

## **Compact Fiber-Based Bioconversion/Bio-filtration Systems**

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### **INVESTIGATORS**

Yong K. Kim (Leader/UMass Dartmouth), Chen-Lu Yang (UMass Dartmouth),  
Francis Scarano (UMass Dartmouth), Armand F. Lewis (UMass Dartmouth),  
Raymond N. Laoulache (UMass Dartmouth)

### **ABSTRACT**

Polluted air and water treatment by bioconversion/biofiltration is a rapidly growing large industry that presently does not involve many textile products. Unlike pollution control methods based on regular filter media, bioconversion does not require disposal of contaminated used-up filter media. Moreover, higher environmental costs of current practices drive the pollution control equipment/media suppliers to shift their focus toward the more compact, high surface area fiber-based bioconversion media. Our research on textiles and fiber coated biofiltration surfaces will lead to opening a new applications area for fiber/textile products. The U. S. fiber and electro-fiber coating (flocking) industry will greatly benefit from this basic research of the proposed fiber based bioconversion surfaces by supplying more fiber and flock products to the potential market. Our research will provide opportunities for developing a new generation of biofiltration media with high specific surface area. Our findings shall provide the US fiber, fiber finishes and fabric producers with basic knowledge not only on how to form textile based biofiltration surfaces using electrostatic principles but also regarding how to engineer the fabric with predetermined geometry and hence predetermined bioconversion properties.

### **OBJECTIVE**

Presently, the detoxification of polluted water by biological processes is done primarily on sand particles (sand filter), plastic beads or shell-like surfaces (trickle filters) or smooth plastic surfaces in the form of PVC plates that rotate in the water media. All of these existing systems are bulky, cumbersome, easily contaminated and highly inefficient. Recent studies in the UMD Textile Sciences laboratory have shown that nylon flocked polymer surfaces are at least 10 times more efficient in the bioconversion of ammonia to nitrite and finally to nitrate than the above mentioned bioconversion (biofiltration) methods [1].

Based on this discovery, the specific objectives of this proposal are to:

- (1) Determine the fundamental materials and geometric parameters that will enable the optimization of flock fiber-coated polymer and textile fabric surfaces for bioconversion activity.
- (2) Model and establish the hydrodynamic flow characteristics of water across fiber coated (e.g. flocked) surfaces and bioconversion efficiency of the fiber surface to design compact, efficient bioconversion/biofiltration water remediation devices.
- (3) Establish the chemical and mechano-physical conditions that will enable the fiber coated bioconversion surfaces to be easily regenerated, should they become contaminated or coated with excessive biomass.
- (4) Investigate the effects of using flocked surfaces in bioconversion reactions related to air biofilter applications.

## INTRODUCTION

In research experiments carried out by Kim and Lewis [1], the efficacy of using textile flocked fiber surfaces as a media for bioconverting ammonia to nitrates in land-based aquaculture, closed-system operations was established. It was found that 3/16" thick polycarbonate (PC) plates flocked with nylon fibers are an excellent substrate for ammonia converting *nitrosomonas* and *nitrobacter* bacteria. During ammonia contaminated water immersion testing, all the flocked samples showed a rapid decrease in ammonia concentration accompanied by an increase in nitrate concentration. This indicated the proper functioning of the *nitrosomonas* and *nitrobacter* bacteria in the water media. All the flocked panels showed a visibly heavy growth of bacteria on their surfaces compared to the controls, unflocked and flock adhesive coated PC plates. Similar studies on textile fabric surfaces flocked with nylon fibers also showed remarkable bioconversion activity. It appears that flock fiber material positioned on surfaces is an important factor in this observed enhanced bioconversion effect.

Bioconversion systems (known as biofilters) are designed for the purpose of biochemical converting water polluting chemicals such as ammonia, hydrogen sulfide and other chemical pollutants dissolved in water into non-toxic chemical species. A very common bioconversion/biofilter application is the removal of ammonia and nitrites in land based (closed system) aquaculture operations. Here, the sources of ammonia/ammonium compound are from fish waste products and deteriorated fish food excesses in the growing tanks. The polluted water enters the bioconversion/biofilter either from the aquaculture tank recirculation water or the air washing of the ammonia containing water. Biofilters employ a non-moving surface area that provides a substrate for deliberately deposited bioconversion bacteria to attach and grow. The substrate remains in place while the water flows through the system. The heart of these biofilters is the media used to provide the surface area for the chemically bioactive bacteria. The type of packing of the media used strongly influences both the capital and operating costs of the biofilter. [2, 3, 4, 5]

