Air Bio-Reactor Systems: different designs and operational aspects

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ABSTRACT

Add-on control devices such as incinerators and adsorbers are widely used in U.S. industrial facilities (plants) to meet federal emission standards; however, few facilities are using bio-reactors or bio-filters for that purpose. There may be reasons affecting this selection. This presentation will overview some of the activities that were undertaken by the U.S. Environmental Protection Agency (EPA) to promote the effective use of bio-technology for controlling industrial air emissions. Several designs of bio-reactor systems will be briefly overviewed and relevant monitoring aspects will be discussed. Lastly, a few recommendations will be shared to promote the technology as a tool for compliance beyond the initial compliance test.

INTRODUCTION

There has been a dramatic increase in interest since the early 1990s in the United States, in the use of air bio-reactors for controlling emissions of volatile organic compounds (VOCs) and air toxics (hazardous air pollutants) from industrial operations. This technology has possible application in many industries such as the wood furniture, aerospace, and metal furniture industries to control emissions of organic solvents from coating and cleaning operations. Bio-reactors can also be used to control odors from a variety of sources such as bakeries, chicken farms, and hog farms. The emissions from such sources contain a relatively low concentration of pollutants and large volumes of air are most often involved. Bio-reactors are also attractive because a low amount of energy is needed to operate most bio-reactor designs.

Because of the potential uses and possible cost-advantage under certain operating environments a number of us in the Office of Air Quality Planning (OAQPS) followed the developments in bio-reactor technology with interest, for a little more than 10 years. During that period, we met with designers, vendors, and industry representatives who wanted to use air bio-reactors to reduce emissions from coating operations. In June 1997, OAQPS hosted a one day bio-reactor meeting, during which several aerobic bio-reactor designs were presented.[1] The forum provided persons in industry and in academia an opportunity to interact with one another. For the EPA, it was an opportunity to explain data requirements for validating such systems. It also provided the participants at the meeting with an opportunity to ask questions related to monitoring and compliance. During that same period, another cooperative effort involving another branch of EPA was underway. In this case a water-trickling bio-reactor pilot study developed by the EPA Office of Research and Development was being used to control odor due to ethanol emissions from a bakery. [2]

The following sections will provide a brief overview of several bio-reactor designs that have potential for controlling emissions of VOCs and toxic pollutants from industrial operations. Aspects related to operation, control, and costing of bio-reactors will be discussed. These aspects should be of interest to both users and regulators.

DESIGN ASPECTS OF AEROBIC SYSTEMS

Bio-degradation can be a cost-effective way of removing low concentrations of air pollutants (usually, less than 500 ppmv). This technology uses biological agents (micro-organisms) or their products (enzymes) to degrade or reduce the hazardous nature of the organic materials that are captured in a moist environment. Organic materials are usually degraded to carbon dioxide and water, and various ions (hence the term mineralized). Unlike more conventional add-on controls, bio-reactors have to be more specifically tailored to the type of organic materials they are designed to destroy. However, there are distinct differences in design and hence, in validation, operation, and monitoring requirements. EPA is aware of several designs of air bio-reactor systems that can remove pollutants in air streams. [1] They can be grouped under two broad design types. In the first type, capture and destruction of pollutants occur in one unit operation (e.g., a column with a packed bed). In the second type, capture and destruction of pollutants occur in separate unit operations. A *bio-reactor system* will include other units such as a particulate filter and a heating unit in addition to units needed for capture and destruction of pollutants. The term *bio-reactor* is used to refer to the unit in which bio-oxidation (degradation) of the pollutants occurs.

<u>Packed-bed bio-reactor system.</u> Capture and destruction (micro-oxidation) of air pollutants occur together in the same unit operation. This commonly occurs in a packed bed. The open design bio-reactors (bio-filters) are being used in Germany and the Netherlands, mainly for odor control (less than 50 ppmv). A few of these units were built in the 1990's in the U.S. for VOC control. [3] Some were the size of a football field. [4] The bio-reactor units designed today in the U.S. are closed systems and have a much smaller footprint. [5-7] A system may include a separate pretreatment or humidification unit followed by one or more bio-reactor beds. These beds may be one on top of the other or a series of separate columns. Packed beds usually contain a natural source of nutrients composed of compounds with , e.g., nitrogen, phosphorous.

