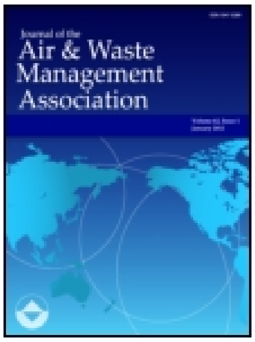


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# Evaluating Design Options for Biofilters

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## ABSTRACT

Biofilters are now increasingly offered and accepted in North America for air pollution control. However, prospective buyers often lack the technical and economic criteria to select a suitable biofilter design for their applications. This paper summarizes past experiences with full-scale biofilters and emerging design trends. Since control of the filter media's moisture content is essential for effective pollutant removal, the processes affecting moisture content are reviewed and ranges for evaporation rates and dry-out periods are estimated. High VOC concentrations and elimination rates cause high moisture removal and require additional irrigation; excessive irrigation or condensation of moisture from hot off-gases routinely cause over-watering and poor performance. Consequently, an application's moisture balance should be evaluated carefully prior to selecting a biofilter design. High VOC loadings and the need for low maintenance and verifiable pollutant removal favor fully enclosed vessels with automatic moisture control. Open biofilters with a low level of moisture control are suited for dilute off-gases, e.g., in non-critical odor control applications. Typical cost ranges for biofilter installations in North America are presented. Other design selection criteria, including choice of media, space demands, and monitoring requirements are reviewed. Three case examples of full-scale biofilters for VOC control illustrate our findings.

**IMPLICATIONS**

Biofilters treating VOC concentrations >0.5 g/m$^3$ and achieving elimination capacities >50 gm$^{-3}$h$^{-1}$ are prone to rapid bed dry-out. Biofilter applications in chemical and other manufacturing industries often fall in this category. Estimates of moisture gains and losses should be established before selecting a biofilter design and moisture control strategy. At even higher VOC elimination capacities, heat-up and evaporation make it increasingly difficult to maintain optimum moisture content, even with automatic moisture control. Thus, the difficulty of controlling moisture in a large, heterogeneous reactor constitutes a major nonbiological limitation to high volumetric VOC removal in biofilters.

## INTRODUCTION

Since the mid-1980s, biofiltration technology for treatment of off-gases containing odors or low concentrations of volatile organic compounds (VOC) and hazardous air pollutants (HAPs) has been established in Europe as an often cost-effective and environmentally benign alternative to combustion and sorption technologies. Following two decades of very limited use of open biofilters for odor control, they are now also more widely accepted, researched, and applied in North America. Domestic suppliers of biofilters have carried out pilot tests in a wide range of emitting industries. Since the late 1980s, approximately thirty, usually enclosed, large full-scale systems (more than 100 m$^3$ of filter material) for VOCs, HAPs, and advanced odor control have been built. Another estimated 50-100 simpler open biofilters were installed for odor control at wastewater treatment, composting, and food processing operations. More than 50 small enclosed biofilters (<20 m$^3$ of media) are used to treat off-gas from soil vapor extraction operations and small odorous gas streams.[1-5]

Prospective buyers are faced with a diverse selection of biofilter systems that vary with respect to reactor design, composition and projected life of filter media, level of process control, and consequently, performance and price. Most buyers still lack field experience with this emerging technology and the criteria for selecting the appropriate design. This article reviews the major technical, economic, and operational aspects to be considered in the selection. Because of its particular relevance to filter performance, the balance and control of media moisture is discussed in more detail. Three examples of full-scale biofilters illustrate our conclusions.

## OPERATING EXPERIENCES AND DESIGN TRENDS

Early biofilters built in Europe and the U.S. in the 1960s consisted of perforated pipes for off-gas distribution that were covered with mineral soils as filter media. These systems often achieved sufficient control of odors, but operational problems such as clogging of the air distribution systems, uneven off-gas distribution, and dry-out of the beds were common.[6,7]

In the 1970s, more advanced, open biofilters were developed in Europe. They have been widely used for odor control, and typically consist of one or more open beds at ground level enclosed by concrete walls, with an air distribution/media support system based on molded concrete plates or blocks of various designs. The filter material consists typically of a mixture of compost or peat with a structural support medium (heather, branches, wood chips, bark, or mineral granulates) that reduces the risk of compaction, and the resulting increase in pressure drop and potential for channeling of untreated off-gas.

With the emergence of these systems, biofilters became increasingly popular in Germany and the Netherlands because of their often lower capital cost and energy demand compared to competing technologies. Most installations were for odor control, but emerging regulatory requirements to remove VOCs or HAPs also stimulated interest in their treatment by biofilters. A growing number of installations also demonstrated operational and performance problems. Common problems included dry-out and over-watering of the filter material, rapid media compaction, and acidification by degradation products, causing insufficient pollutant removal, increased pressure drop and energy cost, and a shorter bed life.

In the 1980s, these problems and the increasing desire of regulatory agencies to ascertain biofilter performance (particularly for VOC and HAP control applications) stimulated the development of a new generation of biofilters. They are usually fully enclosed, use a more porous media that involves slowly degradable or inert support material, and often provide for automatic monitoring and control of the media's moisture content. After a decade of development and full-scale demonstration in a variety of applications, these systems are now accepted by regulatory agencies and industry in several European countries. They are generally considered a reliable, cost-effective, and environmentally benign control option for off-gases containing low concentrations (typically several hundred parts per million measured as carbon [ppmC], of gaseous, biodegradable air pollutants. Open systems of various designs also continue to be built for odor control. More recent operational experiences and design trends in North America are similar. More detailed discussions concerning various design concepts and the performance of full-scale biofilters can be found in the literature.[8-14]

Because of the higher capital cost of fully enclosed, more controlled biofilters, simple, open systems are routinely considered for the removal of VOCs and HAPs from process off-gases. Unfortunately, their use in unsuitable applications, particularly for the treatment of higher concentrations and loads of VOCs without proper moisture control, has repeatedly resulted in media dry-out and poor performance, and given biofiltration the reputation of a somewhat unreliable technology. Yet despite the obvious importance of moisture control, there has been little quantitative evaluation of the factors affecting media moisture and the suitability of various available control strategies.[15]

## THE MOISTURE BALANCE OF A BIOFILTER

The moisture content of a biologically active filter media is the operating parameter most relevant to performance and most sensitive to changes. Insufficient moisture prevents formation on the filter particles of a wet "biofilm" that supports microbial growth and respiration. Excessive moisture, on the other hand, reduces mass transfer of hydrophobic substances, clogs available pore space, and thereby reduces biofilm surface available for pollutant transfer; it also increases pressure drop, contributes to slime formation, and may cause irreversible, structural damage to the media through wash-out of small particles. The optimum moisture content for a given installation depends primarily on media composition and physical characteristics of the target VOC. Literature and the authors' experience with pilot and full-scale biofilters for VOC control suggest that for most applications, the moisture content at which optimum, sustained performance is achieved is between 40 and 60% by wet weight. For compact, poorly drained media and for the treatment of hydrophobic VOCs, a moisture content at the lower end of this range is desirable. Lighter, highly porous media treating hydrophilic VOCs may have an optimum moisture content above 60%. While the moisture content by weight is only an indirect indicator of the moisture actually available to microorganisms, it can be measured gravimetrically and constitutes a reasonable control parameter for a given off-gas and media.[11,16]

