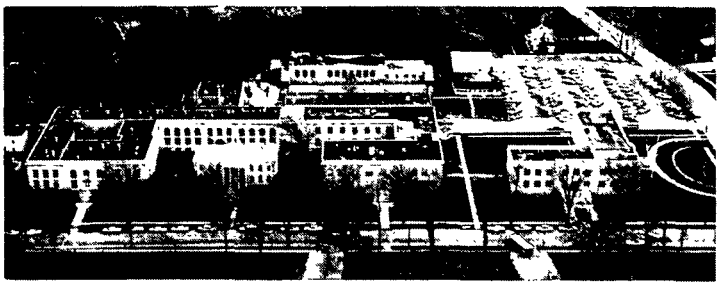

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RETENTION DYNAMICS FOR SMALL PARTICLES ON CYLINDRICAL FIBERS. II. EXPERIMENTAL VERIFICATION OF A MODEL SIMULATING PARTICLE RETENTION

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Retention dynamics for small particles on cylindrical fibers. II. Experimental verification of a model simulating particle retention

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KEYWORDS:

INTRODUCTION: To accompany a study of the retention of small, spherical particles on cylindrical fibers (1), as described by a mathematical model (with which the effects of various interactions between particle and fiber were considered), we have completed an experimental program from which collection efficiency values could be obtained and compared with those predicted.

The experimental program involved a permeation procedure to measure the retention obtained when a dilute suspension of small particles is passed through a preformed bed of synthetic fibers. The fiber pad was then sectioned into layers and each layer analyzed for the mass of retained particles. The result of this procedure was a profile of particle distribution over pad thickness. The profile was then used to calculate a value of collection efficiency for comparison with model predictions.

We used titanium dioxide particles and nylon fibers. We were guided by procedures and results obtained by several other investigators who studied particle retention within porous media composed of synthetic or natural fibers. Johnson (2) studied retention within a pad of nylon fibers, whereas Han (3) and Han and Chang (4) utilized dacron fibers and studied the retention of fines as well as particles. Miller (5) investigated the retention of titanium dioxide

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on bleached sulfite pulp fibers. Such fibers were not considered for use in the present study because of their irregular shape and compressibility. Williams and Swanson (6) studied the filtration of a suspension composed of bleached kraft fibers, fines, and titanium dioxide. They discovered that colloidal effects were a major factor in the retention of this type of particulate matter, and that significant collection occurred prior to filtration. This indicated that, for the present study, the pad would have to be formed before a separate particle suspension was passed through it.

Experimental program

Materials

The materials used in the permeation procedure conformed to assumptions made in the development of the model. For example, the fibers had to be circular in cross section, and their surfaces had to be very smooth. It was also desirable that these fibers be easy to disperse in water and when dispersed, swell very little. We chose a quarter-inch long 3 denier (20 μm) nylon staple fiber. Ash content of the fiber was approximately 0.3%. Fig. 1 is a scanning electron micrograph of several fibers. It is shown that the surface is very smooth. Other evidence indicated that the fibers were fairly uniform in size and their cross section was circular.

The use of titanium dioxide for the particulate component was appropriate for a variety of reasons. First of all, there have been several investigations on the use of this pigment in filtration or permeation processes applicable to the paper industry. Second, titanium dioxide particles generally fall within a small size range, and they are nearly spherical in shape. A dispersion of these particles can be stabilized easily, requiring only a small amount of dispersant. A commercial grade of titanium dioxide (Titanox RA50) was dispersed in distilled water with Calgon as the dispersant. The solids content was

maintained at 30%. Storage in a continually rotating container allowed the use of the original suspension over a time span of several months, with no apparent decrease in stability. An analysis of particle size within the dispersion indicated that the distribution was narrow, and the large majority of particles had diameters between 0.2 and 0.3 μm.

Previous investigations have shown water quality to be important in any type of filtration or permeation procedure. Unwanted ions in either the fiber or particle suspensions could impair the stability of the dispersions and reduce retention. The water used in the present study was freshly deionized and distilled. The result was water with a pH of approximately 7.0 and a conductivity less than 0.2 μmhos/cm.

