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Research Article

Drag Reduction of Bacterial Cellulose Suspensions

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Drag reduction due to bacterial cellulose suspensions with small environmental loading was investigated. Experiments were carried out by measuring the pressure drop in pipe flow. It was found that bacterial cellulose suspensions give rise to drag reduction in the turbulent flow range. We observed a maximum drag reduction ratio of 11% and found that it increased with the concentration of the bacterial cellulose suspension. However, the drag reduction effect decreased in the presence of mechanical shear.

1. Introduction

In order to resolve various environmental issues, numerous investigations are currently focusing on energy conservation techniques. One topic of particular interest is drag reduction in heat transport systems. The addition of drag reducing agents leads to reduced frictional loss, and a corresponding reduction in pumping power, and results in effective energy conservation [1].

Additives such as polymers, surfactants, and fibers are well-known drag reducing agents and offer a simple means of reducing drag. Since Toms [2] observed drag reduction with the addition of polymers in 1949, numerous investigations into drag reducing agents under various conditions have been carried out. Among these, surfactants [3–5] have been researched intensively due to their effectiveness and low mechanical degradation. However, as most of these additives are synthetic chemicals, they contaminate rivers and soil when solutions are drained directly, and therefore require careful disposal. Although biopolymers [6–8] are not subject to such disposal issues, they are not practical due to their significant mechanical degradation. On the other hand, fibers [9–11] such as asbestos or nylon are resistant to mechanical degradation but have a disadvantage with regard to environmental load, while pulp, which is a plant-based fiber, requires high concentrations to achieve drag reduction effects.

Bacterial cellulose, a type of fiber, is considered to have a low environmental load, as it is a naturally derived cellulose produced by acetic bacteria. In addition, nanometer-scale fibers of bacterial cellulose produce large networks as a result of complex interactions. Such networks are closely related to the drag reduction effects induced by polymers and surfactants. Therefore, drag reduction can also be expected with bacterial cellulose solutions if their networks behave similarly.

In the present study, the drag reduction effects of such bacterial cellulose solutions are empirically evaluated.

2. Experimental Setup and Procedure

The syringe pump experimental setup is shown in Figure 1. The piston operates in a range from 10 to 15 mm/s, and the volume of the syringe is 200 mL. The velocity of the piston is controlled by a personal computer. The range of Reynolds numbers based on the viscosity of the solvent solution is about 500∼8,000. The test pipe is made of aluminum, having an inner diameter of 2.00 mm and a smooth internal wall. The inner diameter of the pipe was measured in cross-section using an optical microscope. Pressure taps with diameters of 0.2 mm were placed 50 mm and 150 mm from the outlet of the pipe. The length of the test section was 100 mm. The pressure taps were connected to a Validyne differential pressure transducer (DP15, ±0.25% F. S. accuracy) using clear vinyl tubing. The entrance length was 150 mm. The suspension was first taken up by the syringe and was then pushed into the test section by the piston, after which the pressure drop was measured. The reported value of the

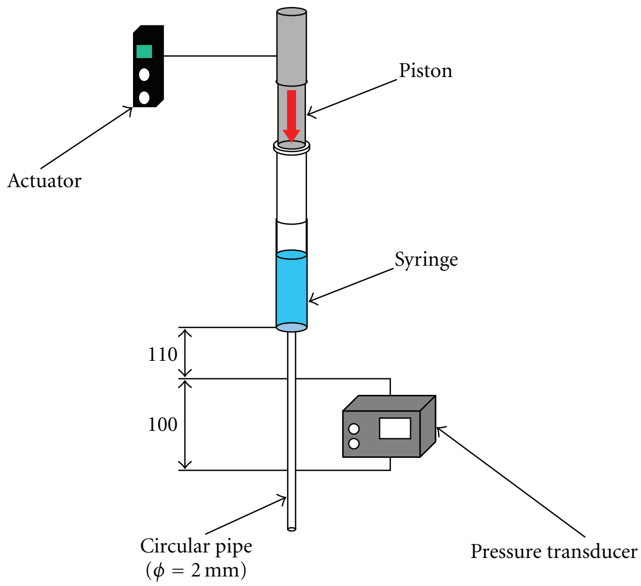


Figure 1: Experimental apparatus.

