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MODELING AND ANALYSIS OF DEEP BED FILTRATION

Quarterly Status Report No. 9

Period Covered: February 1 – April 30, 2002

Submitted to:
Chandra Mysore
U.S. Filter / Vivendi Water Technology Center
Two Sun Court, Suite 220
Norcross, GA 30092-2841

Prepared by:
A. Amirtharajah
and S. Jeffcoat

School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0512

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Summary of the main activities:

- **Completion of initial matrix of variables**
  - The matrix of variables presented during the conference call of September 2001 has been completed. The results from sixteen experiments in the matrix of variables are now in the final steps of being compiled and analyzed. Once all of the results are completely analyzed, the macroscopic model will be used to simulate the results from the bench scale experiments. This aspect of the research should begin in the next few weeks.

- **Proceedings for the American Water Works Association Annual Conference submitted**
  - The paper entitled "Deep Bed Filtration: Analysis and Modeling" and authored by S. Jeffcoat, S. Leveau, A. Amirtharajah, and M. Chandrakanth has been submitted to the American Water Works Association for publication in the conference proceedings. Stuart Jeffcoat will be presenting the paper in the Universities Forum on June 18, 2002 in New Orleans at the conference. Attached to this quarterly report is a copy of the submitted paper.

Deep Bed Filtration: Analysis and Modeling

Stuart B. Jeffcoat
PhD Candidate
Georgia Institute of Technology
Department of Civil and Environmental Engineering
200 Bobby Dodd Way
Atlanta, GA 30332-0340

Sabine Leveau
Graduate Research Assistant
Georgia Institute of Technology
Department of Civil and Environmental Engineering
200 Bobby Dodd Way
Atlanta, GA 30332-0340

Appiah Amirtharajah
Professor
Georgia Institute of Technology
Department of Civil and Environmental Engineering
200 Bobby Dodd Way
Atlanta, GA 30332-0340

Mysore Chandrakanth
Drinking Water Programs Manager
US Filter/Vivendi
Two Sun Court, Suite 220
Norcross, Georgia 30092-2841

The validity of a macroscopic model to accurately predict the filtration cycle from ripening to breakthrough was investigated. A laboratory scale filter column containing soda lime silica glass beads was used to filter a latex particle suspension, and the data collected was used in operating the modeling program. Further, the study also endeavored to determine the significance of hydrophobic and hydrophilic forces in filtration theory. The variables in the investigation were: influent particle concentration ($4.5 * 10^5$ particles/ml and $1.35 * 10^6$ particles/ml), filter media depth (5 cm and 15 cm), filtration rate (5 m/hr and 10 m/hr), and particle type (hydrophobic and hydrophilic).

A macroscopic model was tested, through simulation and calibration. Simulation of the influence of the different parameters on the removal and headloss curves showed the interdependence of the different parameters. The detachment term and its link to headloss development added complexity to the usage of the model. The shape of the breakthrough stage was mainly determined by the detachment parameter and the headloss curve. The calibration process for the model was very sensitive to the initial parameter guesses and to the balance desired between particle removal and fitting of headloss curves. The model could be fitted to laboratory scale experiments, in well-defined conditions and with

influent close to monodispersed particles, and exhibiting only the ripening and working stage.

INTRODUCTION

Deep bed, high rate filtration is an important and essential process in the treatment of drinking water today. As regulations regarding pathogens such as *Giarda* and *Cryptosporidium* become even more stringent, the need for understanding the fundamentals of this process and being able to adequately model its performance becomes of even greater importance. Similarly, the mechanisms of particle removal during filtration must be completely understood as the potable water industry moves toward higher filtration rates. In the mid 1970s through the early 1980s, there was a gradual acceptance of filtration rates up to 4 gpm/ft^2 with conventional pretreatment rather than the traditional 2 gpm/ft^2 filtration rate. At the present time, the potable water industry is seeing filtration rates increasing to rates as high as 15 gpm/ft^2 for both production and capital cost requirements. With this trend towards ever increasing filtration rates, concerns over the effluent quality in terms of pathogen removal and other quality parameters become significant. Thus, to ensure the safe design and operation of filters, the mechanisms for filtration must be better understood and modeled.