Various types of packings exist for fixed surface biological filters, such as sand, rock and gravel, fiber mesh pads, brillo pads, random or stacked packings, and structural packings. Each type has advantages and disadvantages but in terms of overall cost and suitability, the structured packings are the best choice for commercial designs. Structured packings are widely used for many applications other than aquaculture biofilters. They have virtually all of the characteristics in ideal packings. Structured packings have been used in biofilter applications for over 30 years. For the municipal and industrial wastewater treatment industry, they are the packing of choice. [6]

Structured packings are typically fabricated from vacuum formed sheets of PVC (polyvinyl chloride). Continuous vacuum forming is a high-speed automated process that can efficiently produce large amounts of substrate material. This method of construction allows structured packings to be produced for a much lower cost per unit surface area than injection molded, randomly stacked packings. Also, PVC is a relatively low cost polymer with much better mechanical properties than PP or HDPE. In wastewater, PVC is initially hydrophobic but normally becomes fully wettable within 1 to 2 weeks of conditioning in the bioactive aqueous media. [7] This technology used for fixed film biofilters is not unique to aquaculture. While some minor application details are different for aquaculture, the solutions to efficient and economical water quality management have been identified and developed by several other industries. The goal of this project is to confirm the effectiveness of the unique textile based surface treatment process to enhance the efficiency of packing and surface area that is available for bioconversion/biofiltration.

Specific surface area is the measure of how much biologically active area is contained in a given volume. Typical units of measurement are square meters per cubic meter or square feet per cubic foot. For biofilter media, specific surface areas vary widely but generally speaking, many types of packing will fall between 100 and 820 m<sup>2</sup>/m<sup>3</sup> (30 and 250 sq.ft. /cu.ft.). This specific surface area is often referred to as the "packing density". Typically, flock densities are 100 to 400 fibers /mm<sup>2</sup> with 3 denier, 2.5mm long nylon flock. Assuming the flocked fabric surfaces are arranged 10mm apart, this type of biofilter substrate can have a packing density of 1500 to 6000 m<sup>2</sup>/m<sup>3</sup> with low hydrodynamic impediment. It is conceivable that velvet, velour, raised or pile fabrics will also have a relatively high packing density. However, to produce fiber based biofiltration media in massive volume at competitive price on various forms of substrates (linear, 2-D and 3-D geometries), fiber electro-coating (flocking) appears to be the most enabling technology. [8]

The total surface area available for bacterial growth is a good predictor of the capacity of a bioconversion system to convert water polluted with ammonia. The specific surface area is an important variable that influences the cost of the biofilter vessel and support mechanisms. If packing A has twice as much surface area per unit volume as packing

B, then packing B will need a containment vessel twice as large to accomplish the same task as packing A. From an economic, including efficient floor space usage standpoint, it makes sense to use the smallest vessel possible to accomplish a given task. Provided there are no other overriding factors, using a biomedial packing with the most surface area per unit volume will allow for the minimal of vessel and unit operations costs.

It has been stated by Roland [9] that the biological treatment industry is in a state of flux. Vapor and liquid phase biological scrubbing technology has been growing and adapting to new applications. Emphasis is now on reducing system size while increasing throughput. Overall, the proper application of textile materials to a geometrically designed surface structure offers the potential of increasing surface contact area within a small volume. There appears to be many high quality and cost-effective benefits from the fiber-based technology here-in proposed

It is important here to distinguish between total claimed surface area and surface area that is available as a substrate for biological growth and bioconversion. Surface area that is contained in very fine crevices or pores may not always be available to living organisms. As a biofilter matures, the biomass of bacteria steadily increases and the layer of bacteria that covers all available surfaces (biomass) becomes thicker. Since the organisms inside the layer can only receive food and oxygen by diffusion, they receive less and less food and oxygen as the biomass layer grows thicker. Generally speaking, only the outermost layer of bacteria will be operating at peak efficiency for conventional biofilter media. We want to overcome this difficulty by controlling packing geometry of fiber coated surfaces and moving mechanisms such as a continuous belt cleaning system for stripping over-grown bacterial mass.