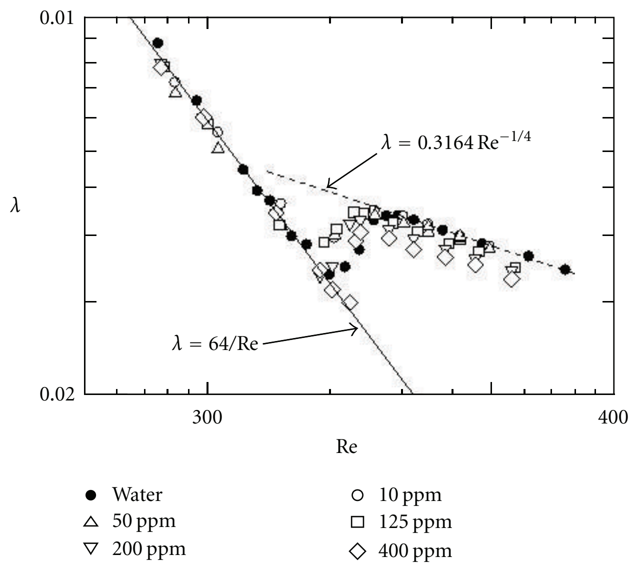


Figure 3: Frictional coefficient of bacterial cellulose suspensions.

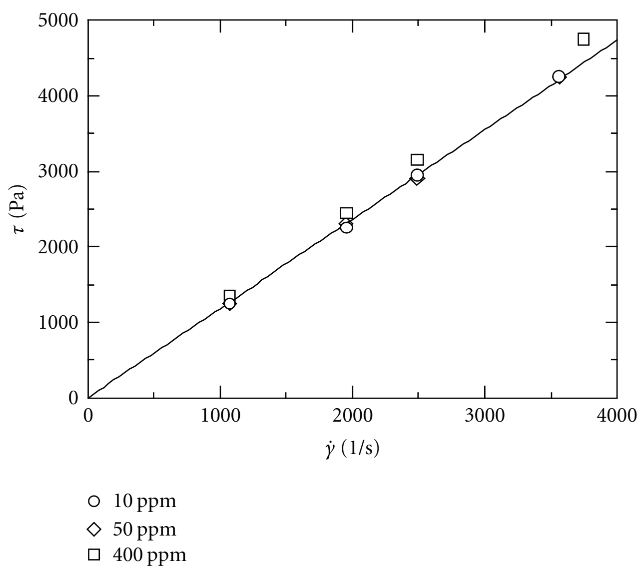


Figure 2: Flow curves for test fluids.

friction factor in the laminar flow range is the best estimate of the result, and with a 95% confidence limit, the value is believed to lie within $\pm 0.89\%$ of it.

The bacterial cellulose additive was made from commercial nata de coco. Since this is preserved in syrup, that is, contains sugar, it was soaked in tap water for over 24 hours in order to dilute the sugar before preparation of the suspension. The desugared nata de coco was then compressed under a load of ~1 ton in order to extract the water (a block of nata de coco contains 99% water and less than 1% bacterial cellulose by volume) and to obtain dried bacterial cellulose. Following compression, the mass of the nata de coco was found to be 0.25% of the original mass. The additive was then mixed with tap water and agitated with a mixer. The weight concentration of the suspension, C_w, was determined based on the mass ratio of compressed nata de coco and tap water. Concentrations of 10, 50, 125, 200, and 400 ppm were examined. In addition, solutions made using the additive before compression were prepared and examined for comparison. Their concentrations were 5, 7.5, and 10 ppm, based on the mass after compression.

Figure 2 shows the flow curves for the tested bacterial cellulose suspensions. The wall shear stress τ and shear rate $\dot{\gamma}$ were calculated from the experimental data in the laminar flow region. The solid line in Figure 2 indicates the value obtained by the viscosity of water. The viscosity is seen to increase with concentration, and the test tested bacterial cellulose suspensions are considered to be Newtonian. The values in Figure 2 were used to calculate the Reynolds number.

3. Results and Discussion

Figure 3 shows the relationship between the Reynolds number Re and the friction factor λ, based on the measured pressure drops for 5 suspensions (10, 50, 125, 200, and 400 ppm). The data show that λ in the region of Re >2500 for the suspension decreases in comparison to the value for water. On the other hand, the critical Reynolds numbers for suspensions with concentrations less than 200 ppm are smaller than that of water.