There are three major filtration mechanisms: transport, attachment, and detachment. In terms of transport, the dominant mechanisms for removal in water treatment are diffusion and sedimentation (Amirtharajah, 1988). For particles smaller than 1 μm, diffusion results from random Brownian motion by agitation of the particle by water molecules. Particles having a larger diameter (approximately 5 μm and 25 μm) and having a significantly higher density than water are subjected to gravitational forces that might lead to collisions with the filter media. Of great significance is the fact that the minimum net removal efficiency for the transport mechanisms occurs for particles approximately 1 μm in diameter (Yao *et al.*, 1971).

The attachment mechanism is primarily a function of surface forces that lead to the capture of particles by the filter media. The types of surface forces involved in attachment include any of the following forces: electrostatic interactions, London-van der Waals forces, or surface chemical interactions (Amirtharajah, 1988). The hydrodynamic retardation of the particle as it approaches the collector requires that attractive van der Waals forces are necessary to bring the particle in contact with the collector. Recent developments (Raveendran and Amirtharajah, 1995; Bergendahl and Gresso, 1999) suggest that short-range forces that are hydrophobic or hydrophilic in nature need to be considered in filtration theory.

The detachment of particles is not a well-understood phenomenon, and its analysis is complex. The work of Payatakes *et al.* (1981) and Ives (1989) noted clusters of particles being detached from the filter media during filtration experiments. The detached clusters of particles reentered the bulk fluid. The detachment mechanism can occur for numerous reasons, such as hydrodynamic shear forces on attached flocs and from changes in filtration rates or chemical conditions (Moran *et al.*, 1993).

EXPERIMENTAL METHODS

Laboratory scale experiments were conducted using a plexiglass filtration column. The column had an inner diameter of 1.5 inches and stands 13.8 inches high. The column had pressure ports located at depths of 5 cm, 15 cm, and 25 cm to allow for measurements of the differential pressure through the filter media. The filter media used in the study was soda lime silica glass beads with diameters between 430 μm and 600 μm. Soda lime silica glass beads are commonly used in laboratory scale filtration studies (Raveendran, 1995; Mahmood, 1996). The glass bead filter media were packed such that the porosity is approximately 0.4.

A latex particle suspension was used in the research. Previous studies have demonstrated their usefulness in filtration studies (Darby, 1988; Tobiason, 1987; Raveendraan, 1995; Bergandhal, 1999). Latex (polystyrene) particles are commercially available in various sizes, surface characteristics, and colors. Latex particles are naturally hydrophobic, but the presence of surface groups can alter this property. Both hydrophobic and hydrophilic particles were used in the study. The hydrophilic particles have surfaces modified with carboxylate to provide this characteristic. Sulfate groups are present on the surface of the hydrophobic particles that were used in this study. The average particle diameter in the suspension was 2.9 microns, which is the size range for the least efficient removal of particles during filtration. In order to destabilize the particles so that they could be filtered, the suspension ionic strength was increased via addition of a concentrated $CaCl_2$ suspension that compressed the double layer surrounding the particles.

At specified intervals during the course of each filter run, effluent samples were taken and analyzed for turbidity, conductivity, and particle counting. In addition, the headloss was prior to effluent sampling recorded using the differential pressure gage at the same time the effluent sampling is performed. After analyzing the samples, the data generated was then used in the macroscopic computer model to model the filtration cycle.

An overall schematic of the laboratory scale filtration system is presented in Figure 1.

RESULTS AND DISCUSSION

Experiments were conducted using various combinations of the variables previously mentioned. The data generated from each of the experiments were used in the macroscopic model. When observing the effluent characteristics, several points must be considered. The conductivity of the effluent was measured as a control parameter. At a conductivity of approximately 8.1 to 8.5 mS/cm, the zeta potential of the filtered water was close enough to zero to ensure adequate destabilization of the latex particles in the influent. Secondly, in all experiments, the headloss increased linearly over the course of the filter run. One of the important results from the effluent sampling and the headloss monitoring was that the linear headloss increase when filtering hydrophilic particles