Procedures

A diagram of the apparatus is given in fig. 2. Freshly distilled water was transferred from the storage tank (A) to a Teflon-lined mixing tank (B) where separate fiber and particle suspensions were prepared. Either suspension was then gravity fed to a Lucite flow tube (C). [The cross-sectional area of this tube was 45.6 cm^2.] The fiber pad was formed within this tube by filtration. The filtrate was pumped from the bottom of the tube at differing flow rates by a variable speed pump (F). Measurement and control of the flow rate was accomplished by a rotameter (E). The fibers were filtered from suspension onto a 35-mesh stainless steel wire. The support (H) for this screen was made from a half-inch thick stainless steel plate. The plate was drilled with quarter-inch holes on five-sixteenth-inch centers in an equilateral triangular pattern. All holes were countersunk to insure a minimum of plate area perpendicular to the flow field which could cause unwanted channelling within the fiber pad.

The procedure used in forming the fiber pad began by deaerating, in vacuo, 10 grams of oven-dried fibers which were dispersed in a liter of boiling water. This suspension was added to 100 liters of distilled water in the mix tank, and the pH and ion concentration were adjusted to the desired level with hydrochloric acid and ammonium chloride. The most common conditions used in the study were a pH of 5.0 and a salt concentration of 0.02 mole/liter. The suspension was pumped through the flow tube, and the pad was formed on the wire. This was done at a low superficial velocity, generally 1.0 cm/sec, to insure that the majority of fibers in the pad would be oriented perpendicular to flow direction. Once the entire suspension had been passed through the tube, the unused fibers were collected, dried, and weighed. This permitted calculation of an accurate weight of fiber in the pad. By knowing this weight and pad thickness, the porosity of the pad was obtained.

After the pad was formed, it had to be compressed to provide the desired porosity for permeation. This was accomplished with a permeable piston arrangement which could be lowered into the flow tube and be forced down onto the fiber pad with hydraulic pressure. The piston was constructed from a half-inch plate of stainless steel, drilled with holes in the same pattern as that mentioned above for the screen support. Both upstream and downstream faces of the piston were countersunk to prevent channelling. Also, the downstream face was covered by a wire screen to prevent fibers from being forced up into the holes. Once the pad was compressed to the desired thickness, the piston was locked into place and kept at this position throughout the permeation procedure. This insured that porosity remained constant during the run.

In the next step, another 100 liters of distilled water were transferred to the mix tank. Approximately 1.5 grams of titanium dioxide, based on the solids content of the stock suspension, was added to the water. Also, the proper

amount of salt and acid were added to provide the correct ionic conditions. This particle suspension was pumped through the fiber pad at a controlled flow rate. At the end of the run, the air-water interface was pulled slowly through the pad to insure that no particles were removed due to surface tension effects.

After permeation of the particle suspension was completed, the fiber pad was carefully removed from the flow tube assembly. By using dissecting needles, we could separate the pad into several layers. This was easy because most of the fibers in the pad were oriented in the X-Y plane due to the slow formation velocity and, in addition, there was no interfiber bonding. The layers were weighed and dried overnight at 105°C. The weight of each dry layer was obtained, and all layers were ashed in a muffle furnace. Slow ashing (7) prevented loss of retained pigment during the decomposition of the nylon. The residue of this ashing procedure would be, essentially, the titanium dioxide retained by the fiber layer. A small correction allowed for the amount of ash found in the fiber itself.

Results and discussion

The above procedures gave us the amount of fiber and pigment in each layer of the pad. These have been the values utilized in calculating and analyzing the results of the permeation procedure. Of primary importance is the fact that significant retention was obtained with this type of system. Fig. 3 substantiates this observation. The micrograph depicts several fibers removed from a typical pad after permeation. As shown, there are many particles attached to the surface. It should be noted that this is not intended to be a quantitative measure of retention, because the fibers shown here were dried and jostled, which removed some particles. The photographs do show that retention is occurring.