Due to the availability of moisture in the biofilter media, the presence of large surfaces for moisture transfer between media and off-gas, and their comparatively long residence time, off-gases usually become saturated in filter media and exit at relative humidities near 100%. The resulting exit moisture load may differ from that of the incoming off-gas due to moisture transfer by evaporation or condensation, which ultimately affect media moisture content and performance, unless it is controlled. A review of the thermodynamics of biofilters suggests that such moisture exchange is caused by five major processes. They are summarized in Table 1. Their fundamentals, quantitative impacts, and moisture control strategies are reviewed in the following sections.

### Incomplete Prehumidification

An off-gas entering the filter media at less than 100% relative humidity (RH) evaporates moisture from the filter's entrance zones until it reaches full saturation. In a psychrometric chart, the endpoint of this change in off-gas state is represented by its adiabatic saturation temperature. The corresponding rate of moisture removal from the bed varies with inlet temperature, initial RH, and (empty bed) residence time. If off-gases are vented to a biofilter without (or with inadequate) prehumidification, this rate becomes substantial. For example, an off-gas with wet- and dry-bulb temperatures of 20 and 13.8 °C, respectively (RH = 50%), and a 30 second residence time removes moisture primarily from the biofilter inlet at a rate of 350 grams per cubic meter of media per hour ($gm^{-3}h^{-1}$). This reduces the moisture content in the initial 20% of the media from 60% to its lower acceptable level of 40% in less than six days.

Industrial off-gases are commonly not moisture-saturated at their point of collection. To avoid an otherwise rapid dry-out at the filter inlet, most open and enclosed biofilter systems now provide off-gas prehumidification for such off-gases. A relative humidity of 90-95%, which is routinely achieved during prehumidification, reduces the rate of dry-out to a level where it no longer causes rapid changes in bed moisture and can be controlled by overbed spraying. A somewhat less than complete prehumidification is also desirable for control purposes, since it provides a limited capability for drying out media that has intentionally or inadvertently received excessive moisture. In installations where the off-gas fan is located between the humidifier and filter bed, off-gas compression by the blower effects an increase in temperature, a corresponding decrease in relative humidity, and additional moisture loss from the biofilter inlet. In case of a high media pressure drop this loss may become substantial. Table 1 compares typical moisture removal rates for unsaturated and prehumidified off-gas.

## Exothermic Biooxidation

As in other combustion processes, the enzymatic biooxidation of organic off-gas constituents in a biofilter is an exothermic process. The resulting increase in off-gas enthalpy causes an increase in off-gas temperature and consequently, evaporation of moisture to maintain complete off-gas saturation. Evaporation rates increase as concentration and heating value of VOC species increase in the raw gas. In a psychrometric chart, this change in state corresponds to a shift along the RH = 100% line. The enthalpy of the endpoint equals that of the starting point plus the total enthalpy of combustion. The latter equals the sum, over all VOC species, of raw gas concentration (in kg of VOC per kg of wet air) times their respective upper heating value (in MJ/kg). Net moisture removal per off-gas volume, or weight of dry air, is calculated as the difference in off-gas moisture between biofilter inlet and outlet, minus moisture formed from oxidation of VOCs. The latter typically provides 10-20% of the total moisture demand

**Table 1.** Impact of processes occurring during biofiltration on off-gas temperature (ΔT), enthalpy (Δh), and moisture content (Δmc).

| *Process* | *ΔT(°C)* | $\Delta h_{total}$[a] *(kJ/m³)*[c] | $\Delta h_{evap}$[b] *(kJ/m³)*[c] | $\Delta_{mc}$ *(g/m³)*[d] | *Response Time (days)*[e] |
|---|---|---|---|---|---|
| *Humidification/Adiabatic Cooling* | | | | | |
| $T_{dry}$ = 20 °C:rH = 50% -> 95%[f] | -5.8 | 0 | 6.7 | 2.7 | 3.5-7 |
| rH = 95% -> 100%[g] | -0.6 | 0 | 0.7 | 0.3 | 35-70 |
| $T_{dry}$ = 40 °C:rH = 50% -> 95%[f] | -9.8 | 0 | 10.3 | 4.3 | 2.5-5 |
| rH = 95% -> 100%[g] | -0.8 | 0 | 1.0 | 0.4 | 20-40 |
| *Biooxidation (@ 20 °C)* | | | | | |
| $C_{in}$ = 0.1 g VOC/m³[h] | 0.7 | 2.8 | 1.6 | 0.7 | 15-30 |
| $C_{in}$ = 0.5 g VOC/m³[h] | 3.2 | 14 | 9.3 | 3.8 | 3-6 |
| $C_{in}$ = 1.0 g VOC/m³[h] | 6 | 28 | 17 | 7 | 1.5-3 |
| *Condensation Losses/Heat Gains*[i] | | | | | |
| Change in $T_{wet}$ from 20 <-> 19 °C | +/- 1 | 4.0 | 2.6 | +/- 1.1 | 10-20 |
| Change in $T_{wet}$ from 40 <-> 39 °C | +/- 1 | 8.9 | 6.8 | +/- 2.9 | 3.5-7 |
| *Media Degradation* | 0.1-0.2 | 0.5-1 | 0.35-0.7 | 0.14-0.28 | 75 |
| *Blower (Δp: 1-2 kPa, 4-8" wg)* | 0.25-0.5[k] | 1-2 | 0.75-1.5 | 0.3-0.6 | 17-70 |

[a] Change in total off-gas enthalpy effected by a process.
[b] Amount of evaporative enthalpy involved in a process.
[c] m³ refers to wet off-gas volumes at actual temperatures.
[d] Difference in absolute off-gas moisture before and after process in g/m³ of moist air.
[e] Period in which respective process increases or reduces average media moisture content by 30 liters/m³, thus requiring operator response. Boundaries correspond to residence times of 30 (low figure) to 60 seconds.
[f] Adiabatic cooling of off-gas (initial $T_{dry}$ = 20 °C), concurrent increase in RH from 50 to 95%.
[g] Complete saturation of a prehumidified off-gas.
[h] Off-gas contains oxygenated solvent, UHV: 27.5 MJ/kg (11,800 BTU/lb).
[i] Moisture gains or condensation losses realized by off-gas undergoing the respective temperature change in bed as a result of heat exchange between vessel and environment.
[k] ΔT after complete re-saturation of off-gas in bed entrance.

resulting from exothermic biooxidation. Upper heating values for VOCs commonly treated in biofilters range from 22.6 MJ/kg (9,700 BTU/lb) for methanol to 50 MJ/kg (21,500 BTU/lb) for alkanes and alkenes. Table 1 indicates that moisture removal due to biooxidation becomes significant as VOC inlet concentration and volumetric elimination capacity approach 0.5 $g/m^3$ and 50 grams of VOC per cubic meter of media ($gm^{-3}h^{-1}$), respectively.