For biopolymers, the results may be affected by the solvent. As the solution used in this experiment was also of plant origin, experiments with different solvents (distilled water and tap water) were performed, and the results are shown in Figure 4. It can be seen that the experimental results with the two solvents are very similar, and thus the influence of the solvent is negligible.

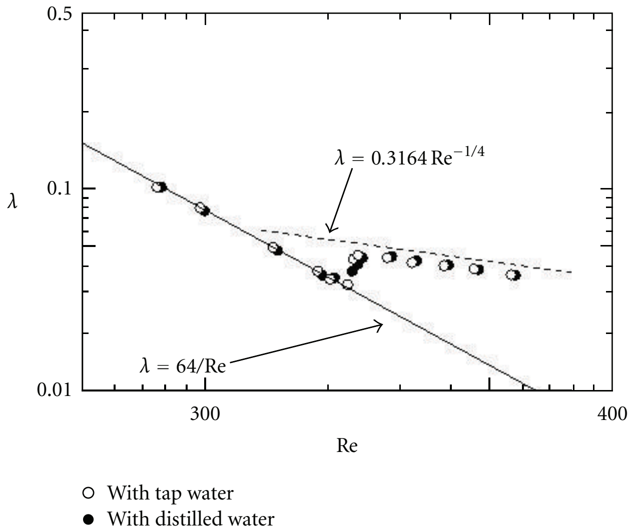


Figure 4: Effects of solvent on frictional coefficient.

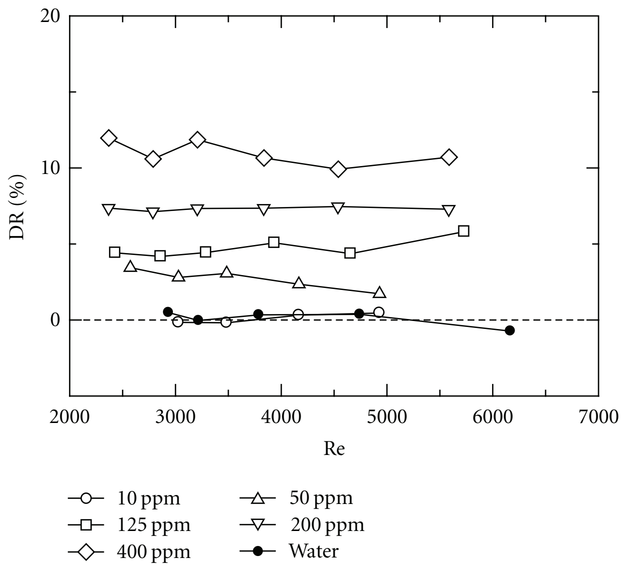


Figure 5: Drag reduction of bacterial cellulose suspensions.

The relationship between the drag reduction DR, which is defined by (1), and the Reynolds number Re is shown in Figure 5:

$$\mathrm{DR}\ (\%) = \frac{\lambda_{\mathrm{water}} - \lambda_{\mathrm{suspension}}}{\lambda_{\mathrm{water}}} \times 100. \qquad (1)$$

In (1), λ_{water} and $\lambda_{\mathrm{suspension}}$ denote the friction factor for the water and suspension, respectively. From Figure 5, it can be seen that DR is almost constant against Re and its maximum value is 11%. Figure 6 shows the relationship between DR and the concentration of the suspension, C_w. DR is seen to increase significantly with C_w under these experimental conditions.

The relationship between $f^{-1/2}$ and $\mathrm{Re}\cdot f^{1/2}$, where f denotes the Fanning friction factor, is shown in Figure 7. It can be seen that in the laminar flow regime, where $\mathrm{Re}\cdot f^{1/2}$

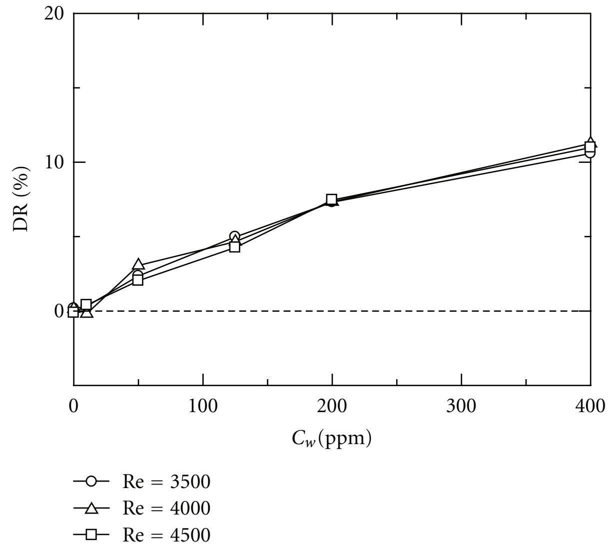


Figure 6: Effects of concentration of bacterial cellulose suspensions on DR.