Definition of effective fiber collection efficiency

There is probably no good experimental procedure available for determining the amount of titanium dioxide retained by a single fiber embedded within a pad. The method used for calculating collection efficiency in the present investigation has been to relate entrance and exit particle concentrations to an empirical definition of collection by a single fiber. Such a procedure was first proposed by Wong (8), and a detailed description of the procedure is presented elsewhere (7).

In essence, the efficiency can be defined as the ratio of the area of suspension flow from which all particles are removed through collision with the fiber, to the projected area of the fiber perpendicular to the flow stream. From this definition, and from a previous discussion (1), it is evident that the definitions of experimental and theoretical collection efficiencies are comparable. This comparison was necessary for investigating the relevance of the mathematical model developed for the simplified retention process.

In terms of system variables, the experimental efficiency can be written as a function of the entrance, C_o, and exit, C_h, particle concentrations around the whole pad or an individual layer:

$$\eta_e = \frac{D_f \pi}{4(1 - \varepsilon)h} \ln (C_o/C_h), \qquad (1)$$

where ε is the porosity of the pad, D_f is the fiber diameter, and h is the thickness of the pad or layer. This definition is dependent on the assumption that the fiber pad is uniform throughout its thickness. By also assuming a monodisperse distribution of particle size and no fractionation of the particles during permeation, we can relate the efficiency to particle mass rather than concentration:

$$\eta_e = \frac{D_f \pi}{4(1 - \varepsilon)h} \ln (M_o/M_h) \qquad (2)$$

Since the pad is compressed during permeation, the porosity is constant through pad thickness; and since the fibers are nylon, they are rigid enough not to deform. If the porosity is constant, then the collection efficiency is constant through the pad.

If the collection efficiency is constant, a plot of ln (M_o/M_h) versus h representing each layer of the pad should be a straight line passing through the origin. The value of η_e could then be calculated from the slope of the line. It was impractical to measure the thickness of individual fiber layers, but porosity was constant, and pad thickness was directly proportional to accumulated pad weight. A plot of the logarithm term versus the accumulated weight would also yield a straight line from which the efficiency could be calculated.

Fig. 4 represents a diagram of this kind for a typical permeation trial. The data points represent individual layers, with the top layer on the left. The data fall on a straight line, and from the slope, the efficiency is calculated to be $\eta_e = 0.007$. The straight line correlation indicates that collection efficiency is constant through pad thickness.

Effect of system conditions on efficiency

Table 1 shows values for efficiency calculated from experimental data. With the process used, there were three system variables that could be studied. These were porosity, approach velocity, and the ionic conditions of the suspension.

The porosity, defined as the fractional volume within the pad available for fluid flow, was calculated from the total flow area, fiber density, and pad

thickness. The efficiency values given in table 1 indicate that retention increases as porosity decreases. Decreasing the porosity means that the void volume within the pad is reduced, effectively placing more particles in a smaller volume. For this reason, an increased number of particles would be situated close enough to the fiber's surface to be influenced by particle transport mechanisms and surface attractive forces which would lead to collision and retention. Thus an increased number of particles would be retained.

The approach velocity of the particle suspension was controlled by the magnitude of the flow rate through the pad. All flow rates were representative of Reynolds numbers below one, based on fiber diameter. It has been shown that collection efficiency decreases as the velocity increases. At the faster velocities, particles would have less time to be influenced by any forces active in the system. This would indicate that a particle which would be affected, and probably retained, if sufficient exposure to these forces were available, would instead pass through the pad uncollected, thereby decreasing the efficiency.