## Heat Exchange with the Environment and Media Degradation

The above discussion assumes implicitly that filter media do not exchange thermal energy with the environment, that heat produced by the gradual biodegradation of media is negligible, and that off-gas and media are always in thermal equilibrium. While heat exchange with the environment can theoretically be eliminated, economic constraints limit the extent of thermal insulation, particularly for larger systems. Thus, in practice, even fully enclosed, well insulated filter vessels gain or lose some heat. This causes temperature differences between off-gas and media and results in net energy and moisture transfer. For enclosed, well insulated biofilters, short-term fluctuations in off-gas temperature and humidity are more important and result in local moisture exchange.

Off-gases entering at wet-bulb temperatures below the bed temperature will heat up and remove moisture from the media. This may be the case for biofiltration of air-conditioned ventilation off-gases in hot climates. On the other hand, warm and saturated off-gases (for example from baking and drying operations) with wet-bulb temperatures above the bed temperature add mist or condensate to the bed, particularly in colder climates. This effect is particularly pronounced during start-up. Since condensation may result in over-watering of the media, it may have to be controlled by forced cooling or by adding dry dilution air.

Some biofilter installations rely on condensation to provide additional moisture to the biofilter inlet by raising the wet bulb temperature to above the bed temperature during prehumidification. However, since the amount of condensate thus produced varies with the rate of heat loss to the environment, i.e., with ambient temperature, it is difficult to control. Undesirable condensation losses are highest, during the cold season after weekend shutdowns. Heat exchange with the environment and its impact on off-gas moisture are strongest in small, open, and poorly insulated filter vessels and at long residence times.

Finally, the gradual exothermic biodegradation of media may add heat to bed and off-gas, thus causing additional evaporation loss. Its rate varies primarily with media composition and age, and with bed temperature. Higher temperatures increase the rate of mineralization, particularly of woody materials that generally degrade only slowly in the mesophilic temperature range. Media degradation has been identified as one of the factors affecting the carbon balance in a biofilter.[17] Table 1 suggests that it is of comparatively low importance to bed moisture balance. It also indicates that changes in the off-gas saturation temperature by 1 °C in poorly insulated beds cause considerable condensation gains or evaporation