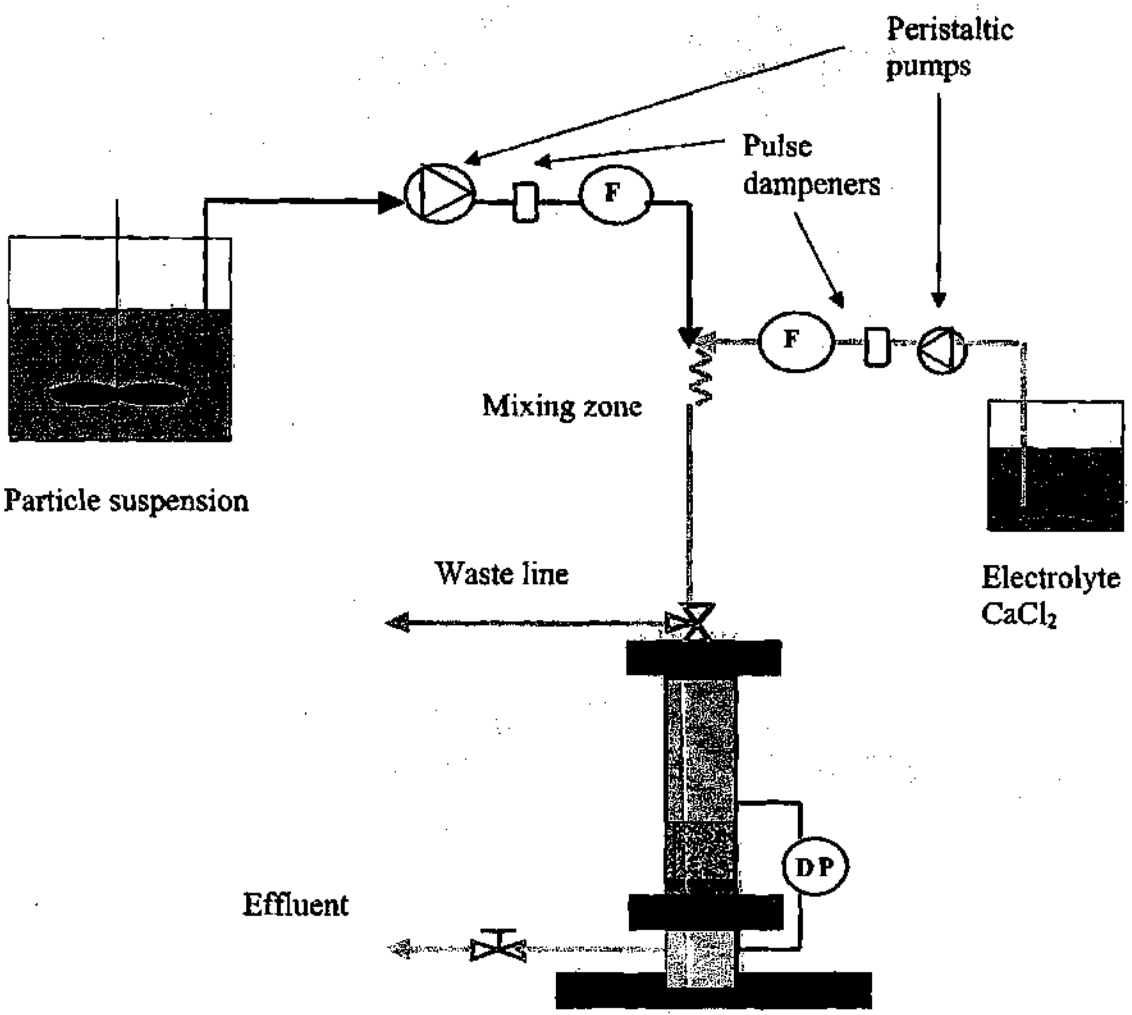


Figure 1: Filtration System Schematic

occurred at a much slower rate than the headloss increased when the hydrophobic particles were filtered. The total increase in headloss over the filter run using hydrophilic particles was never more than 0.2 inches, while the total headloss increase for the filter runs using hydrophobic particles was on the order of more than an inch. Further, it should be noted breakthrough was not achieved in all experiments. Breakthrough was only achieved during the experiments when the 10 m/hr filtration rate was used in conjunction with the 5 cm filter media and also in some experiments using hydrophilic particles. Examples of the typical effluent and headloss data generated during a filter run are found in Figures 2 and 3.

