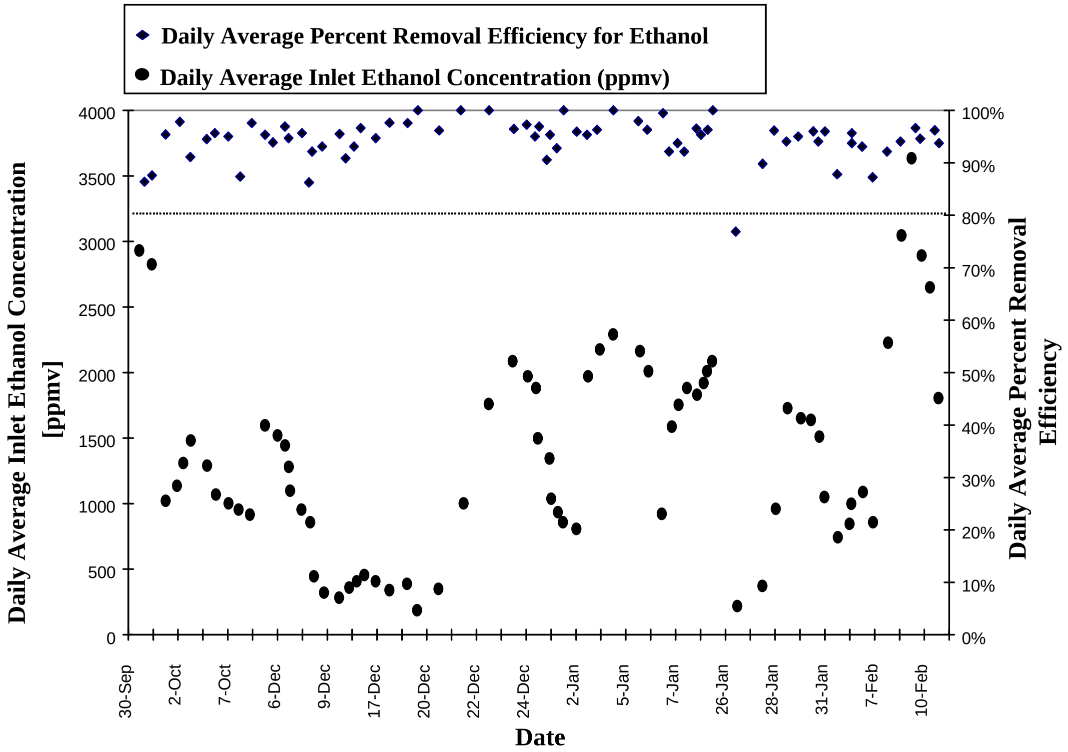

**Figure 4. Total Capital and Annual Cost of the Biotrickling Filter for Various Gas Flowrates.**