Flow characteristics of drag-reducing natural bamboo fiber suspensions with minimal environmental load

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ABSTRACT: The reduction of pipe friction loss by adding drag-reducing agents has attracted attention as an aid to energy conservation. Drag-reducing agents induce drag reduction (DR) effects and should have a minimal environmental load, with natural resource-saving potential.

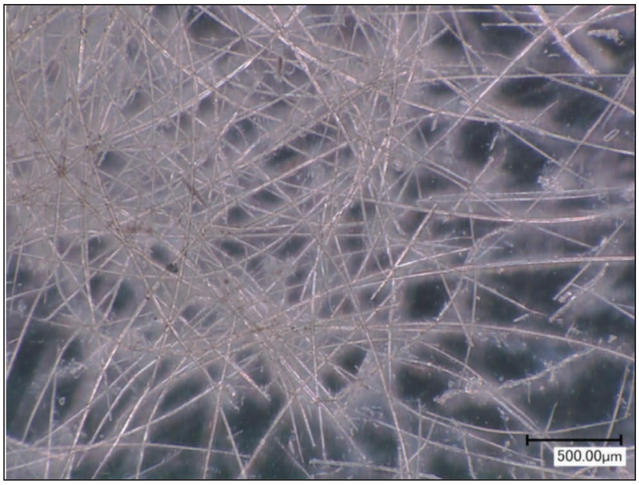
This study demonstrates bamboo fiber as a drag-reducing agent that saves natural resources and has a low environmental load. Using pressure drop measurements, we report DR with suspensions of bamboo fibers with the average diameter of 13.3 μm and aspect ratio of 98.7. The maximum DR obtained in this experiment is 43% at the concentration of 4000 ppm and pipe diameter of 30 mm; DR is affected by the Reynolds number, suspension concentration, and pipe diameter. In addition, the bamboo fibers can be easily removed from the suspensions by filtration. We found that low-environmental-load bamboo fiber has DR effects like those of other fibers; its effects are greater than those of conventional synthetic fibers and wood pulp. Furthermore, it is resistant to mechanical degradation, recoverable, and recyclable. Therefore, DR effects can be selectively obtained by adding the fibers only when DR is needed; the fibers can then be collected when DR is no longer necessary. This method might greatly expand the application range of DR agents. The results demonstrate the usefulness of bamboo fibers as DR additives.

Application: High-aspect-ratio bamboo fibers show excellent drag reduction at low concentrations relative to wood pulp fibers, good recoverability by mechanical filtering and recyclability, and long-term mechanical robustness.

Global warming and the goal of energy conservation have increased interest in research on drag reduction (DR) for equipment used in thermal energy transport systems. Reductions of pressure loss directly correspond to improvements in the efficiency of manufacturing plants, district heating and cooling systems, and building air conditioning, with significant energy reductions resulting [1,2]. Furthermore, because DR technology promotes the efficiency and miniaturization of equipment related to fluid flow, its development is very important. Various methods for DR have been proposed; the method of adding drag-reducing additives to solvents yields very high reductions compared with others (such as riblet wall [3] and highly water-repellent wall [4] construction). Moreover, because changes to existing pipelines are not necessary, DR by additive inclusion is a practical approach to improving efficiency. At present, surfactants [5,6], polymers [7], and fibers [8,9] are studied as drag-reducing additives.

Relatively large DR effects can be obtained with polymers, as shown by many studies performed since the discovery of the Toms effect [7]. However, because the continuous operation of circulation pipeline systems induces mechanical deterioration that hinders the DR effect, polymers are unsuitable for practical use. Meanwhile, surfactants show little mechanical deterioration and can be practically used in circulating systems [10]. Thus, surfactants have been used for urban heat-energy supply pipeline systems and building air conditioning systems [1,2]. However, polymers and surfactant solutions are chemically synthesized and have possible environmental impacts including water pollution and soil contamination from leakage and drainage. Therefore, surfactant application is limited to closed-circuit pipeline systems. Considering this problem, biopolymers with minimal environmental burden have attracted attention, but they are also impractical because of mechanical deterioration effects [11].