The ionic conditions of the particle suspension are important in retention. In the nylon-titanium dioxide system used in this study, both components were thought to possess a negative surface charge when immersed in water. The addition of hydrochloric acid to the suspension would reduce this charge by adsorption of hydrogen ions. In addition, the double layers surrounding the solid components would be collapsed by the addition of an electrolyte. Several of the permeation trials were conducted with differing ionic conditions, and these are listed among the tabulated values. Omission of the salt, ammonium chloride, caused a slight decrease in collection efficiency. This effect can be explained by the stronger repulsive effect of the uncollapsed double layers,

which would permit fewer particles to reach the fiber surface. A much more drastic effect is indicated when no additions are made to the suspension. In this case, the repulsive potential between the particle and fiber would be unchecked, and the repulsion would dominate the attractive molecular forces, permitting no significant retention. These observations led to the conclusion that the degree of retention in this system is highly dependent on the pH of the particle suspension.

Comparison of experimental and predicted efficiencies

Table 2 shows predicted (η_p) and experimental (η_e) collection efficiencies obtained in this investigation. Agreement between the two efficiency values is quite good, supporting the conclusion that the model is appropriate and that it furnishes a satisfactory first approximation as to the retention occurring in a simplified retention system. We may note that the trends shown in the table, representing the effect of various system parameters on efficiency, are the same for both the experimental and predicted results. These include the observations that efficiency decreases with increasing porosity, increasing approach velocity of the suspension, and decreasing suspension ionic concentration. Results of both phases of the work indicate negligible retention will be obtained when no chemical additives were used to control the ionic strength of the suspension.

The differences in collection efficiency values between the experimental and predicted results are fairly consistent, and the experimental values are, in general, slightly lower than the predicted ones. There are several possible explanations for this. One of the most obvious is that, in the experimental system, there could be some removal of particles that had been initially retained by the fiber. This form of particle removal was studied by

passing a volume of water, conditioned to comparable ionic strength, through the pad at a slow flow rate subsequent to the permeation procedure. Some removal was noted, but it was not more than 10% of the amount of particles initially retained. It was felt that this amount was not sufficient to explain the variations between most values in table 2. However, we should also account for particles removed during the permeation procedure itself. In comparison, the mathematical model was not programmed to consider particle removal.

Overprediction of collection efficiencies could be the result of an increased boundary layer existing on the downstream side of the fiber. The creeping motion equations used as a basis for fluid flow in the model (1) are valid only when the Reynolds number vanishes. In this case, the equations would be linear; thus, there would be symmetry of flow between the upstream and downstream faces of the fiber. In other words, the boundary layer around the fiber would be symmetrical. At finite velocities, even at Reynolds numbers below one, this symmetry is lost. The result would be a larger boundary layer on the downstream face of the fiber. For this reason, fewer particles than predicted would be able to cross this barrier to impact on the fiber surface. Neglecting this effect could possibly lead to an overprediction of collection efficiency.

There could be other explanations for discrepancies between the efficiencies. For example, the particle size of the titanium dioxide used in this study was found to be in the range of 0.2 to 0.3 μm. The value employed in the model was 0.3 μm. It has been shown (1) that the model predicts a decrease in efficiency with a decrease in particle size. Therefore, if there is a substantial population of particles with a diameter less than 0.3 μm, the model would predict a larger efficiency than is actually applicable. A final consideration to be noted concerning the overprediction of the model would be the effect of flow perturbations within the fiber pad during permeation. Even though the flow

rates were low, some irregularities in flow patterns could develop due to varying fiber orientations. Although unlikely, there also could be some channelling of the flow through the pad. Such effects might cause variations in particle motion which would lead to decreases in particle retention.

Summary

An experimental program provided retention data for comparison with results obtained from a mathematical model. The comparison has shown that the model performs adequately and yields relevant predictions of retention in a relatively simple system. It was shown that the model can predict various trends in collection efficiency influenced by changes in system parameters. Both the model and experimentation indicated that retention would decrease with increasing porosity, increasing approach velocity, and decreasing ionic strength of the particle suspension. Differences between predicted and measured values were thought to be the result of particle removal during permeation and flow perturbations within the fiber pad.