The macroscopic model was able to be fit laboratory scale experiments for the ripening and working stages of the filtration cycle. Breakthrough was only observed in a few of the laboratory scale experiments so the model was not able to adequately to fit beyond the working stage of the filtration cycle. Figure 4 illustrates the modeling results for the

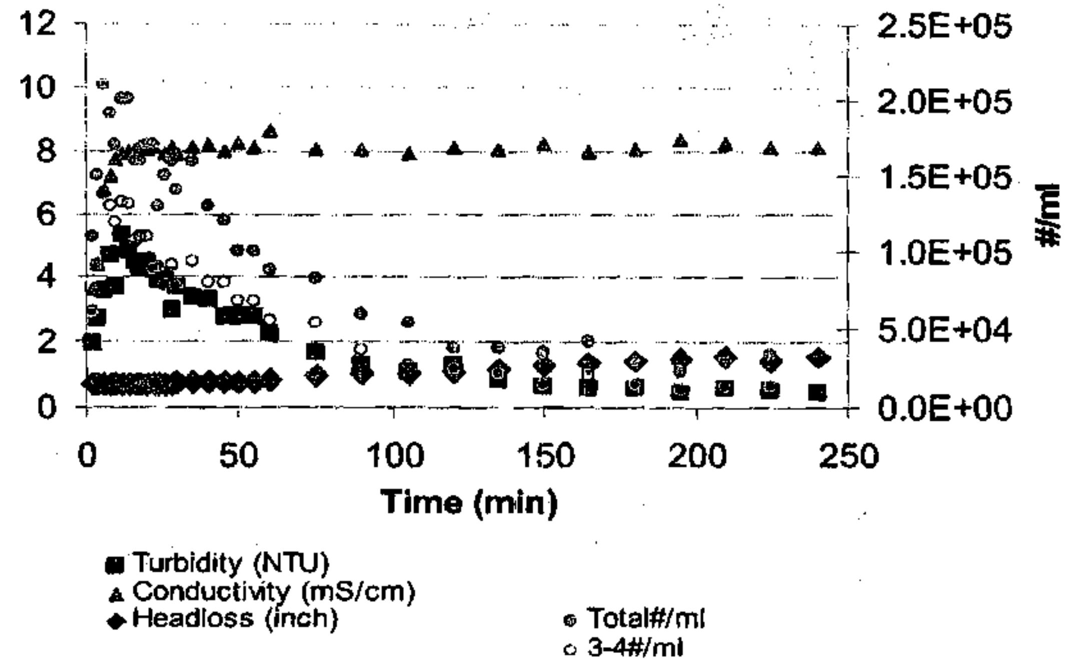


Figure 2: Effluent Characteristics and Headloss Evolution for 5 cm filter depth, 5 m/hr filtration rate, hydrophobic particles, and 4.5 * 10^5 particles/ml