Fibers show less mechanical degradation than other additives. Studies on fibers have frequently investigated synthetic fibers such as nylon, rayon, and asbestos. DR effects reaching 20% and 80% for synthetic fibers and asbestos, respectively, have been reported [12]. However, the chemical syntheses of nylon and rayon also entail environmental concerns. Therefore, the flow characteristics of natural fibers, which are less influential to the environment, have also been studied. The flow characteristics [9,13-16] and DR effects [8,9,17-23] of wood pulp fibers in suspension have also been reported. However, harvested trees require several decades for regeneration. Moreover, to obtain a suitable DR effect, a high concentration is required. Therefore, a fiber with a higher regeneration speed is desired, and it is necessary to consider reusability. DR effects using kenaf fiber, which has a high regeneration rate, have been reported [24,25]. However, depending on the added amount, drag may be increased, and research on the



1. Photograph of bamboo fiber suspension.

DR effect of high-regeneration-rate fibers has not necessarily been sufficient. Furthermore, the amount of DR reported is approximately 10%, which is low for practical use. Studies on the flow of coconut fiber have reported a DR effect of 7.6%, which is smaller than that of kenaf fiber [26].

Regarding treatment after additive use, surfactants and polymers cannot be separated from solutions, so post-use processing is high in cost. On the other hand, because fibers are not dissolved in liquids, fibers of a certain size can be recovered from suspensions. Although this might significantly lower the cost of wastewater processing, details of fiber collection from suspensions have not been reported. It follows that the use of recycled fibers as drag-reducing additives has not been studied.

Drag-reducing additives must exert DR effects and show excellent recyclability with low environmental load. Therefore, to achieve both DR effects and a minimal environmental load, we experimentally clarify the flow characteristics of natural bamboo fibers in suspension.

EXPERIMENTAL APPARATUS AND METHODS

Test fluids

Tokyo Metropolitan Industrial Technology Research Institute provided the bamboo fibers used in this study. To sufficiently distribute the bamboo fibers, suspensions were agitated before addition to the fluid base in a pipeline. We also used an agitator in a tank to prevent fibers from settling and to stabilize the mixture.

We used a digital microscope (KH-7700, Hirox; Tokyo, Japan) to measure the average thickness and length of the bamboo fibers used in this experiment. **Figure 1** shows a micrograph of the bamboo fiber suspension. The fibers are linear and have sharp ends. Measurements from several micrographs showed an average fiber length of 1.19 mm and diameter of 13.3 µm. The average aspect ratio was 89.7. The suspension concentration C_w was determined based on the mass ratio of dried fiber to tap water, as defined by

$$C_w\ [\%] = M_f/(M_f + M_w) \times 100, \quad (1)$$

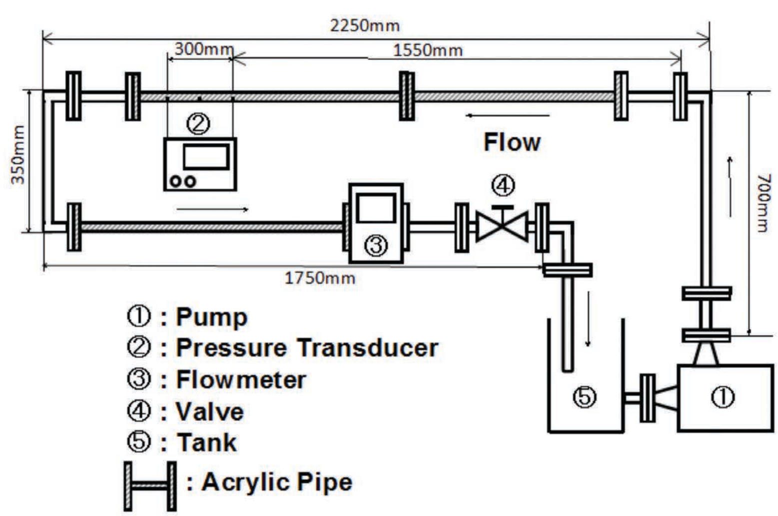
where M_f and M_w denote the masses of fiber and tap water, respectively.

Viscosity

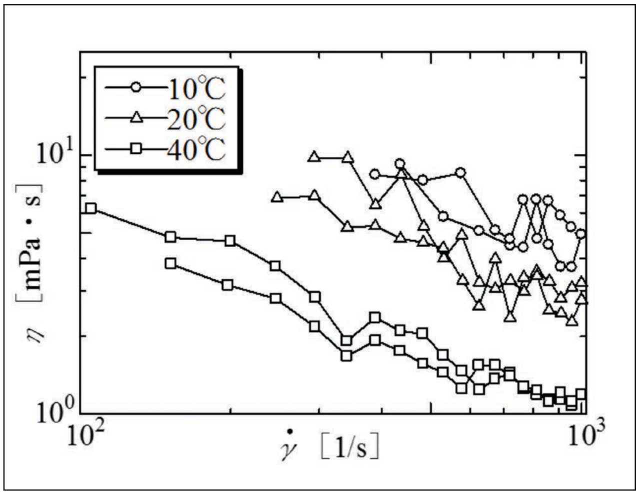
Viscosity was measured using a cone plate-type viscometer (HAKKE ReoStress 600, Thermo Electron; Karlsruhe, Germany). The titanium cone was 60 mm in diameter, with an angle of 1°. The shear rate range is from 100 Hz to 1000 Hz.