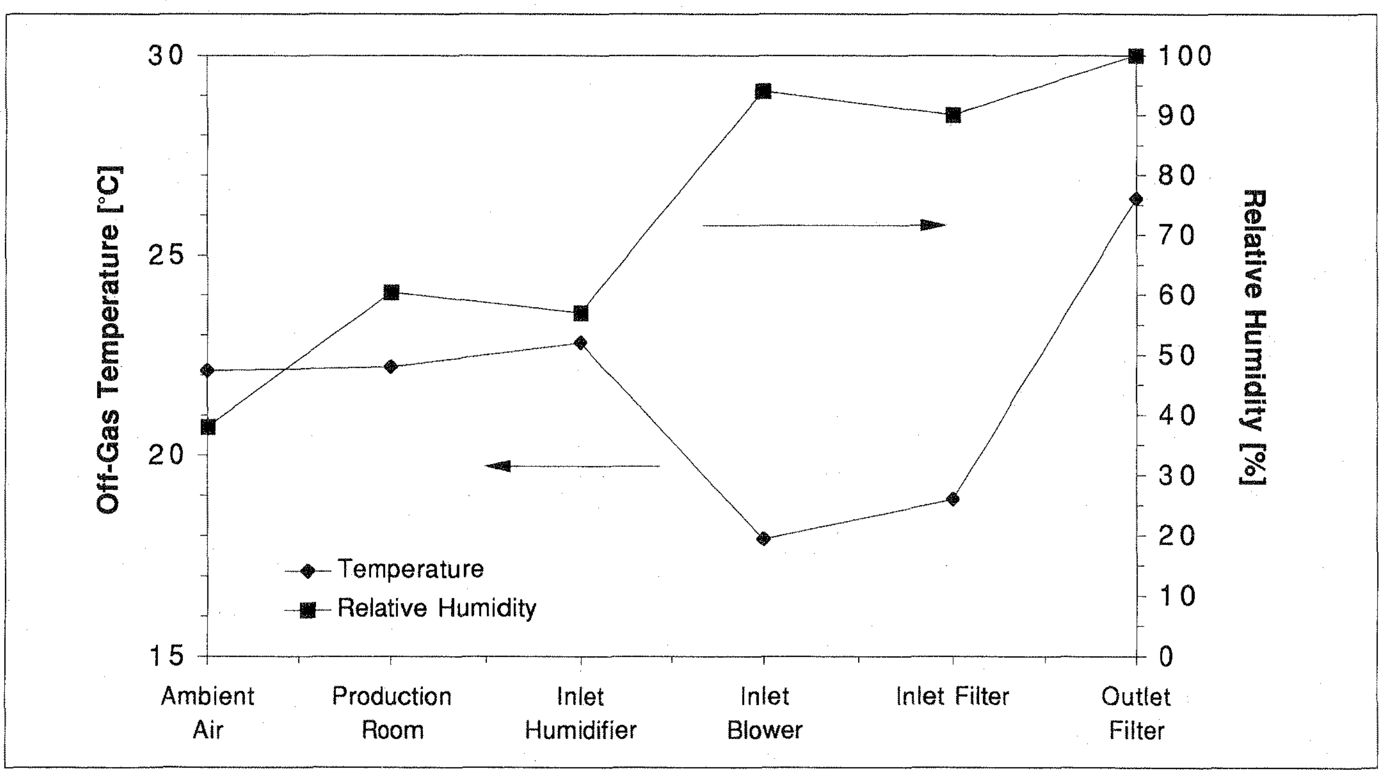


**Figure 1.** Temperature and humidity profiles for off-gas during biofiltration.

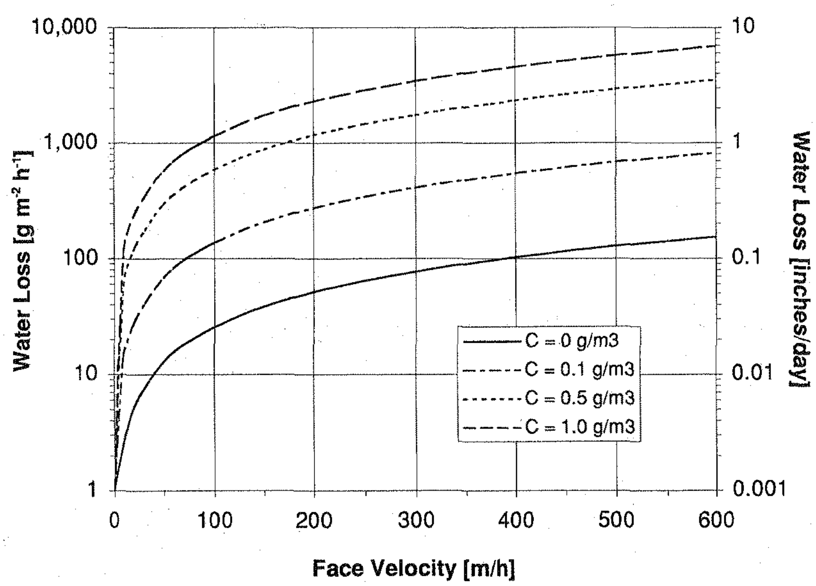


**Figure 2.** Estimated moisture losses from biofilters as a function of face velocity and inlet VOC concentration.

losses in the media. However, since the impacts of these processes vary strongly with vessel design (insulation), off-gas temperature, relative humidity, ambient temperature, and media status, they are not considered in the following calculations.

Table 1 indicates that non-prehumidified off-gases and those containing VOC concentrations approaching 0.5 g/m$^3$ may cause rapid dry-out of filter media. As an example, Figure 1 illustrates the impacts of adiabatic cooling during prehumidification, heat-up by off-gas fan, and biooxidation in the media on energy and moisture balance of an existing full-scale biofilter.[10] It shows profiles of dry-bulb temperature and relative humidity taken at various locations in the path of an off-gas with an average concentration of 1.3 g/m$^3$ of VOCs, primarily ethanol. Figure 2 allows initial estimation of moisture losses due to incomplete prehumidification and exothermic biooxidation. They are expressed as the weight of the corresponding moisture column (10,000 gm$^{-2}$h$^{-1}$ equals a loss rate of 1 centimeter per hour or 10 inches per day). Assumptions include a wet-bulb temperature of 20 °C, raw gas prehumidification to 95% RH, an upper heating value of 27.5 MJ/kg (11,800 BTU/lb) for VOCs, and complete VOC removal in the biofilter. In addition, 20-70% of the applied irrigation water may be typically lost as drainage. Shorter and more frequent spraying generates less drainage losses than long spray cycles. These losses must be added to evaporation losses when estimating actual irrigation demand. Two examples illustrate the range of typical evaporation losses and the use of Figure 1 in estimating them. Discrepancies between text and graph are due to differences in biofilter inlet temperature.

*Case A.* An off-gas entering the biofilter at 35 °C and 95% RH and containing 1 g/m$^3$ of an easily degradable VOC may require a 45 second residence time for complete VOC removal, corresponding to a face velocity of 80 m/h at a 1-m bed height. The high temperature and organic load result in a net evaporation loss of 650 gm$^{-2}$h$^{-1}$, corresponding to an irrigation demand of 1.6 cm/day, assuming no drainage loss.

*Case B.* A cold off-gas (15 °C) with low concentrations of odorous compounds (0.1 g/m$^3$) and a residence time of only 15 seconds, corresponding to a face velocity of 240 m/h, may cause bed moisture to evaporate at a rate of 0.5 cm/day.

It is suggested that the reader estimate moisture removal rates for other off-gas conditions with a psychrometric chart. This will provide a better understanding of the mechanisms affecting moisture balance and a sense of their quantitative effects.

## MOISTURE CONTROL OPTIONS

Our estimate suggests that the rate of moisture removal from filter media varies considerably between applications. Even for a given source, moisture demand will fluctuate with off-gas temperature, VOC loading, and ambient conditions. Considering the significance of moisture content for microbial activity and filter performance, effective bed irrigation must involve some form of monitoring and control of bed moisture. Figure 2 suggests that the required monitoring frequency and accuracy of the control approach increase with increasing VOC load. The four most commonly used monitoring and control strategies for bed moisture are listed in Table 2. Their suitability for a given application depends on the extent of moisture loss and the acceptable level of monitoring and maintenance activity. These strategies are best distinguished by whether monitoring of media moisture is performed manually or automatically.

### Manual Monitoring

Manual sampling involves perforation of the media by an auger, or similar sampler, and the recovery of several representative samples from various locations in the bed. It is followed by visual or gravimetric evaluation of moisture content and the determination of irrigation needs, if any. Irrigation is administered by rainfall, manually (spray hose), by an installed overbed spray system with manual control valve, or by a timer-controlled, semi-automatic spray system. Systems relying on manual moisture monitoring are suitable where moisture removal by the off-gas is slow and allows for monitoring at reasonably long intervals, i.e., weeks to months, without risking loss of performance. More than 90% of all large biofilter systems built to date rely on one of these three control approaches involving manual moisture monitoring.

Manual monitoring of filter of material for moisture is time-consuming. The number of samples required to establish a representative moisture profile depends on the spatial variability of bed irrigation patterns, with five samples per 200 $m^3$ of filter material as a typical value. Considering that the medium often dries out preferentially at the filter inlet, samples should be obtained from different heights in the bed. Sampling usually involves walking on the media and its perforation by the sampling device. It is to be conducted carefully to minimize compaction and the formation of channels. The recently more common bed heights of 1.5 m make sampling from the bottom zone increasingly difficult. Thus, where moisture removal rates are high and variable, and where monitoring efforts are to be minimized without risking impaired performance, automatic moisture monitoring and control become desirable.

### Automatic Monitoring and Control

Biofilter suppliers use two approaches to automatic moisture monitoring. Some systems obtain spot measurements from one or more locations in the bed(s), e.g., by measuring electric conductivity or capacity. The accuracy of this approach is limited by the small area represented by a spot measurement, the typically large filter volume and nonhomogeneity of filter media, and by the low sensitivity of these methods in the target moisture range. More commonly used is the measurement of bulk moisture content by weighing all or sections of the filter material continuously with load cells. This approach is offered by several biofilter vendors in the U.S. and provides for the registration and control of bulk weight gains or losses attributed to irrigation or evaporation. For accuracy, this control method requires even bed coverage by the irrigation system, and that variations in the total weight of the filter material reflect only changes in its moisture content. This limits its applicability to fully enclosed systems, since the growth of weeds, snowfall, and wind affect weight measurements in open systems. Periodic recalibration may be required to adjust for media decomposition and for losses of filter material into the drainage. Data obtained from both spot and bulk monitoring methods are usually processed in a programmable logic controller (PLC) that determines irrigation needs and controls the duration and frequency of spraying. Uneven spraying patterns are known to contribute to considerable spatial variations in bed moisture content. They impair performance and affect how representative moisture measurements are, particularly spot measurements. Thus, even coverage of the beds by a carefully designed irrigation system is paramount for producing meaningful moisture content data.