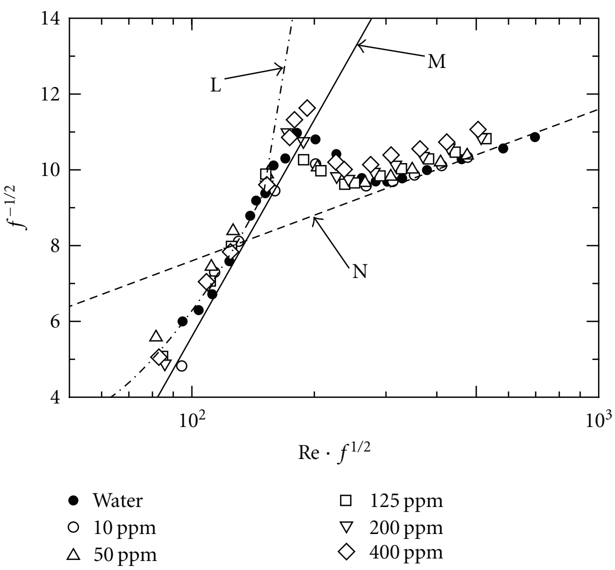
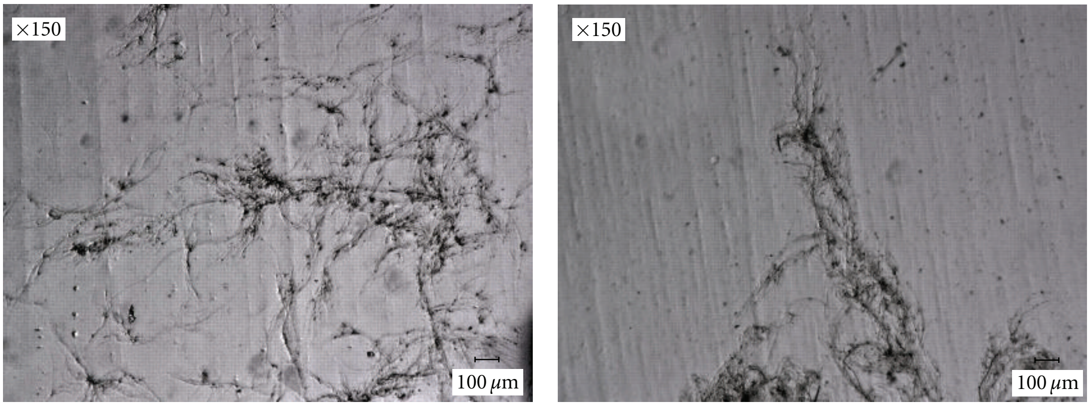


Figure 7: $1/\sqrt{f}$ versus $\mathrm{Re}\sqrt{f}$.

is small, the data is well fitted by a Newtonian laminar flow curve (L). In contrast, in the turbulent regime, the data is aligned parallel to the curve (N) in order of concentration (higher concentrations are located higher in the graph). This indicates a type B drag reduction, which can be seen in fiber suspensions and polymer solutions. Generally, a type B drag-reducing mechanism is associated with suppression of vortices. For fiber suspensions, it is thought that flocs produced in the flow field influence the fluid resistance, and the fibers suppress vortices when they are uniformly distributed in the flow direction, thus resulting in drag reduction.

A micrograph of a bacterial cellulose suspension is shown in Figure 8(a). The bacterial cellulose is in fiber form, and



(a) Bacterial cellulose suspension ($N = 0$)

(b) Nata de coco ($N = 0$)

Figure 8: Micrographs of test fluids (before experiment).