Pressure drop measurement

In this study, we used a circular experimental apparatus (**Fig. 2**). Experiments were performed by measuring the pressure drop and flow rate in the pipe. The measurement part of the pressure drop was fabricated using acrylic pipe with inner diameters of 5 mm, 10 mm, 15 mm, 20 mm, and 30 mm to confirm the conditions of test fluid distribution. The



2. Experimental apparatus.



3. Viscosity η versus shear rate γ̇ measured by cone–plate viscometer.

length of the pressure drop test section was 300 mm. Because the entrance length was 1550 mm, flow in the turbulent region was fully developed before the pressure was measured [27]. The suspensions were circulated by a pump (MD-55R, Iwaki Pumps; Tokyo, Japan) controlled by an inverter (Sysdrive 3G3MV, Omron; Kyoto, Japan). The flow rate was adjusted with a valve and measured with an electromagnetic flow meter (COPA-XE, Nippon Flow Cell; Shinbashi, Japan). The electromagnetic flow meter was initially calibrated by a gravimetric method at a low flow rate. The pressure drop was measured with a pressure transducer (DP15, Validyne; Northridge, CA, USA). The pressure transducer data were recorded with a data logger (NR-1000, Keyence; Osaka, Japan). The pressure drop was determined by averaging 50 data points measured at intervals of 100 ms. The temperature of the suspension was maintained within ±0.5°C of the target temperatures of 10°C, 20°C, and 40°C using a constant-temperature reservoir (LTB-125, As One Corp; Osaka, Japan).

Velocity profiles

Velocity profiles were measured by particle tracking velocimetry. The interior of the circular tube was illuminated with a sheet light (PIV Laser Power Supply LD-WL206, Kato-Koki Co. Ltd.; Kanagawa, Japan), under which continuous images were acquired with a high-speed camera (FASTCAM-Neo, Photoron; Tokyo, Japan). Orgasal (density: 1.03 g/cm³; mean diameter: 48–52 µm) was added to the suspension for particle visualization. The image acquisition conditions used the frame rate of 4000 frames/s and shutter speed of 1/8000 s.

Fiber recycling experiment

Bamboo fibers were recovered from the suspension after testing in the circulation system for recycling. We installed a filter with a pore size of 0.3 mm at the outlet of the flow path to recover the fibers. As the device continued operation in this state, the change in DR percentage with time was examined. We repeated the experiment using the collected fibers.

EXPERIMENTAL RESULTS AND DISCUSSION

Viscosity of test fluids

Figure 3 shows the viscosity of the bamboo fiber suspension with C_w = 1000 ppm. Measurements were made twice at all temperatures. The viscosity of the suspensions decreased with increasing temperature, but was larger than that of water. At all temperatures, the viscosity decreased with increasing shear rate. Viscosity values varied greatly. We attributed that to the effects of centrifugal force on the fibers during the measurement, which induced distribution biases, but the details of these effects are unknown. The measured value is unstable for C_w > 1000 ppm. This is also attributed to the influence of centrifugal forces, which remain similar as the fiber concentration increases.

Because of this variation in the collected viscosity data, we used the viscosity of water to organize the experimental results, as with aqueous surfactant solutions. The viscosity of the suspension exceeded that of water; therefore, the actual Reynolds number *Re* was assumed to be lower than the experimental value.

Frictional factors of test fluids

The experimental results are expressed in terms of *Re* and the friction coefficient λ of each suspension. These are respectively defined by Eq. 2 and Eq. 3:

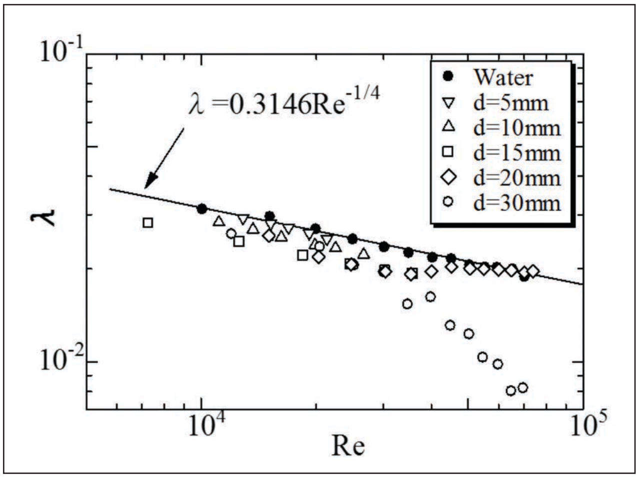
$$Re = v\, d/\nu \quad (2)$$

$$\lambda = (\Delta p\, d/l) / (\rho\, v^2/2) \quad (3)$$

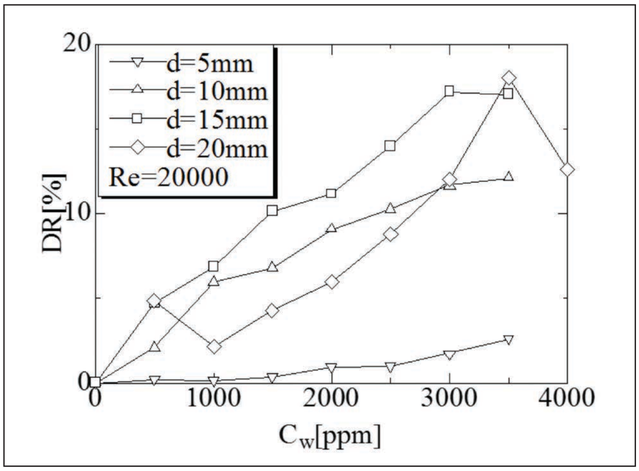
where v is the mean flow velocity, d is the pipe diameter, ν is the kinetic viscosity of tap water, Δp is the measured pressure drop, l is the length of the test section across which the pressure drop is measured, and ρ is the density of tap water.

The concentration was set to 3500 ppm, as discussed later. The measurement results of water agree well with the Blasius equation (within ±1%), indicating sufficient accuracy of the measurement equipment.

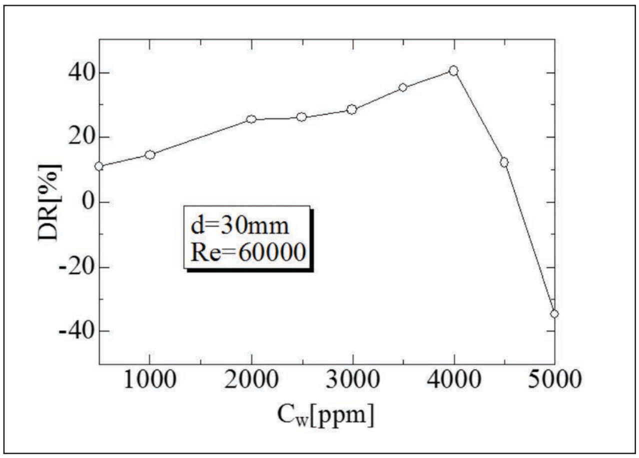
In **Fig. 4**, the friction coefficient of the bamboo fiber sus-



4. Effect of pipe diameter d on friction coefficient λ.



5. Effect of concentration on drag reduction for* d *= 5 mm, 10 mm, 15 mm, and 20 mm (DR = drag reduction;* d *=pipe diameter;* Re *= Reynolds number;* C_w *= suspension concentration).



6. Effect of concentration on DR at* d *= 30 mm (DR = drag reduction;* d *=pipe diameter;* Re *= Reynolds number;* C_w *= suspension concentration).

pension is decreased compared with that of water at all pipe diameters. The rate of decrease increased as the pipe diameter increased. This indicates that the bamboo fiber suspensions have DR effects.

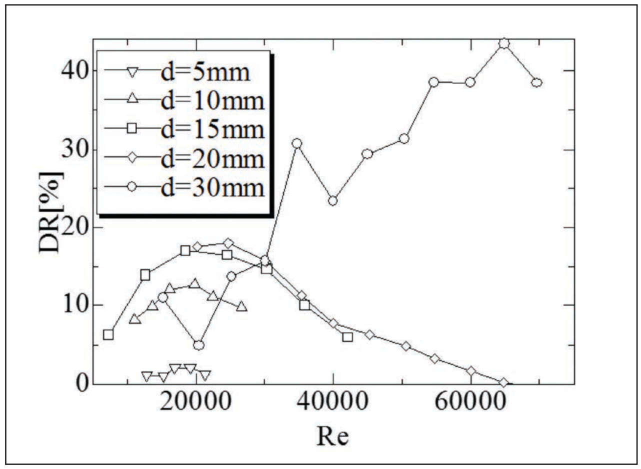
To quantitatively estimate the degree of DR, the experimental results are expressed in terms of the DR coefficient:

$$DR\ [\%] = (\lambda_{water} - \lambda_{suspension})/\lambda_{water} \times 100 \quad (4)$$

where λ_{water} and $\lambda_{suspension}$ denote the friction coefficients for tap water and bamboo fiber suspensions, respectively.