**Table 2.** Moisture control options for biofilters.

| *Method* | *Description* |
|---|---|
| Automatic | The moisture content of the filter material is measured automatically by bulk or spot methods. The monitoring results control an automatic media spraying system. Excessively high or low moisture content may trigger an alarm or cause shutdown. |
| Semi-Automatic | Spraying frequency and duration are controlled by a timer which is adjusted periodically based on media sampling or automatic moisture monitoring. |
| Manual/Periodic | A bed spraying system with a manual valve is installed. Spraying is conducted periodically based on periodic media sampling. |
| Manual/Ad hoc | No spraying system is installed. The moisture content of the media is monitored several times per year and, if necessary, adjusted manually with a spray hose. |

### Other Moisture Control Features

In addition to these active measures for moisture monitoring and control, several passive control features are commonly employed. Enclosed biofilters are now increasingly built for downflow operation. This allows preferential irrigation of the bed inlet (i.e., those zones frequently subject to moisture removal and dry-out). For off-gases containing acidifying compounds (reduced sulfur and nitrogen compounds or chlorinated VOCs), upflow may be preferable since it allows for more efficient flushing of acidic degradation products.[20] The use of more porous, well drained filter media reduces the risk of over-watering and formation of moisture saturated zones and channels, and constitutes another passive moisture control measure. Such media, for example those composed of coarse, chipped root wood, are now frequently used in European applications. Their inherently low sensitivity to overwatering allows application of conservatively high watering rates, thus minimizing the risk of dry-out. Their main trade-off is lower pollutant removal per volume of media.[21]

As an alternative to measuring bed moisture directly, the calculation of moisture demand based on continuous monitoring of temperature and relative humidity in biofilter inlet and outlet has been considered. The limited accuracy of relative humidity measurements in off-gases close to saturation and the partial, unavoidable discharge of irrigation water to drainage following bed irrigation limit the reliability of this approach.

### Selecting Moisture Control Options

The previous discussion suggests that moisture evaporation rates and corresponding dry-out periods provide useful screening criteria for the four moisture control options in Table 2. The objective of any moisture control strategy is to avoid fluctuations in media moisture that are sufficiently large to impair performance or damage the media. It has been found that deviations from the optimum media moisture content by as much as 30 liters of water per $m^3$ of filter material do not cause a significant loss in performance. For a given difference in off-gas moisture content across the filter media ( mc, measured in grams per cubic meter of off-gas) caused by the processes listed in Table 1, and a given residence time $\tau$, measured in minutes, the total evaporative loss $Q_e$ ($gm^{-3}h^{-1}$) from the media can be calculated as:

$$Q_e = mc * 60 / \tau \quad (1)$$

Assuming $Q_e$ represents an average evaporation rate, beds should be watered at a minimum frequency, or within a typical response period n, measured in days, of:

$$n = 1{,}250 / Q_e \quad (2)$$

to avoid a reduction in moisture content by more than 30 $l/m^3$. This simple model assumes even moisture loss from the media. In practice, media close to biofilter inlets tend to dry out more rapidly, and the required response times may be shorter.

Table 3 suggests ranges of evaporative losses for which each of the four control options provides a sufficiently fast response. Off-gases with high VOC concentrations and face velocities—i.e., those with high organic loadings, insufficient prehumidification, and/or high temperatures—require frequent monitoring and spraying and are preferably controlled automatically. Dilute off-gases with low face velocities absorb less moisture, and occasional manual watering or even moisture control by precipitation may suffice. Whether an open biofilter can be operated without any overbed spraying depends on local precipitation rates and the extent of condensation losses or additional heat gains. For a quantitative evaluation, dry season precipitation and the fact that up to 70% of the rainfall may be lost as drainage must be considered.

The four control options are technically downward compatible; i.e., fully automatic systems are also appropriate for off-gases which cause lower evaporation rates. If properly designed and installed, they require less maintenance and improve the operational reliability of a biofilter. They also result in higher capital cost for the fully enclosed vessel, monitoring and control systems, and possibly for the integration into an existing facility control system. These considerations on moisture balance in filter media suggest that the need for its accurate maintenance may pose nonbiological limitations on the suitability of biofiltration for treatment of high VOC concentrations and volumetric loadings. At VOC elimination capacities of more than 100 $gm^{-3}h^{-1}$, the high corresponding evaporation rates and short response times of less than one day make maintenance of an even moisture content increasingly difficult, even with an automatic moisture control system. The relative compactness of filter media and reliance of moisture transport on gravity contribute to this difficulty.

## OTHER DESIGN AND CONTROL OPTIONS

Other available biofilter design options relate to reactor design, media selection, and other process monitoring and control features.

**Table 3.** Recommended moisture control methods for biofilters as a function of evaporative loss.

| *Evaporation Loss [$gm^{-3}h^{-1}$]* | *Response Time [days]* | *Recommended Method of Moisture Control* |
|---|---|---|
| <50 | >25 | Manual / Ad hoc method |
| 50-180 | 7-25 | Manual irrigation / periodic media monitoring for moisture content |
| 180-400 | 3-7 | Semi-automatic (timer controlled) method.Requires routine manual media monitoring and timer adjustment. |
| >400 | <3 | Semi-automatic method and the use of coarse, well drained media or fully automatic moisture control |

### Biofilter Reactor

The biofilter reactor consists of an air distribution system contained in a partially open or fully enclosed vessel or reactor, with one or more layers (beds) of the biologically active filter material, and possibly an overbed humidification system. Open and fully enclosed vessels are best distinguished by whether they can be operated under both pressure and vacuum. The walls of open biofilters are most commonly made from concrete, either precast or poured on site. Walls of coated or stainless steel or wood have also been used. In the U.S., open systems for odor control are also frequently installed in excavations without separate walls. Enclosed vessels are usually built as steel frames with insulated sheet metal walls, or as pre-cast or poured on-site concrete structures. Smaller systems (<60 $m^3$) often involve standardized steel transportation containers, and tanks made from polyethylene or fiberglass-reinforced epoxy resin. Designs of air distribution systems cover the range from slotted PVC pipes with a rock cover to precast concrete plates or blocks accessible to heavy equipment, and with metal grids and support mats made from synthetics.

On a per-volume basis, open biofilters are generally less expensive to build than fully enclosed vessels. They also provide for easier access and loading and unloading of the filter material. Since multi-story design diminishes some of these advantages, almost all open biofilters have been built on a single level. Fully enclosed vessels are predominantly used in recent VOC and HAP control applications in Europe and the U.S. They provide for better insulation and control of media temperature and eliminate the impact of rainfall and plant growth on the media. They also allow for accurate, single point monitoring of the treated off-gas and for better dispersion of residual pollutants. Finally, they are preferred where space constraints dictate the use of a reactor with two or more stacked beds.

## Process Monitoring and Control

In addition to bed moisture, the rate of media compaction, temperature, nutrient availability, and pH must be controlled actively or passively in order to maintain a biofilter's mechanical and biological performance. The following approaches are now commonly applied.