<u>Water Trickling bio-reactor system</u>. This system is similar to a conventional packed-bed bio-reactor, in that capture and destruction of air pollutants occur in the same unit. [2, 8, 9] The main advantage of this design of bio-reactor system is its ability to handle large amounts of air pollutants containing halogens or sulphur. A secondary tank containing a neutralizing agent (and to which nutrients are added) is attached to the unit containing the micro-organisms and the pollutants. Hence, an additional set of parameters would need to be adjusted and monitored.

<u>Activated carbon bio-reactor system</u>. The operation is composed of two stages. Air pollutants in the air stream are first adsorbed by the activated carbon that is housed in a rotating wheel [10] and then leached into a bath of oxygenated water as the wheel rotates. A moist film of

micro-organisms is attached onto the rotating carbon surface. Hydrocarbons dissolved in the water serve as food to the micro-organisms. Oxygen is provided to the water by blowing air through two immersed perforated pipes. The nutrients are added to the water bath.

Scrubber bio-reactor system. Capture and destruction occur in two separate units. [11, 12] The air flow containing the air pollutants are entered into a non-clogging tray tower in which biomass is pumped countercurrent to the air flow. The biomass flow (containing the absorbed pollutants) is then returned to another unit, referred to as the bio-reactor, where the nutrients are added and most of the pollutants are metabolized (decomposed or destroyed). A given volume of fluid containing dissolved pollutants is returned to the bio-reactor tank and the same volume of sludge is pumped (discharged) from the bio-reactor as blowdown. The bio-reactor is aerated by blowing ambient air which is then mixed with the input pollutant laden air stream going to the scrubber tower. Nutrients are fed directly to the bio-reactor tank.

Membrane bio-reactor system. Capture and destruction of the pollutants also occur in two separate units. [13, 14] Particulates prefiltered air is first passed into a membrane separation/concentration unit made up of bundles of of microporous, hydrophobic hollow fibres. The air stream flow is inside the hollow fibres and the extracting fluid is on the shell side of the bundle. The stripping fluid helps to concentrate the pollutants and should have a low volatility and a high fluid/air partition coefficient. The pollutant laden stripping fluid is then directed into another membrane unit where the micro-organisms are located. The pollutants diffuse across one side of the membrane pores and are destroyed by the bacteria on the other side where the aqueous nutrient stream flows. The separation in that membrane unit is governed by the partition coefficient in the stripping fluid/air and stripping fluid/aqueous system containing the micro-organism.

OPERATION AND MONITORING ASPECTS

Unlike incinerators where destruction of pollutants by oxidation can occur in seconds, reactions involving microorganisms require relatively more time. Whereas, the older open type bio-reactors (bio-filters) require large volumes and surface areas to achieve a high degradation rate, the newer packed-bed designs are closed systems. The pollutant destruction efficiency [(input - output)/input] can be measured more accurately in a closed system, which makes a closed system more desirable from a regulatory point of view. However, the performance of a bio-reactor system is more often reported in terms of the utilization ratio, which is a measure of the rate of pollutant destruction normalized by a design parameter (e.g., volume in the case of a packed-bed, or surface area in the case of a membrane bio-reactor). Hence, the utilization ratio provides a measure of performance that is cost-oriented, whereas destruction efficiency is more oriented towards the pollutant concentration.

The performance of a packed-bed bio-reactor system is influenced by the bed filter material selected. Peat and soil are two natural support media that are most commonly used in the United States, whereas compost is more commonly used in Europe. Soil and compost contain a natural population of microorganisms, which release enzymes that decompose the pollutants (hydrocarbons) that have attached onto the pore surfaces. [3 - 7] Some of the pores of peat and compost are filled with water. These pores serve as the reaction sites. The presence of an aqueous environment is critical to health of the indigenous micro-organisms and must be maintained, as the hydrocarbon pollutants must be in an aqueous environment before they are degraded. Water is added by humidifying the air and spraying water at the top of the bed. Too much water in certain parts of the bed could affect the pressure drop distribution. Hence, it is important that channeling of the air flow does not occur in packed bed type bio-reactors as that will result in certain areas of the bed being dryer, thus reducing the retention of the pollutant laden air flow. [2, 3, 11] This will also result in uneven temperature regimes, and could affect overall performance of the packed bed bio-reactor. Therefore, an operator would need to maintain the pressure drop across a packed bed and the humidity (moisture content) within the design range.