Effect of concentration of test fluids

Figure 5 shows the relationship between the concentration C_w of the test fluid and DR at pipe diameters 5 mm ≤ *d* ≤ 20 mm and *Re* = 20000. **Figure 6** shows the relationship between C_w and DR at *d* = 30 mm and *Re* = 60000. The DR increased for all pipe diameters with increasing concentration to C_w = 3500 ppm. However, for 5 mm ≤ d ≤ 20 mm and C_w > 3500 ppm, and d = 30 mm and C_w > 4000 ppm, DR decreased, sometimes approaching zero. In particular, at *d* = 20 mm, DR approached zero when the local maximum value of the concentration causing DR was exceeded. Drag is increased when the local maximum value was exceeded at *d* = 30 mm. Considering these behaviors, the experiments were conducted using the selected concentration of C_w = 3500 ppm.



7. Effect of* Re *on DR (DR = drag reduction;* d *=pipe diameter;* Re *= Reynolds number).

In conventional fiber research [12], DR rate is increased as the concentration increases to a critical value; past this value, the reduction effect disappears. The results observed here show the same tendency. Because synthetic fibers of approximately the same size must be applied at C_w = 5000–20000 ppm to achieve 20% DR [12], bamboo fibers can obtain equivalent DR at lower concentrations.

Effect of pipe diameter and Re on DR

Figure 7 shows the effect of *Re* on DR, indicating that DR depends on *Re*. At the pipe diameter d = 5 mm, DR is minimal. DR increases with increases in pipe diameter *d* to the maximum of ~43% at *d* = 30 mm. These results are specific to fibers at which a maximum value of DR exists for any tube diameter. *Re* has the maxima of 20000 at 5 mm ≤ *d* ≤ 20 mm and 60000 at *d* = 30 mm. From this, the *Re* at which DR is maximized depends on *d*, and DR increases with increases in pipe diameter. This result is consistent with those reported for pulp and synthetic fibers, and contrary to those for nanoscale additives such as polymers and asbestos [17].

Table I summarizes the maximum DR for each pipe diameter. For comparison, the table also shows results obtained using wood pulp. As shown in the table, bamboo fiber has a larger DR at smaller tube diameters. From this result, we conclude that DR begins at diameters of >15 mm. In the case of *d* = 30 mm, because of the limit of the experimental equipment, we could not experiment with more *Re* values. However, at *d* = 30 mm, after the DR was maximized, the DR decreases with increases in *Re* and approaches the turbulent Blasius equation. This is similar to the DR behavior of *d* = 20 mm.

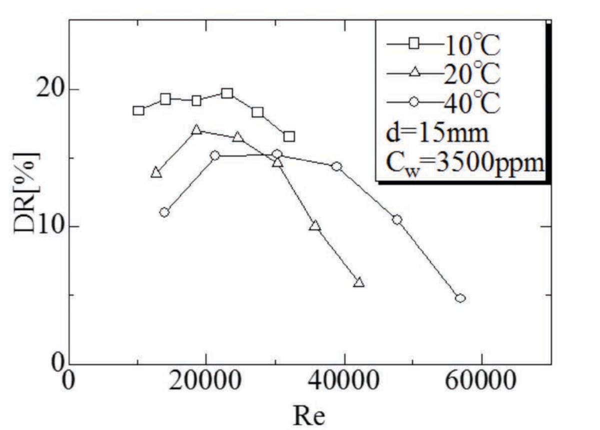
Pipe Diameter, mm	DR of Bamboo Fiber, %	DR of Wood Pulp Fiber, %
5	2.1	—
10	12.6	—
15	17.0	—
20	18.0	16.0
30	43.5	—
50	—	22.0
100	—	35.0