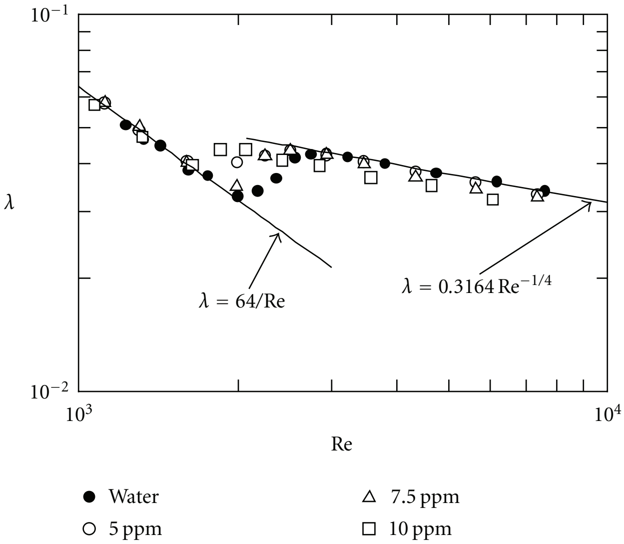


Figure 9: Frictional coefficient of nata de coco suspensions.

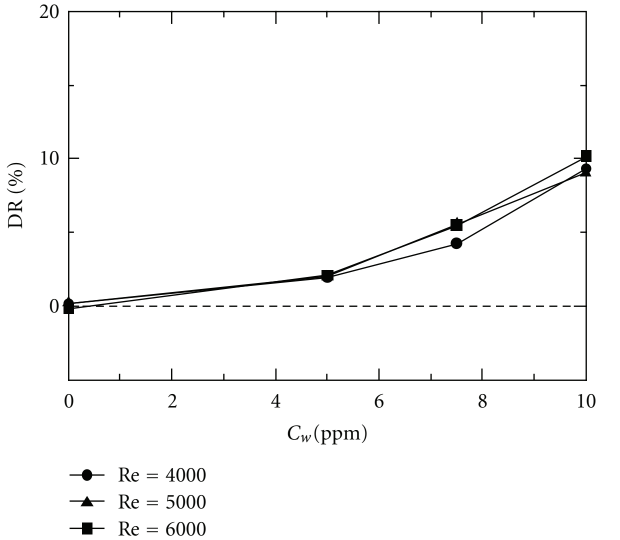


Figure 10: Effects of concentration of nata de coco suspensions on DR.

similar suspensions made from synthetic fibers, such as nylon or rayon with aspect ratios of 40–100, show up to 20% drag reduction at high concentrations (5000–20000 ppm). On the other hand, asbestos fiber, which has an aspect ratio of 10^5, shows a high DR (20–85%) at low concentrations (25–500 ppm). In the case of bacterial cellulose, although drag reduction has been observed in the low concentration region, similar to that for asbestos, its DR value is similar to that for nylon or rayon. Although it is impossible to determine the aspect ratio of bacterial cellulose based on the image, the reason that the DR value of bacterial cellulose is lower than those of asbestos fiber or biopolymers may be due to that the fibers and/or their assemblies in the test fluid are shorter.

Bacterial cellulose forms nata de coco when bacteria accumulate and stratify. Figure 8(b) is a micrograph of a suspension of uncompressed nata de coco that was agitated with a mixer. The fibers are closely associated and the assemblies are thick in comparison with those of bacterial cellulose. It is clear from the traditional experimental results that the thickness and aspect ratio of fibers have a large influence on drag reduction. Hence, the drag reduction mechanisms for the nata de coco suspension shown in Figure 8(b) differs from those of the bacterial cellulose suspension shown in Figure 8(a). Therefore, experiments with suspension made from agitated nata de coco were performed in order to investigate the influence of the bacterial cellulose fiber shape.

The results of the pressure drop measurements are shown in Figure 9. Although drag reduction is observed, similar to the case for the bacterial cellulose, the critical Reynolds numbers for the examined concentrations are smaller than that of water. The relationship between C_w and DR for the nata de coco suspension is shown in Figure 10. The DR value is seen to increase significantly with concentration, in comparison to the bacterial cellulose suspension (Figure 6). The higher drag reducing effect of the nata de coco suspension at lower concentrations may be