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Table 1. Effective fiber collection efficiencies

Porosity	Velocity (cm/sec)	Ionic conditions of suspension	Efficiency (η_e)
0.85	1.50	Salt/acid	0.0045
0.75	1.50	Salt/acid	0.0052
	1.00	Salt/acid	0.0070
	1.00	Acid	0.0059
	1.00	None	0.0008

Table 2. Comparison of theoretical and experimental collection efficiencies

Porosity	Velocity	Ionic conditions of suspension	Efficiency	
			η_e	η_p (d = 0.3 m)
0.85	1.50	Salt/acid	0.0045	0.0064
	1.00	Salt/acid	0.0069	0.0068
0.75	1.50	Salt/acid	0.0052	0.0093
	1.00	Salt/acid	0.0070	0.0103
	1.00	None	0.0008	Negligible

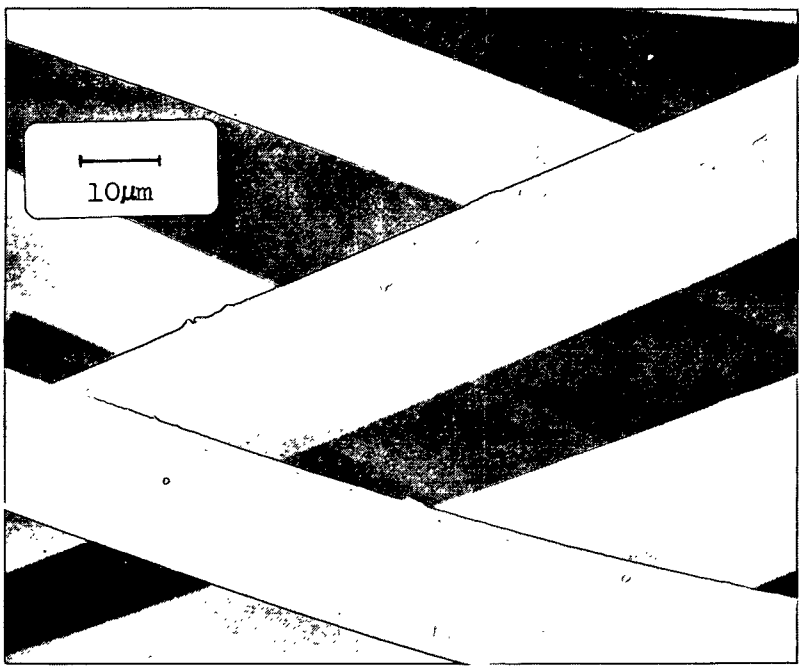


Fig. 1. Nylon fibers

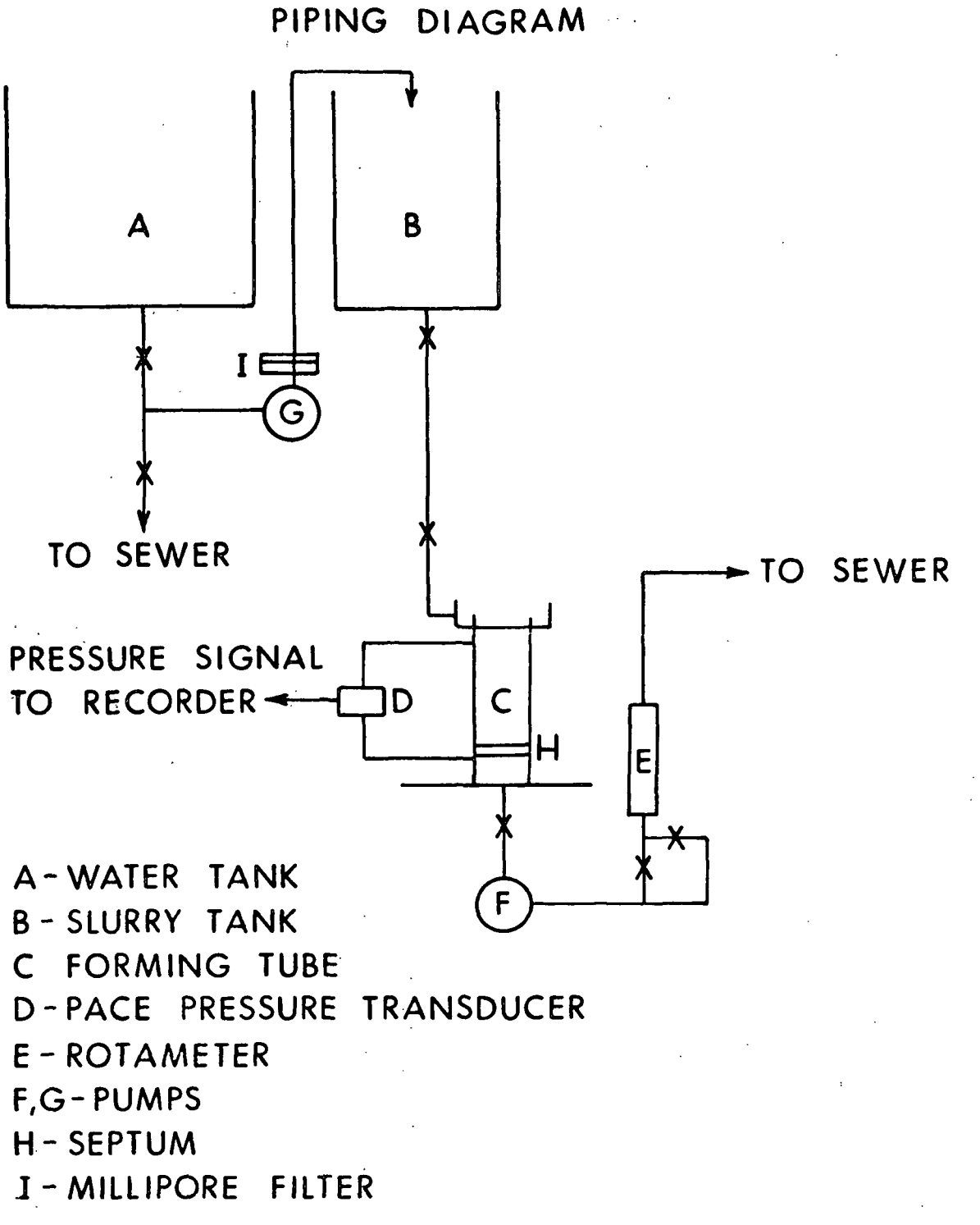
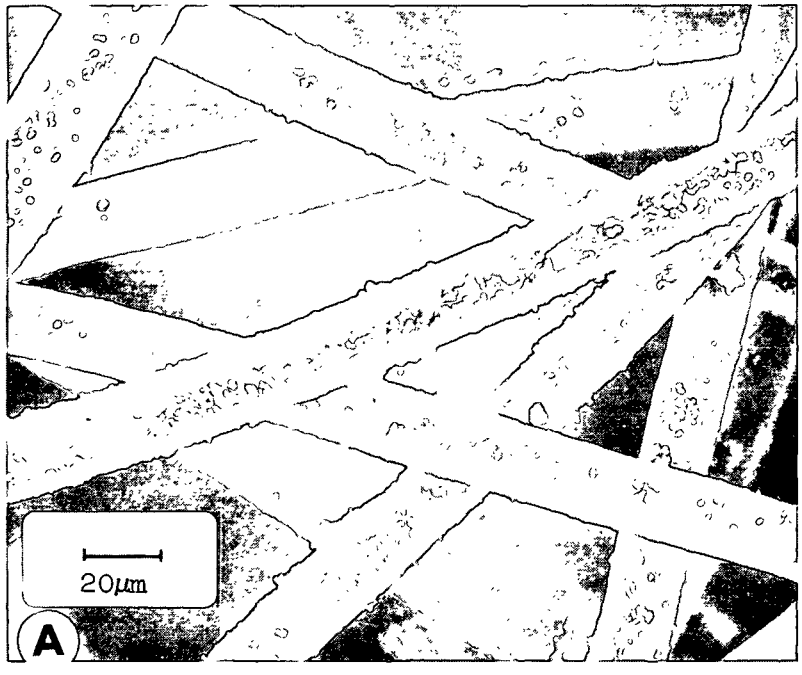
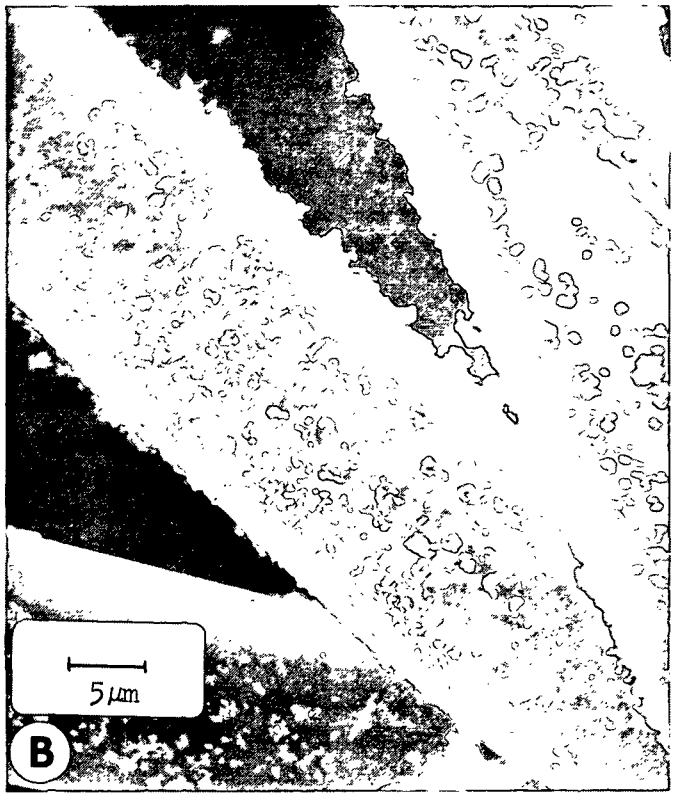