Trickling bio-reactors also need to maintain a healthy population of micro-organisms in a biofilms that grow on the support media, without too much biomass buildup. The support medium is usually synthetic and the medium is kept moist using a recycle stream into which necessary nutrients are added. [2, 8, 9] Hence, the water level needs to be monitored. However, that step does not control the nutrient requirements. [2] To maintain nutrient pH at the required level, an automatic feeder of buffering solution would be needed for each tank. Also, it may be necessary to aerate the nutrient recirculating tank to overcome the depletion of oxygen resulting from the presence of biological culture (washdown from the bio-reactor). Growth of biomass would need to be controlled to prevent clogging of the trickling bio-reactor, which would build up the bed pressure drop and affect the efficiency of the system.

Water washing (scrubbing), activated carbon, and membrane bio-reactor systems provide other ways for transferring air pollutants from air to water. Because both the capture and destruction steps occur in separate units, these designs of bio-reactor systems allow more flexibility and control of bio-reactor operation. This involves aspects such as controlling pH level, residence time, and biomass buildup. Equipment size may also be minimized, considering that these systems have the ability to concentrate the pollutants in the air stream. These pollutants will be available as a source of carbon and energy for the micro-organisms, should the inflowing air be low on pollutants. This last feature is important during periods when there is no production. For example, many operations close down during evenings or weekends. As a result, pollutant emissions in the air stream are low and the microorganism would need to be fed with a source of carbon and energy. Under such conditions the temperature of the biomass must be maintained, which may require heating the air to sustain metabolic activity [9] to temperatures usually between 15 ^{o}C and 40 ^{o}C. However, certain organisms may have metabolic activity much below or above this range.

Designs where capture and destruction of pollutants occur in one unit, such as packed-beds also have to deal with periods where the pollutants feed is much reduced or cut-off. This is sometimes achieved by adding to the packed bed activated carbon, which provides a surface where pollutants can adsorb and during downtimes desorb, thus providing food and energy to the micro-organisms. [15] A carbons adsorption unit may also be added upstream of the humidifier, which usually precedes a packed-bed bio-reactor unit. It acts as a buffer, to control the pollutant concentration to the bio-reactor. [16] A major difference between a scrubber type bio-reactor and a packed-bed bio-reactor is the relative volume of water involved. Also, a bio-scrubber system involves a "submerged dispersions of the process mediating culture," whereas a packed-bed bio-reactors involves an exposed bio-film. [12]

Although the five types of bio-reactor systems discussed above, are each composed of different units, they all strive to do the same thing: First, capture the hydrocarbon pollutants in a water medium and then have the micro-organisms oxidize them. However, how quickly a bio-reactor system acclimatizes or re-acclimatizes is very important, especially from a regulatory perspective.

COST OF BIO-REACTOR SYSTEMS

It is often necessary to compare alternative add-on control technologies (incinerators, chemical scrubbers, or bio-reactors) for removing air pollutants. Although there are various ways of estimating such costs, for air regulatory purposes the costing approach is based on the most recent version of the *The EPA Air Pollution Control Cost Manual.* [17] The cost basis is the 'purchased' equipment cost. Hence, estimated total capital cost of a bio-reactor system (annual costs, purchased equipment costs, and indirect costs) is based on the direct and indirect costs which are based on multipliers of purchased equipment costs. [1, 17] The multipliers and other assumptions regarding annual depreciation rate and interest rates are provided in the cost manual. The relative costs estimates of purchased cost of the control equipment will be a function of the size of add-on control system, which should be designed on the basis of the maximum airflow that would need to be remediated, for a representative influent constituent composition of pollutants.

There are a number of articles in the literature that show that the cost of bio-reactors are much lower than those of alternative technologies. These results often refer to the packed-bed type of bio-reactor systems. However, it is likely that the cost of a system will vary with the particular bio-reactor system design and operation under study. In general, a bio-reactor system includes capture media (packed bed, water washing column, or activated carbon). Other cost items include temperature and flow controllers for the air stream. Temperature and pH controllers are needed for the water/nutrient stream when a bio-reactor system utilizes an external tank for buffering or humidity control. A bio-reactor system may include a blower, a fan, and sometimes a compressor. In determining total cost of a bio-reactor system one would need to account for the cost of replacing bed materials, or regenerating the separation medium. Waste handling of depletable materials and liquid waste streams are other cost items.