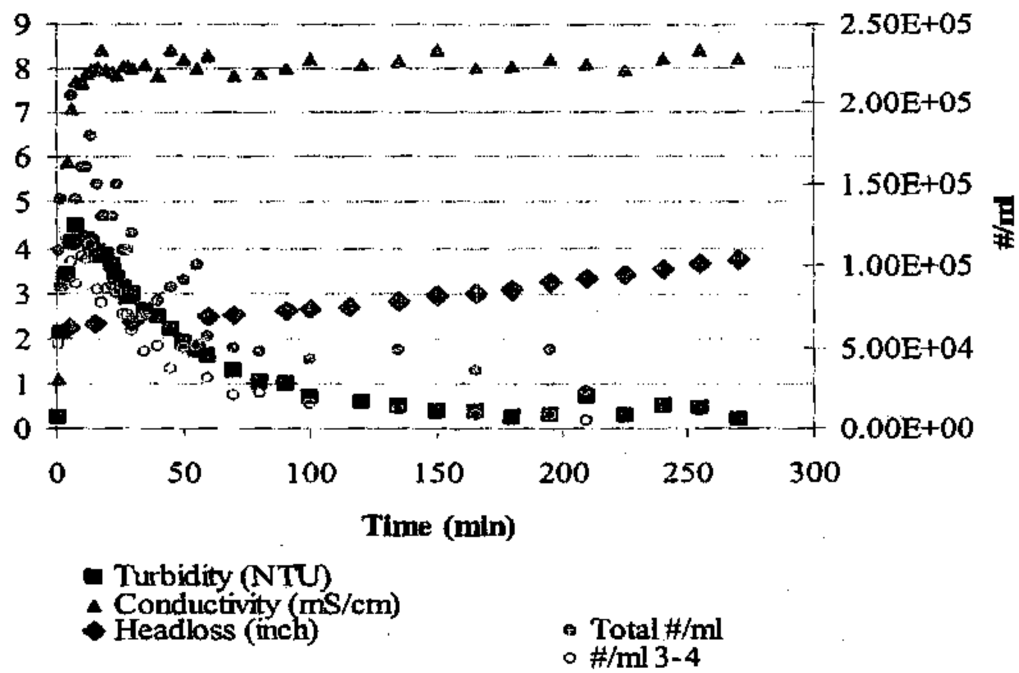


Figure 3: Effluent characteristics and Headloss evolution 15 cm media depth, 5 m/hr, hydrophobic particles, 4.5 * 10^5 particles/ml

same conditions as found in the experimental results presented in Figures 2 and 3.

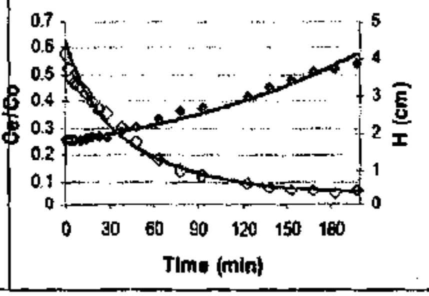
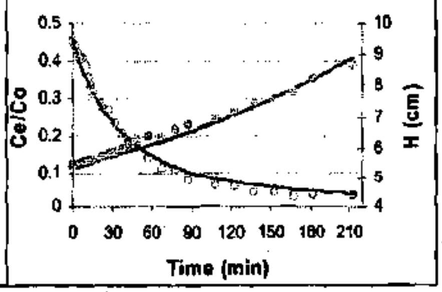
:	Media Depth: 5 cm	Media Depth: 15 cm
Initial removal, $\alpha\eta_o$	5.21 E-3	2.944 E-3
Ripening, $\beta\alpha_p\eta_p$	0.307	0.182
Detachment, β_2	0.00	0.00
Headloss, β'	0.748	1.18
R^2 average	0.974 (Fact=10)	0.983 (Fact=10, no constraint on β')
		

Figure 4: Modeling Results for Experimental Runs with 5 and 15 cm Media Depth

When analyzing the results from the modeling of the data generated during the experimental runs, several issues must be addressed. The headloss coefficient, β', corresponds to the fraction of the particle surface area that contributes to headloss increase. In the 15 cm filter media depth case for the operating conditions 5 m/hr filtration rate, hydrophobic particles, and $4.5 * 10^5$ particles/ml, the headloss coefficient slightly greater than one was used. While using a value larger than one for the headloss coefficient might bring about questions to the validity of the model, Darby (1988) suggested that pore blockage might be the cause of an increased headloss compared to considering only the surface area.

Another important aspect of the modeling results is the detachment parameter. In both sets of modeling results provided, the detachment coefficient used was zero in order to obtain the best fit with the experimental results. While neglecting detachment seems to be in conflict with filtration theory, it should be noted that the only the ripening and working stages of filtration are being modeled. Breakthrough has not yet been achieved. Therefore, the results imply that detachment is not an important parameter in the early stages of the filtration cycle, but it is important during breakthrough.

The initial removal coefficient, $\alpha\eta_o$, is another important factor in the modeling of the experimental data. The choice of the initial removal value bears some uncertainty as it coincides with the initial transient stage in which the influent goes through the filter and is diluted with liquid remnants in the column. The initial removal is determined by multiplying the collision efficiency and the overall collector efficiency for a single collector, where the collision efficiency is taken to be 1.0 since the particles are considered to be perfectly destabilized.

CONCLUSIONS

The results of the investigation successfully demonstrate the efficacy of a macroscopic model in fitting experimental data. The macroscopic model is capable of accurately fitting experimental results under controlled conditions. The results also indicate the significance of the detachment parameter and at what stage of the filtration cycle it becomes important. When modeling the ripening and working stages of filtration, the best results were obtained by neglecting the detachment mechanisms, indicating that its primary usefulness in filtration theory is during the detachment phase. The experimental results also demonstrate the importance of hydrophobic and hydrophilic effects and suggest that they are a significant short-range force that should be included in filtration theory and thus, filtration modeling.

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