## TECHNICAL APPROACH

- (1) Determine the effect of fiber material type (nylon, polyester, cellulose acetate), flock density, fiber length on the bioconversion efficiency of flocked surfaces. Use the bioconversion of ammonia to nitrite then to nitrate using *nitrobacter* and *nitrosomonas* bacteria as a model biochemical conversion system. Construct an instrument controlled, laboratory scale bioconversion/biofilter tank system to carry out these experiments.
- (2) Develop a hydrodynamic model for the interaction of pollutants-dissolved-in-water with flocked and highly napped textile surfaces. Consider effects of bio-growth on the reaction and the residence time needed for reaction. Verify this model by conducting hydrodynamic resistance experiments on these napped textile surfaces.
- (3) Determine the effectiveness of using textiles of various geometric shapes as flocked substrates for bioconversion media. Establish the chemical and physical conditions that will enable these surfaces to become easily regenerated should they become contaminated with excessive biomass.
- (4) Establish the efficacy of using textile surfaces for the bioconversion of odor causing air pollutants such as ammonia and H<sub>2</sub>S based on pollutant converting, moist air biofilter/biochemical reactions. For example, the key would be to provide an ideal habitat for the growth of sulfide-oxidizing bacteria, to the exclusion of competing microbes that normally predominate in aerobic treatment processes. [10]

## ACCOMPLISHMENTS TO DATE

### 1. RBC and Trickling Biofilter Studies

The project team has been meeting regularly to direct the project. Kim, Laoulache, Yang, Scarano, Lewis and the graduate students hired to assist with the project, attended these meetings. Biofilter designs were discussed. Results were reviewed pertaining to some UMD experiments that were recently conducted on comparing the ammonia conversion effectiveness of (a) RBCs (Rotating Biological Contactors) having been modified with flocked surfaced plates and (b) RBCs with non-flocked plates. RBC technology involves allowing wastewater to come into contact with a biological medium for the removal of contaminants. In its simplest form, an RBC consists of a series of discs mounted on a shaft that rotates the discs at right angles to the contaminated (with ammonia for example) water. The discs are usually made from corrugated PVC plates that when mounted are arranged to be 40 % immersed in a tank containing the contaminated water. The shaft manages to rotate the RBC discs (40% immersed

in the wastewater) through the wastewater at a rate of 1 to 2 RPM. In the case of our experiment, the RBC discs were inoculated with *nitrosomonas* and *nitrobacter* bacteria. After a few days, a layer of slime forms on the RBC plates. This slime contains the biological species responsible for the bioconversion of ammonia to nitrite and finally to nitrate. The RBC system is now ready for the bioconversion testing.

In the UMD tests, two separate tanks each containing a commercial size RBC [RBC440 - Aquatic Eco-Systems, Apopka, FL] were started up with an equal volume of water containing 5 mg/l of ammonia (NH<sub>3</sub>) in each tank. One tank had an RBC with nylon fiber flocked discs; the other was an RBC whose discs were not flocked (the control). The ammonia, nitrite and nitrate concentrations were measured at intervals of time for a four-week period. Data taken over this 30 day period illustrated the more rapid bioconversion of ammonia to nitrate in the flocked disc RBC compared to the un-flocked RBC. This observation coincided with the more rapid creation of nitrate by the Flocked disc RBC. These new data support the previous reports by Kim and Lewis [1] on the effectiveness of flocked surfaces in bioconversion reactions.

While this RBC experiment was found to demonstrate the enhancing bioconversion effects of flocked surfaces, it was decided that this biofiltration process was not suitable for our planned future studies. Our work will continue using a trickling biofilter as our experimental bioconversion material testing methodology. This technique is much more adaptable to evaluating different biofilter media. A picture and schematic of a trickling biofilter system is presented in Figure 1. Here the biofilter media under test is placed in a chamber where water “contaminated” with ammonia is “trickled” through ammonia converting bacteria (*nitrosomonas* and *nitrobacter*) coated media. During this first year work, a trickling biofilter media test module, as shown in Figure 1, has been constructed and is now being evaluated for its water flow-through characteristics. The plan is to construct a second identical trickling biofilter device that will be used as a “control”. It is planned that these two biofilters will be operated side-by-side; one system containing the experimental biomedial, the other containing a “standard”, known-performance biofilter media. The idea here is to start both systems with identical ammonia concentrations in both tanks. The media effectiveness will be evaluated in terms of the rate and overall ability of each media material to lower the ammonia concentration in each reservoir tank, under identical processing conditions.