I. Effect of pipe diameter on drag reduction (DR).

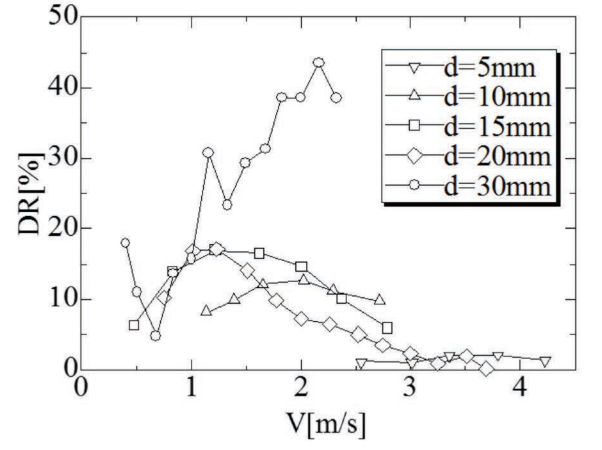
DR increases with increasing *Re*, and the behavior with a local maximum at a certain *Re* is the same as that of surfactants, polymers, and other fibers [12]. *Re* indicating the maximum DR effect is shifted to higher values as the pipe diameter increases. Gasljevic et al. [28] reported a similar phenomenon. In fiber studies, *Re* corresponding to the maximum DR value has been reported to vary with the type of fiber, concentration, and tube diameter [18]. In the low-*Re* region, fibers are poorly dispersed and flow in a floc state with no DR. However, at a certain *Re*, the fibers in the floc state begin to disperse uniformly. Because the arranged fibers suppress turbulent vortices, the fiber suspension generates DR. Afterward, as *Re* increases further, the fiber arrangement collapses and DR decreases [21]. The behavior of bamboo fiber shows the same traits as that of pulp.

Effect of temperature on DR

Figure 8 shows the effect of the temperature of the test fluid on DR, which is decreased with increases in temperature. At low *Re*, DR is decreased as the temperature is increased, but



8. Effect of* Re *on DR at different fluid temperatures (DR = drag reduction;* d *=pipe diameter;* Re *= Reynolds number;* C_w *= suspension concentration).



9. Effect of mean flow rate on DR at different pipe diameters (DR = drag reduction;* d *=pipe diameter;* V *= velocity).

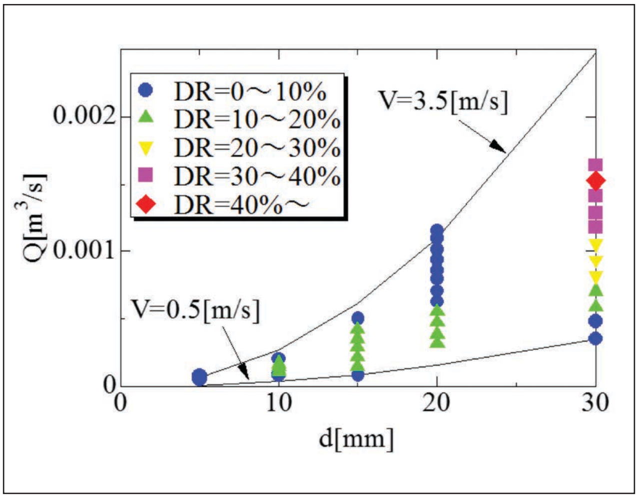
at high *Re*, DR is increased. Temperature-dependent phenomena have also been reported for polymers [29] and asbestos fibers [19]. These are attributed to the decrease in the extensional viscosity of the solution with the increase of temperature. Decreases in the extensional viscosity increase turbulence, vortex formation, and drag. In addition, the *Re* at maximum DR is slightly increased with increases in temperature. This result has also been reported in experiments using asbestos [19]. Although we did not measure the extensional viscosity in this study, we presume that the observed results are related to the extensional viscosity.

Effect of mean flow rate on DR

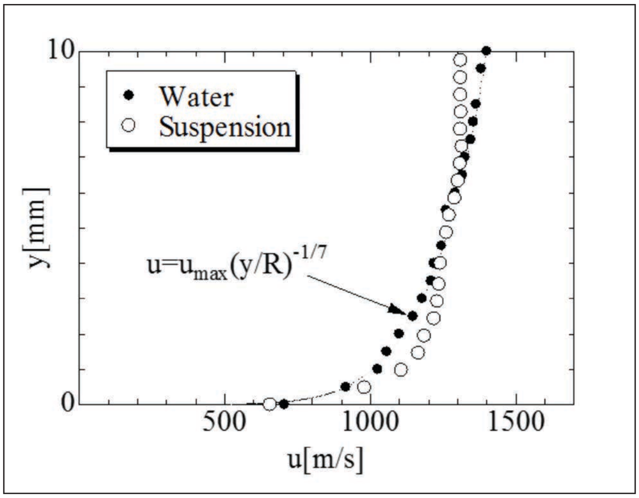
The previous results showed that DR of the bamboo fiber suspension cannot be determined by *Re*; instead, it depends on the tube diameter and fluid temperature. In previous research on additives [28], flow velocity was reported as a suitable parameter for adjusting DR, so the results obtained here were also organized according to the average flow velocity of the bamboo fiber suspension.