DISCUSSION AND CONCLUSIONS

The requirements for compliance with an environmental regulation may vary depending on the prescribed federal rule requirements. Federal and state emission rules usually require submission of operation and maintenance plans, startup, shutdown, and malfunction procedures/plans. These requirements help determine the periods of compliance and the episodes of non-compliance. In addition, some rules require training procedures and compliance certification reports. Any add-on control (abatement system) must address these requirements.

Several bio-reactors designs were briefly discussed, even though some of them did not yet have not yet completed pilot stage testing. However, all design types would require that the following aspects be considered during the design phase and for controlling the operation:

1. Composition and amount of pollutants
2. Microorganism mix
3. Humidity (or moisture content)
4. Temperature
5. pH value in the bio-layer
6. Pressure drop

The sensitivity of a bio- reactor system to fluctuations in e.g., humidity and temperature will vary from one design to another. Hence, there have been numerous attempts to predict performance under different operating conditions . [7, 8, 18 - 21]

The requirements for more traditional add-on control technologies such as adsorption units or incinerators, which have been around for a long time, seem to be pretty well understood by the regulating community. The same cannot be said about bio-reactor systems. This is partly due to lack of uniform procedure for reporting cost and compliance related information, which makes it difficult to compare the different systems designs, as a basis for a first screening. Hence, the different designs/types of bio-reactor systems were presented to highlight the similarities and the differences in the approaches used to capture the pollutants from an air stream. separation.

A question that would be in the mind of a facility owner (or operator) contemplating using a bio-reactor system, or in the mind of a regulator, is the nature of the data that would need to be collected to validate and maintain the destruction efficiency of this type of technology used as an add-on pollution control. Once the parameters that need to be controlled in bio-reactor system are defined, the testing and monitoring methods for demonstrating both initial and continuous compliance can be identified. A performance test would need to identify the initial adaptation period, adaptation period when pollutants are not emitted during brief periods (e.g., evenings and weekends) and/or after plant shut downs for a week and for longer periods. The re-adaptation period identifies the amount of time a bio-reactor needs to recover to its designed destruction efficiency. The performance test data collected would need to satisfy EPA's quality assurance and quality control requirements. [1]

The destruction efficiency of bio-reactor systems is often defined as a measure of their performance. This requires determining the inflow and outflow concentrations of air pollutants to the bio-reactor system. It may also be important to ascertain that negligible amounts of pollutants are released with the liquid effluent. The extent of instrumentation and logging of pertinent operating parameters will depend on the specific bio-reactor design. These need to be identified as they will then be incorporated as part of a permit agreement. Sometimes the inflow to bio-reactor originates from more than one point source. In this case, warning devices may be necessary to ensure that the design capacity of the add-on control system is not exceeded or that the fluctuations in the airflow composition of the pollutants in the air stream do not reduce performance below that required.

There is no doubt that bio-reactors have the ability to oxidize single pollutants or mixtures of pollutants in an air stream, as a recent review of 40 pilot plant studies and full-scale application at waste water treatment plants (odor control) would indicate. [20] However, there are those who still believe that the technology is not yet fully developed and that more work needs to be done to build up enough confidence, so that more bio-reactor systems are selected in the U.S. to meet regulatory requirements. We are likely to get there sooner or later, judging on the volume of technical publications and annual meetings. Also, many of the new emission standards are structured in such a way that the limits are achievable using a combination of pollution prevention practices and destruction efficiencies below 90 percent . However, a review of the literature shows that a common vocabulary needs to be adopted for the benefit of the interested public. Also, any conditions that would generate waste that is toxic should be discussed during a demonstration test.

Lastly, an effort to develop a generic verification protocol for add-on devices, which utilize microorganisms for removal of air pollutants is now being undertaken under the Environmental Technology Verification (ETV) Program sponsored by the EPA Office of Research and Development, in Research Triangle Park. Those involved in this activity will no doubt be influenced by the related work done for the biological treatment of waste water streams. [22] Information regarding the ETV protocol activity will be posted on the OAQPS website. [1]

DISCLAIMER
This work represents the views of the author and not necessarily those of the Agency.

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KEY WORDS
bio-reactors
bio-reactor system
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