Fig. 2. Experimental apparatus





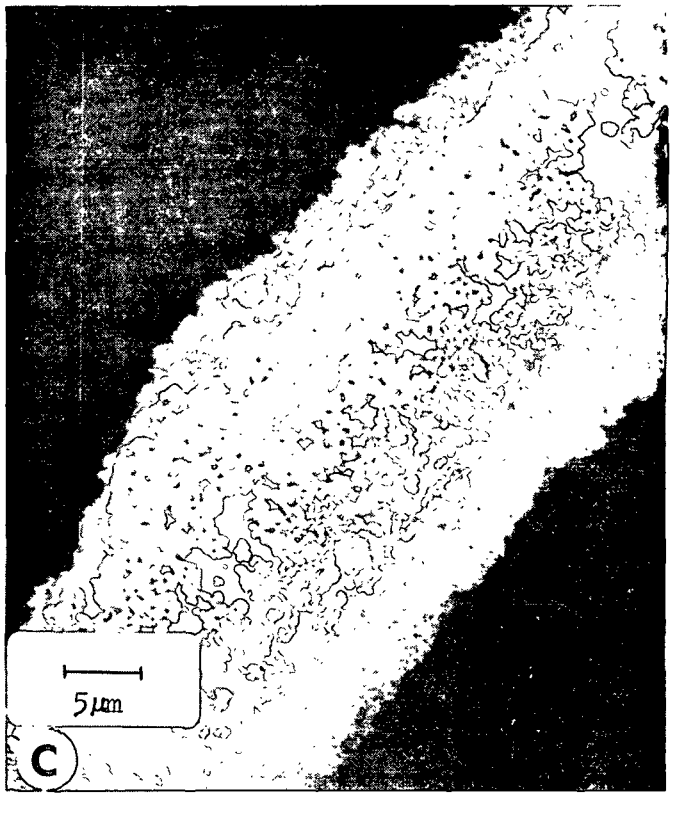


Fig. 3. Titanium dioxide retained on fiber surface

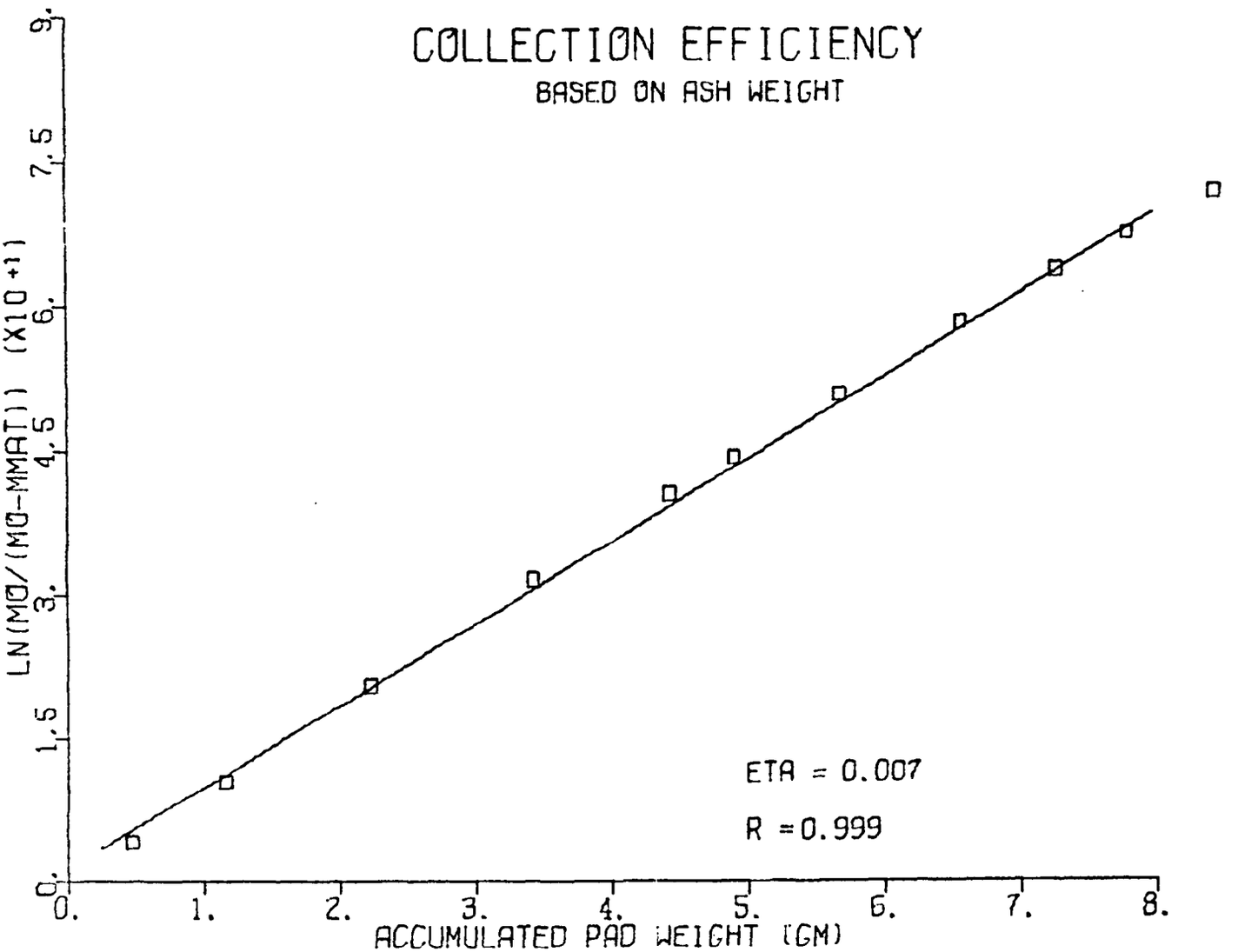


Fig. 4. Calculation of collection efficiency