*Pressure drop and selection of filter material.* Rapidly compacting media may require mechanical turning or even replacement after less than one year. To limit pressure drop passively and increase media life, many vendors now employ designed filter materials that involve composted organic matter supported by a larger volume of inert or slowly degradable constituents, such as ceramic, plastic, granular activated carbon, or wood chips. Such media achieve lower pressure drop and longer bed life but are also more expensive than mixtures of unprocessed compost.

*Nutrient supply and pH.* Most microorganisms capable of degrading VOCs show optimum growth at pH values in the biofilm of between 6.5 and 7.5. To buffer acidic by-products in the media and maintain a neutral pH, most suppliers of biofilters add alkaline buffers to the filter material, usually calcium carbonate lime. The use of a biotrickling filter which allows for active pH control should be considered where high loads of acidifying compounds would otherwise limit the useful bed life.[16] Compost-based media usually supply sufficient quantities of inorganic nutrients for film growth, primarily nitrogen, potassium, and phosphorus. Since some loss of biomass with drainage occurs, particularly in nutrient-poor filter materials, i.e., those with a high fraction of inert or wood based ingredients, these may require the addition of nutrients, preferably poorly water-soluble synthetic fertilizers. Since it may result in excessive biofilm growth, nutrient addition to media or spraying with nutrient solution must be conducted carefully.

*Relative humidity and temperature.* Off-gas prehumidification by spray nozzle humidifiers, packed bed towers, and steam injection is provided in most recent full-scale biofilters. Selection criteria include their respective space requirements, energy consumption, and sensitivity to particulates and high pollutant loads. For the mesophilic microorganisms that are almost exclusively used, bed temperatures between 10 and 42 °C (50-108 °F) are acceptable, with an optimum range for biological activity of 30-35 °C (85-95 °F). Bed temperatures outside of the 10-42 °C range generally result in reduced pollutant removal and may require off-gas preheating or precooling, which results in additional capital and operating costs. Heating by steam injection or in-duct burners has been practiced in some installations to improve volumetric performance. Adiabatic cooling by prehumidification allows for cooling of hotter off-gases with wet-bulb temperatures below 40 °C. Cooling with ambient dilution air is feasible but generally increases biofilter size and capital cost. Active cooling by heat exchangers and refrigeration is rarely practiced. In some installations, particularly in the tobacco industry, bed temperatures between 45 and 50 °C have been maintained without causing a significant loss in performance. Further research is required into the microbiological mechanisms and the potential applicability for other off-gases with elevated temperatures. Finally, the use of thermophilic microorganisms for treating off-gases with wet bulb temperatures in excess of 50 °C is currently being investigated.[21, 22]

*Process monitoring.* Biofilter systems may include instrumentation for monitoring off-gas temperature, relative humidity, pressure drop, off-gas flow, moisture content of the filter material, and pH of the drainage. Depending on the number of parameters monitored and the sophistication of data display and logging, the corresponding costs vary considerably. For example, the inlet off-gas temperature may be displayed by an analog thermometer, monitored and recorded continuously, or connected to an alarm or shut-down switch. If required by regulation, biofilter inlet and outlet may also be monitored continuously for total organic carbon, using a flame ionization detector (FID). This allows for a more representative evaluation of VOC removal, particularly from streams with fluctuating loads. Screen displays of system status, trends, and alarms are also used in more recent installations. Designs in which neither the temperature and relative humidity of the raw gas nor the pressure drop across the filter beds are measured are becoming increasingly rare in Europe, since they do not provide even minimal diagnostic information on a system's status and potential performance problems.

## COST AND OPERATIONAL CONSIDERATIONS

### Capital Cost

For a given application, total installed capital cost (TIC) may vary considerably among designs. Their costs can be compared on a per-volume or a performance basis. Figure 3 shows the typical range of TIC per volume of media installed for systems larger than 100 $m^3$ that have been proposed and/or installed in the U.S. since 1990. On a per-volume basis, open systems rank at the low end, with enclosed and controlled multi-level biofilters at the high end. Enclosed concrete vessels with a 1.5-m bed height fall in between.

A cost comparison between systems on a per-volume basis is only meaningful if they achieve the same volumetric VOC removal, thus requiring the same residence time and media volume. In practice, many open systems involve less efficient off-gas distribution systems, non-optimized filter materials, and little moisture and temperature control and routinely require longer residence times than fully enclosed, controlled systems, which improves the competitiveness of the latter. The impact of residence time on TCI per installed flow (in $/cfm) is shown in Figure 4. The required cost per media figures were assumed to be the average of the range shown in Table 3. Figure 4 suggests that biofilters become increasingly competitive with the capital costs of incineration systems at residence times of less than one minute. For large open biofilters, TICs of less than $3/cfm have been reported.[4] An accurate cost comparison between competing technologies and designs for a specific application usually requires pilot testing or experience-based vendor information. With the still small number of fully enclosed systems installed in North America, the biofilter market is not yet mature and prices reflect not only differences in technological sophistication, but also the current competitive marketplace and the suppliers' generally low level of full-scale experience.

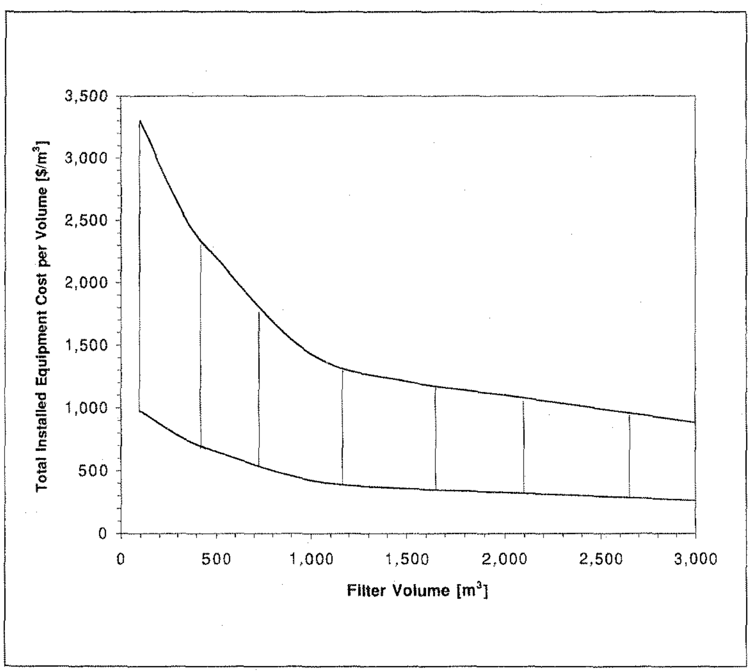


**Figure 3.** Estimated range of capital cost for biofilters >100 $m^3$.

### Operating Cost

Operating cost items for a biofilter include charges for electricity, replacement of spent media, consumption of water, monitoring, and maintenance and repairs. A brief assessment of how filter design may affect these items follows.