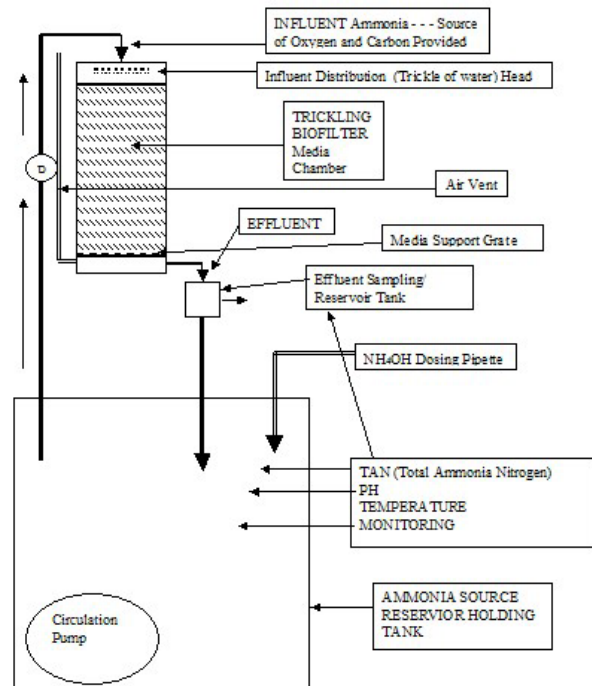


Figure 1: Recirculating Trickling Biofilter Media Testing Module and Its Operational Diagram.

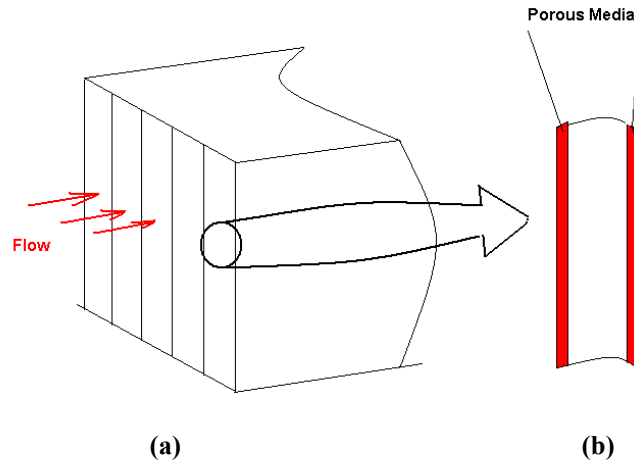
## 2. Waterborne Biofiltration Fluid Dynamics Modeling

### Nomenclature

$c_F$  = Forchheimer coefficient;  $h$  = fluid height;  $H$  = channel height;  $K$  = permeability;  $L$  = channel length;  $P$  = pressure;  $t_R$  = residence time;  $u$  = velocity;  $u_D$  = Darcian or superficial velocity;  $u_i$  = interface velocity;  $w$  = channel width;  $x$  = coordinate in the flow direction;  $y$  = coordinate normal to the flow direction;  $\mu$  = dynamic viscosity;  $\mu'$  = effective viscosity;  $\rho$  = density;  $\phi$  = porosity

### Preliminary Analysis

Consider the fluid flow in a multichannel biofilter, as shown in Figure 2, which is constructed using  $N$  parallel plates. The side of each wall is covered with a porous media.



**Figure2: Fluid flow in (a) multichannel biofilter and (b) cross section of a typical channel with porous media on the wall.**

In a typical channel, the fluid flow is modeled using the following equations [11]:

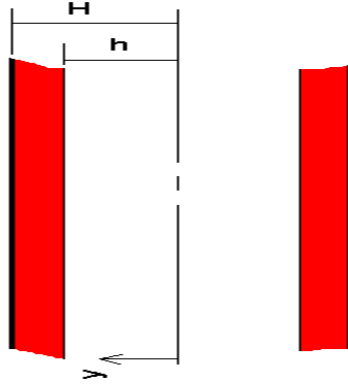
$$-\frac{dP}{dx} + \mu \frac{d^2u}{dy^2} = 0; \quad 0 \leq y \leq h \quad (1)$$

$$-\frac{dP}{dx} + \mu' \frac{d^2u}{dy^2} - \frac{\mu}{K}u - \frac{\rho c_F}{K^{1/2}}u|u| = 0; \quad h \leq y \leq H \quad (2)$$

where the geometric variables are shown in Figure 3. Integrating Eq. (1) and applying the symmetry condition

$$\frac{du(0)}{dy} = 0 \text{ at } y = 0, \text{ and the boundary condition } u(h) = u_i \text{ at } y = h \text{ yield}$$

$$u(y) - u_i = \frac{1}{2\mu} \frac{dP}{dx} (y^2 - h^2); \quad 0 \leq y \leq h \quad (3)$$