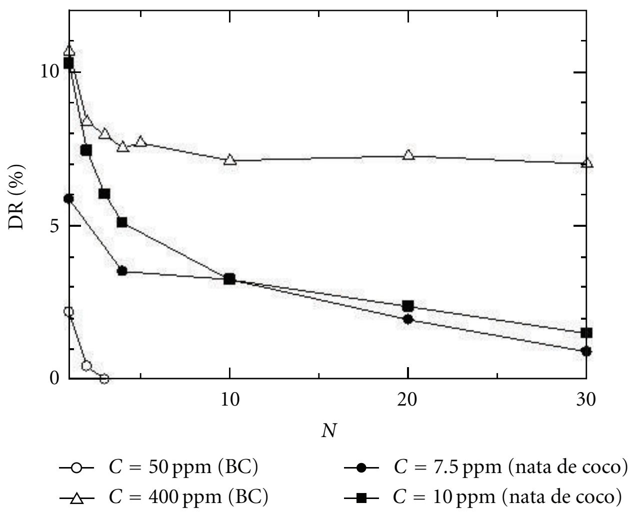


FIGURE 11: Experimental results for mechanical degradation: BC denotes bacterial cellulose suspensions, and nata de coco denotes nata de coco suspensions.

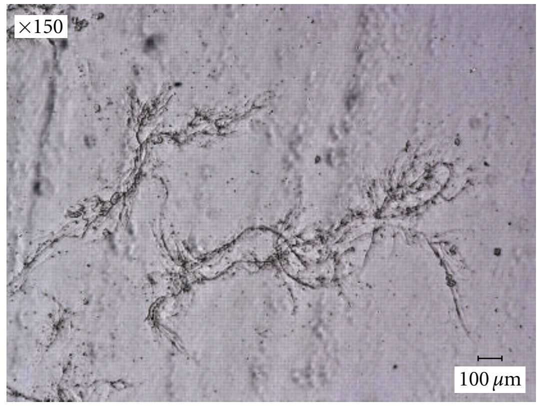
explained by the presence of thicker fiber assemblies (Figures 8(a) and 8(b)).

Figure 11 shows the results of a mechanical degradation experiment for suspensions of bacterial cellulose and nata de coco. For 400 ppm bacterial cellulose, the initial DR ($N = 1$, where N is the number of passages of the test fluid) was 11%, gradually decreased until $N = 5$, and thereafter maintained an almost constant value of about 5%. DR decreased immediately for the 50 ppm concentration. In contrast, for the nata de coco suspension, both the 7.5 and 10 ppm concentrations exhibited a decrease in DR with increasing N, and the drag reducing effect vanished for $N = 30$. These results suggest that bacterial cellulose suspensions are less susceptible to mechanical degradation.

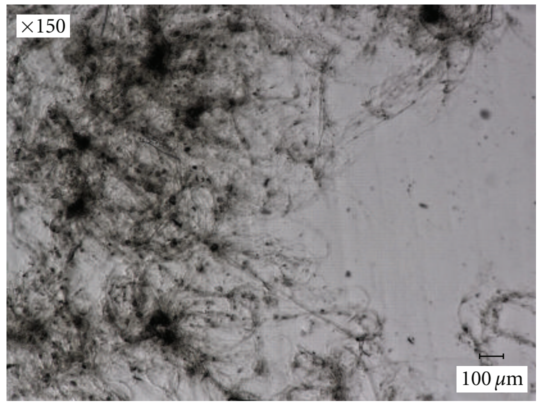
Micrographs after the degradation experiment are shown in Figures 12(a) and 12(b). In comparison to the bacterial cellulose suspension (Figure 12(a)), the degree of breakup of fiber assemblies, which were closely associated before degradation, was greater for the nata de coco suspension (Figure 12(b)). Bacterial cellulose tends to contain gelled assemblies (liquid), and nata de coco is composed almost entirely of such ensembles. In addition, the degree of conglutination between bacterial cellulose fibers increases due to hydrogen bonding when the liquid in the gelled assemblies evaporates. This occurs even when the bacterial cellulose is in water. Since conglutination is weaker in nata de coco than in bacterial cellulose, and the fibers are fragile, the nata de coco suspension may suffer additional damage (mechanical degradation) when the fluid passes through an orifice or capillary.

4. Conclusions

Pressure drop measurements for bacterial cellulose suspensions flowing in a circular pipe were performed, and the following results were obtained.



(a) Bacterial cellulose suspension ($N = 30$)



(b) Nata de coco ($N = 30$)

FIGURE 12: Micrographs of test fluid (after mechanical degradation).

(1) The drag reduction of bacterial cellulose increased with concentration and showed a maximum of 11%.

(2) The drag reduction decreased due to mechanical degradation, and finally became constant.

(3) Suspensions of nata de coco, which is a layered form of bacterial cellulose, showed a higher drag reduction at lower concentrations, although the effects of mechanical degradation were larger.

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