*Energy consumption.* This is primarily due to off-gas transport through ducts, humidifier, and media beds. Pumps and controls contribute smaller amounts. Bed pressure drop depends on structure and moisture content of filter material, off-gas face velocity, and bed depth. It is routinely higher for open filters, where non-optimized media with a higher specific pressure loss are more common because of their lower initial costs. For a given residence time and media, single-bed biofilters show the lowest pressure drop. Systems with two beds in series have twice the face velocity and effective bed height and at least four times the pressure drop of a single layer system. This mandates the use of designed filter materials with a low specific pressure drop and media life. Total bed pressure drops in full-scale applications may range from 50 to more than 3,000 Pa (0.2-12 inches of water column,"wg). Corresponding power demand for a 30,000 $m^3$/h (18,000 cfm) stream varies from 0.7 to 41 kW, indicating a potentially considerable impact of media selection and bed design on energy cost.

*Water consumption.* Due to their inherently higher condensation gains and heat-up losses, the water balance of open systems may differ considerably from that of enclosed systems treating the same off-gas. Also, some of their water demand is provided by natural precipitation. However, the corresponding cost savings are insignificant, typically less than $200 per year for a 1,000 $m^2$ bed.

*Operation and maintenance.* For a biofilter performing well, monitoring and control of its moisture content and checking and recording other basic operating parameters constitute the major routine maintenance requirements. Respective labor requirements depend on the system's moisture balance, choice of moisture control, data monitoring, and control systems. An

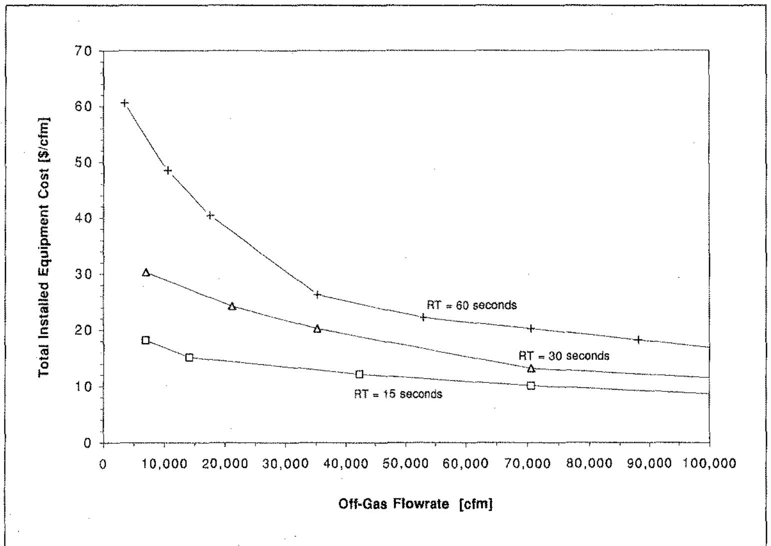


**Figure 4.** Total installed capital cost for biofilters at various residence times.

open filter of several hundred m² which treats off-gas with fluctuating VOC concentrations frequently exceeding 1 g/m³ may require as much as several person hours per day to maintain the proper moisture content. Biofilters with an effective automatic moisture control system, and well designed open biofilters treating low pollutant loadings for odor control, typically require five to ten minutes of maintenance per day. Performance problems with full-scale biofilters due to media dry-out or compaction have routinely caused additional demand for inspection, maintenance and repair work.

*Media replacement.* Replacing the filter media is the most arduous biofilter maintenance item. Depending on its initial composition and operating conditions, replacement is typically required every 2 to 7 years when the bed pressure drop has become unacceptably high and performance decreases. At typical media loading rates of 50-200 m³/day, replacement may require several days. In open systems using cast concrete air distribution elements, easier access to the filter material facilitates its replacement and its periodic fluffing with frontloaders to extend useful life. Since the latter is impractical for enclosed systems, their vendors usually employ the already mentioned designed media with a targeted useful life of 4 to 7 years.

Annualized filter material replacement costs depend on the media's useful life, media volume, and cost per volume. Open systems are more likely to use less processed media, usually obtained from local composting facilities. Tradeoffs for their lower cost, typically $30-$50/m³ excluding installation, may include a shorter useful life and lower performance, resulting in a larger required filter volume. Designed media now routinely achieve bed lives of more than five years while maintaining a low pressure drop,[23] but at a total replacement cost of typically $100-$300/m³. Cost savings from extended life and lower energy cost may only partly justify their higher initial cost. Their generally higher performance and reliability, and longer periods between bed replacements, argue in their favor.

## OTHER CRITERIA FOR SYSTEM SELECTION

### Operational Reliability

Because of their limited control of temperature and moisture, open beds are more sensitive to loss of performance in applications with short dry-out and response times; i.e., they are inherently less reliable. Enclosed systems with automatic moisture control and more durable filter material are intended to minimize this risk. A lower level of control may suffice for dilute off-gases in climates without extreme temperatures and precipitation, or if regulatory requirements need not be met consistently and some variation in performance is acceptable. The latter situation is common for odor sources without immediate residential neighbors, generally lower odor levels, and seasonal emission patterns.

### Siting Considerations

Footprint and volume of biofilters are large compared to competing air pollution control systems. To date, most biofilters have been installed at ground level. Where a biofilter competes with other facility operations or expansions for space, rooftop installations are common. They may also allow for siting directly above the emitting source, thus reducing ducting cost. Since existing buildings can rarely support concrete biofilters, rooftop installations usually involve steel or plastic reactor vessels. They are predominantly built as enclosed systems, although some open rooftop installations have been built in Europe.[12]

### Off-Gas Monitoring and Dispersion

If biofilters are applied for VOC or HAP control, their compliance with quantitative regulatory standards must be verifiable by monitoring pollutant concentrations in the raw and/or treated off-gas. In open systems, the lack of a single discharge point and the common spatial variations in filter performance, including channeling, impair the reliability of performance measurements with monitoring hoods. Closed systems discharge the entire treated stream from a stack and allow potentially continuous single-point monitoring for total VOC or selected organic species.

Stack discharge from closed systems also provides for better off-gas dispersion, typically by a dilution factor of 50-250 at the facility boundary. Thus, residual odors in the off-gas from a properly functioning biofilter, which are typically in the range of 50-100 odor units, are rarely noticed by neighbors. Open systems emit such odorous residues at lower exit velocities and at ground level. As a result, poor performance of an open system is more likely to cause odor nuisances in its vicinity, which have been experienced in some cases. The same applies to distribution of the moisture plume typically emitted by biofilters, particularly during cold weather.

**CASE EXAMPLES**

Three case examples of full-scale biofilters for VOC and HAP control illustrate the relationship between off-gas characteristics, moisture balance, system design and maintenance needs. The systems were installed in the early 1990s for the control of VOC or air toxics from industrial processes, one in the Netherlands, the others in the U.S.