**Figure 3: Geometric configuration of a typical channel.**

Eq. (2) has no analytical solution since it is nonlinear. Thus, in lieu of this equation we will introduce the boundary condition. [12]

$$\frac{du(h)}{dy} = \frac{\alpha}{\sqrt{K}}(u_i - u_D); y = h \quad (4)$$

where  $\alpha$  is an empirical coefficient. Eqs. (3) and (4) yield the interfacial velocity

$$u_i = \frac{h\sqrt{K}}{\mu\alpha} \frac{dP}{dx} + u_D \quad (5)$$

The volume flow rate per channel is given by

$$\dot{V} = 2 \left[ \int_0^h u(y)w dy + \int_h^H u_D w dy \right] \quad (6)$$

Using Eqs. (3), (5) and (6) yield

$$\dot{V} = -\frac{2}{3\mu} \frac{dP}{dx} w h^2 \left( h - 3 \frac{\sqrt{K}}{\alpha} \right) + 2Hw u_D \quad (7)$$

The residence time is defined as

$$t_R = 2 \frac{hwL + (H - h)wL\phi}{\dot{V}} \quad (8)$$

Substituting Eq. (7) in Eq. (8) yields

$$t_R = \frac{L}{u_D} \frac{1 + \left(\frac{H}{h} - 1\right)\phi}{\frac{h^2}{3\mu u_D} \frac{dP}{dx} \left(3 \frac{\sqrt{K}}{\alpha h} - 1\right) + \frac{H}{h}} \quad (9)$$

Thus, for a given biofilter geometry, Eq. (9) shows that the residence time is a function of pressure gradient, fluid viscosity, media porosity and permeability, the superficial velocity, and the empirical coefficient.

### 3. Preparation of Experimental Biofilter Media

The constructed trickling biofilter media test apparatus (Figure 1) was designed to fit a biofilter material volume of approximately 12" x 12" x 18" high. Therefore, if an engineered textile biofiltration media is to be studied, a moderated volume of material must be stacked/packed to accommodate this volume of space in the trickling biofilter flow chamber. In this regard, a number of high surface area fabric media test sheets have to be fabricated. The orientation of these fabric panels in the trickling biofilter chamber has not yet been decided. This work is continuing.

### 4. Evaluation of Flocked Fiber Media for Airborne Biofiltration

Biofiltration is also used in air pollution control technology. Here a polluted air stream is passed through a porous and moist filter bed in which the pollutant gases are absorbed, stored and degraded by the inhabitant microorganisms. The main objective of this proposed research project is to develop criteria based on the use of flocked fiber as air-biofiltration media. Work plans are in progress in terms of:

- Determining the major parameters governing the air-biofiltration operation.
- Establish any mutual relationships
- Relate these parameters to efficiency and performance.

The ultimate purpose is to determine the efficacy of using flocked filter media in promoting the biofiltration of polluted air. Presently, the project plans to focus on the use of flocked media in either organic vapor or else H<sub>2</sub>S emission control.

### WHERE DO WE GO FROM HERE?

- (1) The trickling biofilter work will continue with the construction of a second (identical) biofilter apparatus (see Figure 1) that will serve as a "control" in our studies. Ammonia that is bio-chemically oxidized to nitrite and nitrate by *nitrosomonas* and *nitrobacter* bacteria will continue to be the biochemical process of study. Several configurations of flocked textile fibers will be prepared and evaluated in the context of determining the parameters that control the biofilter/biochemical effectiveness of flocked surfaces. Nylon and PET flock fibers will be evaluated in these studies.
- (2) The fluid flow modeling studies reported in Year 1 will continue by applying the model to the function of the trickling biofilters and flocked surfaces under study. The hydrodynamic resistance of water passing over flocked surfaces will be evaluated. The correspondence between theory and the trickling biofilter experimental results will be evaluated.
- (3) Plans for the construction of an Air-Biofiltration apparatus will be finalized and its construction will begin. The air pollutant to be studied will be determined after establishing industrial needs and the availability of bacteria to perform the desired biochemical/biofilter media reaction.

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