Figure 9 shows the relationship between the mean velocity V and DR. DR occurs in the range $V = 0.5–3.5$ m/s. Except at $d = 5$ mm, the local maximum of DR occurs approximately between $V = 1.0$ m/s and 2.0 m/s. From this, we conclude that DR does not occur at d = 5 mm because V is high. Because V greatly affects the fiber dispersion, the bamboo fiber dispersion state at which DR is maximized appears to be between $V = 1.0$ and 2.0 m/s. In conventional surfactant studies, the mean velocity range at which DR occurs is approximately 4-5 times greater than that for bamboo fiber [28].

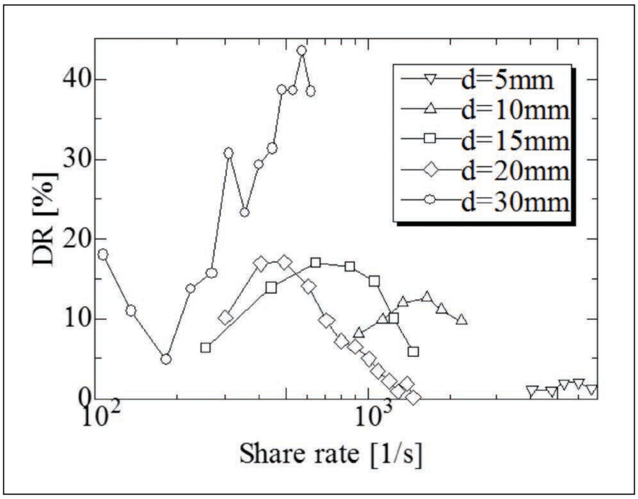
The flow rate was calculated from this average velocity range. **Figure 10** shows a DR map of the flow rate and pipe diameter. The solid lines in the figure indicate the upper limit ($V = 3.5$ m/s) and the lower limit ($V = 0.5$ m/s) of the average velocity at which DR occurs in the bamboo fiber suspension. DR is small near each solid line and larger near the center; it increased with increases in the pipe diameter, and the flow



10. Effect of flow rate Q on DR at different pipe diameters (DR = drag reduction; d =pipe diameter; V = velocity).



12. Velocity u of flow in pipe of 2R = d = 20 mm and Re = 20000 at distance y from pipe wall (d =pipe diameter; Re = Reynolds number).



11. Effect of shear rate on DR at different pipe diameters (DR = drag reduction; d =pipe diameter).

rate range at which high DR can be obtained is broadened. These results indicate the range of flow rates at which DR can be obtained with a bamboo fiber suspension.

Effect of shear rate on DR

Figure 11 shows the relationship between shear rate and DR. The range of shear rates differs from that of flow rates corresponding to DR maxima. DR begins at the shear rate of 100 s^{-1}. The maximum DR value is shown at different shear rates for each pipe diameter in the range of 400–1100 s^{-1}. The shear rate at which DR disappears differs for each tube diameter. The results show that shear rate does not effectively manipulate DR; therefore, the average flow velocity is more suitable as a parameter to control DR.

Velocity profiles

Figure 12 shows the velocity profiles of water and the bamboo fiber suspension with concentration C_w = 1000 ppm. The water results agree well with the equation of the 1/7th power law for turbulent flow. However, in the bamboo fiber suspension, the velocity u in the area near the pipe wall (at y approaching R, where $R = d/2$) is higher than that of water, whereas in the center of the pipe, it is lower than that of water. The flow showing such a velocity profile is called a plug flow. The same velocity distribution was observed in a conventional fiber suspension [18]. This plug flow greatly affects the DR mechanism of the fiber suspension. Because the plug holds the fiber, a network is formed at the center of the tube in which turbulent vortices are suppressed. As mentioned, the bamboo fiber suspension is considered to have the same DR mechanism as conventional synthetic fibers and wood pulp.

Effect of mechanical degradation

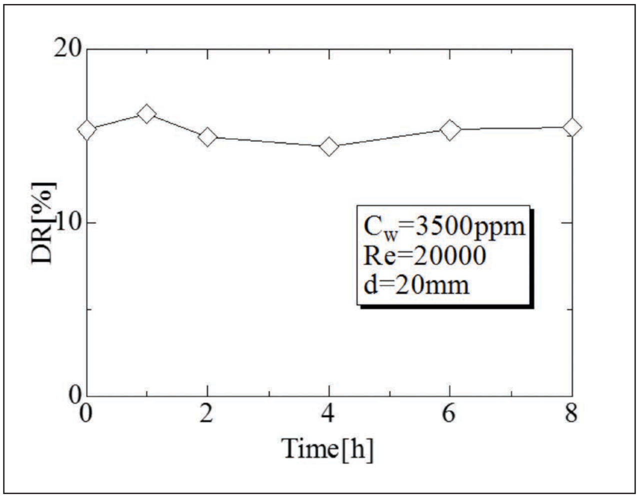
Figure 13 shows the results of mechanical degradation with long-term pump operation. The figure shows that even if the bamboo fiber suspension is circulated for 8 h, mechanical degradation from shearing (as during pumping) does not occur. This shows that bamboo fiber is suitable for practical use as a DR agent.