*Case example 1.* A two-level open biofilter is used to treat 17,000 $m^3/h$ (10,000 cfm) of off-gas from the mold production at an investment foundry in Los Angeles. As a function of production rates, the off-gas contains often high (up to 3 $g/m^3$) and strongly fluctuating concentrations of VOC, predominantly ethanol. At a residence time of ~60 seconds and an inlet wet-bulb temperature of ~20 °C, temperature increases across the bed of more than 5 °C and moisture losses of more than 500 $gm^{-3}h^{-1}$ are common. A typical humidity and temperature profile for this unit is shown in Figure 1. Although a timer-based, semi-automatic sprinkler system controls spray humidification, it has been difficult to maintain proper bed moisture at these evaporation rates. The considerable need for irrigation, typically 2 cm/day, also caused flush-out of fine particles which were present in excess in the original bark and sewage-sludge compost based filter material. Subsequently, compaction and an increase in bed pressure drop to more than 3,000 Pa (12" wg) required replacement with a less compact, wood-chip based media after two years of operation. Moisture monitoring of the filter material and adjustment of irrigation patterns were labor-intensive but did not avoid repeated dry-out, particularly in the bottom zones. Three years of operating experience support the suggestion made in Table 3 of using automatic moisture control for evaporative losses exceeding 400 $gm^{-3}h^{-1}$.

*Case example 2.* Two single-level open biofilters were installed in 1992 to treat similar off-gas streams from polymer manufacturing facilities in Springfield, MA and Trenton, MI. The off-gas flow rate is about 35,000 $m^3/h$ (20,000 cfm) and the off-gas contains between 0.4 and 0.7 $g/m^3$ of total VOC, predominantly ethanol plus aldehydes and esters. Biofilter VOC removal efficiency is measured every few months at between 90 and 95%. It is limited by several high molecular weight VOCs which are present in low concentrations in the inlet off-gas but are the primary compounds in the treated exhaust gas.

Just prior to entering the biofilter, the off-gas is saturated by spray nozzles and the gas temperature is controlled between 30 and 35 °C, i.e., above average ambient temperature. The residence time of the off-gas in the biofilter is about 100 seconds and the elimination rate for total VOC is 15-25 $gm^{-3}h^{-1}$. The filter material, a compost/wood chip mixture, is sampled in several locations every few months for moisture content and other attributes. The compost mois ture content has varied between 50 and 70% by weight, som what higher than the 40-60% optimum. Initially, water spray systems were not installed on either biofilter. For moisture c ntrol, media relied on rainfall and temporary condensatio of moisture from the warm off-gas. This has been adequate- with the exception of two extended periods of hot, dry weather when water was manually sprayed to prevent dry-out f the filter material. A manual bed spraying system has ecently been installed on one of the biofilters to improve the moisture distribution compared to

spray hose. Experiences with these two open biofilter demonstrate that rainfall and condensation may provide sufficient moisture to open beds not equipped with additional ed spray, if VOC concentrations in the raw gas are low, its - wet bulb temperature exceeds the ambient temperature, and t e off-gas is humidified just prior to entering the bed. They lso indicate the potential for dry-out in case of extended hot dry periods and for condensation of moisture in the filter - material during colder periods.

*Case example 3.* A fully enclosed biofilter with two stacked beds operated in series (total media volume: 1200 $m^3$) is used to treat 140,000 $m^3/h$ (80,000 cfm) of easily degradable solvents. VOC concentrations in the raw gas are fairly constant and typically average 500 ppmC. The wet-bulb temperature is 20 °C. At the designed residence time of 30 seconds, the biofilter achieves 90% VOC removal, sufficient to meet regulatory standards which limit organic carbon concentrations in the treated off-gas. The biofilter is equipped with an automatic moisture control system which consists of load cells, overhead sprays, and a PLC control system, and maintains a constant bulk moisture content in the filter material.

The unit has been in operation with the initial batch of filter material for more than six years. At a face velocity of 240 m/h (13 fpm), the total pressure drop across the beds has gradually increased by ~25% to 500 Pa (2" wg). The system achieved reliable moisture control of the beds, required little maintenance, and demonstrated the advantages of an enclosed system with automatic moisture control for treating off-gases with high face velocities and medium VOC concentrations. It also provided several lessons on the compatibility of biofilters with sophisticated industrial processes. First, it demonstrated that biofilters are suitable as an add-on control technology for production processes which require that negative pressure at the production side be maintained within tight limits. Second, after several years of operation, bed irrigation had caused some compaction of the surface layer. Raking of the top 10 cm of filter material in the top bed, which typically requires three person shifts of labor, decreased the pressure drop to previous levels. Raking is now performed on an annual basis. Finally, in order to maintain an even moisture content across the height of the beds, minimum and maximum spraying duration had to be adjusted to changes in average VOC concentration. For the same total irrigation rate, longer and less frequent spraying achieves better bed penetration and brings relatively more water into the lower levels of the media. This is typically required at higher VOC inlet concentrations.

## CONCLUSIONS

This review of biofilter thermodynamics, general operational experience, and several full-scale case examples illustrated the relevance of moisture balance and control to biofilter performance. In a biofilter, evaporation and condensation rates are determined by the VOC concentration in the off-gas, face velocity (or residence time), degree of prehumidification, inlet temperature, heat and moisture exchange of the media with the environment, and media degradation. These parameters and the resulting evaporation rates vary widely in full-scale biofilters, typically 1-30 mm of water column per day. Considering drainage losses, actual irrigation demand will be higher. The period in which detrimental dry-out of the media occurs and the appropriate moisture control varies accordingly. This is illustrated by the following two typical cases.

Open systems without an installed irrigation system maintain acceptable moisture content and performance if moisture losses are sufficiently low to be replaced by spraying on less than a monthly basis, by rain, or by condensation gains. This is the case for off-gases with wet bulb temperatures at or above ambient levels and VOC concentrations of $<0.1$ g/m$^3$, typical for many odor control applications. In those applications, their lower capital cost compared to fully enclosed, controlled systems make open biofilters attractive.

VOC concentrations and elimination capacities exceeding 0.5 g/m$^3$ and 50 gm$^{-3}$h$^{-1}$, respectively, cause high evaporation rates and require increasingly sophisticated moisture control systems, typically involving fully enclosed filter vessels. Over the last decade, these systems have achieved a reasonably accurate and reliable control of media moisture. The necessary monitoring, control, and data-logging equipment may add considerably to system cost. As VOC elimination capacities exceed 100 gm$^{-3}$h$^{-1}$, the resulting moisture removal rates make maintaining the proper moisture content in large, heterogeneous reactors increasingly difficult, even with automatic moisture control. This constitutes a major nonbiological limitation to high volumetric VOC removal in a biofilter.

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