Fiber recovery experiment

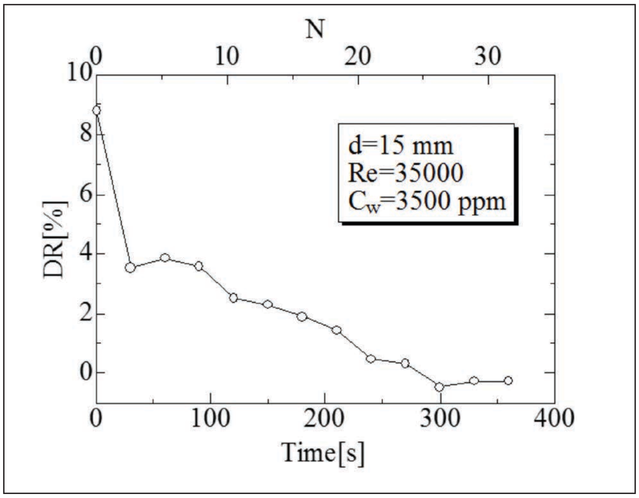
Figure 14 shows the results of the fiber removal test. The experimental results are expressed in terms of the time elapsed since filter installation and the number of passes N of the suspension through the filter. N is calculated from the flow rate Q, the volume of the pipe and tank V, and the time since filter installation T, as:

$$N = V / Q\ T. \qquad (5)$$

DR is decreased with increasing time and N. DR approaches zero at T = 300 s and N = 25. This result demonstrates that fibers can be easily removed from the suspension, with the viscosity gradually returning to that of tap water. In addition,



13. DR over time (DR = drag reduction; d *=pipe diameter;* Re *= Reynolds number;* C_w *= suspension concentration).*



14. Recovery of tested fibers from suspension, shown as DR over time (DR = drag reduction; d *=pipe diameter;* Re *= Reynolds number;* C_w *= suspension concentration).*

experiments using the recovered bamboo fibers revealed that they generate DR in the same manner as fresh suspensions. This result shows that the bamboo fibers remain mechanically stable throughout the experiment.

CONCLUSIONS

In this study, we investigated the flow characteristics of bamboo fiber suspensions in pipes of different diameters. The results obtained in this study can be summarized as follows:

1. Suspensions of bamboo fibers with the average diameter of 13.3 µm and aspect ratio of 98.7 have DR effects. The maximum DR obtained in this experiment was 43% at the concentration C_w = 4000 ppm and pipe diameter d = 30 mm.
2. The DR effect cannot be predicted by *Re*; instead, it depends on the pipe diameter, concentration, and temperature of the suspension. For each *Re*, concentration, and tube diameter, a maximum DR value exists.
3. The DR effect occurs within a limited velocity range. In this experiment, DR occurred in the mean flow rate range of 0.5–3.5 m/s under all conditions.
4. After 8 h pump operation, almost no influence of mechanical deterioration on the DR effect of bamboo fiber was observed.
5. The bamboo fiber can be recovered from the suspension by attaching a filter with a pore size of 0.3 mm to the experimental device. In pressure drop experiments using the recovered fibers, the DR effects were similar to those observed using fresh fibers.

Bamboo fiber, which has a low environmental load, has DR effects like those of other fibers. It is also resistant to mechanical degradation, recoverable, and recyclable. Therefore, DR effects can be selectively obtained by adding the fibers only when DR is needed; the fibers can then be collected when DR is no longer necessary. This method might greatly expand the application range of DR agents. The results demonstrate the usefulness of bamboo fibers as DR additives. **TJ**

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Ogata

We conducted this study because we were interested in drag reduction in fluids. A benefit to mills is the energy saving effect of improved flow in piping.

Low-environmental-load bamboo fiber has drag reduction effects like those of other fibers. However, its effects are greater than those of conventional synthetic fibers and wood pulp. Furthermore, it is resistant to mechanical degradation, recoverable, and recyclable.

We found that there are many fibers on the earth that can reduce fluid drag. A surprising discovery was the reusability of bamboo fibers for drag reduction.

A challenge in conducting this study was production of equipment that could provide accurate measurement data. Future research will look at drag reduction using nanocellulose.

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