A new method for characterizing turbulent mixing in semiconcentrated suspensions

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ABSTRACT: A high-frequency conductivity probe was used in conjunction with advanced signal processing to measure the turbulent fluctuations of a passive scalar, namely a saline solution, injected into semiconcentrated, monodispersed suspensions consisting of either 2-mm rayon fibers or 130-μm microspheres. The probe was mounted in a pipe flow so that its radial position could be adjusted manually. A saline solution was injected into the centerline of the pipe at a specified velocity relative to the suspension flow. The mean conductivity signal gathered with this tool enabled estimation of the local concentration of salt at a given point in the flow, i.e., the mean spatial dispersion of the dosed component. Further analysis of the high-frequency fluctuating signal enables characterization of the local mixing energy and turbulent spectrum, i.e., the spectral mixing scales available in the suspensions under a given set of conditions.

Application: Producers of paper and board products are given new insights into minimizing unwanted variability in paper properties that may result from poor mixing of stock components, uneven addition of chemical additives, or dilution of the thick stock prior to the headbox.

Mixing of different pulp streams and mixing of chemicals into the furnish are basic unit operations in papermaking. The quality of mixing in the approach flow affects the uniformity of the stock composition and subsequently the uniformity of the paper web. Mixing quality can also affect the performance of chemical additives such as retention aids. For example, large-scale consistency variations in the furnish prior to the headbox can appear as unstable machine direction-cross direction (MD-CD) grammage streaks in the final product. Small-scale variability in the distribution of retention aids contributes to formation, dewatering, and runnability issues [1]. On the other hand, a well-mixed stock forms the basis for a uniform paper web and improved retention of fine particles in the forming section, allowing for the possibility to form the same product with fewer fibers (savings in production costs).

Mixing of multiple streams into a papermaking stock depends on the dynamics of the local flow, in particular the ratio between the inner (dosed) and outer (stock) velocities [2], the rheological properties of the inner and outer flows [3], and characteristics of the fiber suspension, i.e., fiber length, stiffness, coarseness, and concentration [4]. The process is complicated by the tendency of fibers to form flocs. High shear and turbulence levels are generally needed to disrupt these fiber flocs, while turbulence is required to enhance dispersion at various scales. However, the presence of even the smallest amount of particles in a flow can strongly alter the turbulence, rheology, and transport properties that are responsible for good mixing. Further, the size, shape, and morphology of the solids particles can have significantly different effects on the turbulence [5].

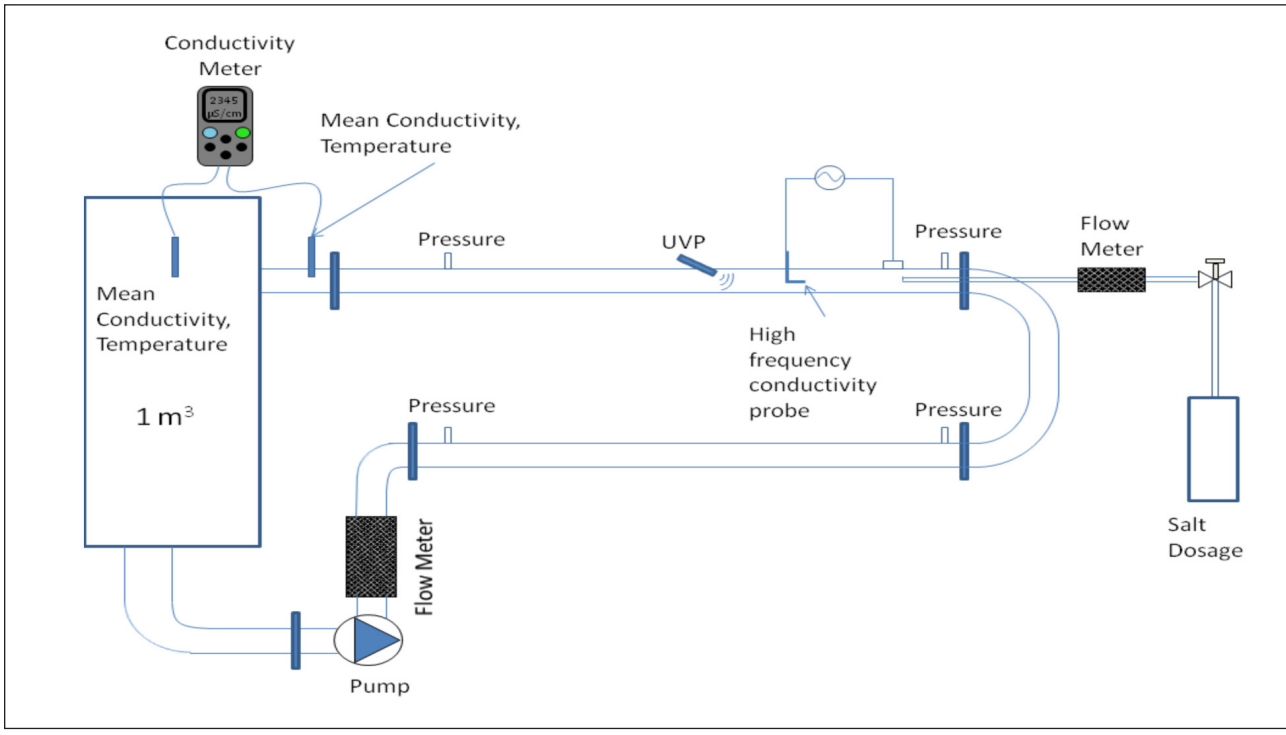
Despite this very basic understanding of stock mixing, qualitative relationships between mixing conditions and mixing quality are still poorly understood. One major difficulty is the characterization of mixing at a spectral level in these suspensions. The difficulty is due to the inherently high solids concentration, the broad particle size distributions, and the opacity of the papermaking suspensions, in particular. Traditional measurement techniques, i.e., laser and/or optical methods, rarely work within these suspensions.

Conductivity-based measurements provide one class of measurement technique that can be used in almost any type of suspension under arbitrary flow conditions. The measurement principle with conductivity-sensing probes is based upon detecting local variations of electrical conductivity (or resistivity) in a flow. Low-resolution conductivity probes have previously been used to study the mean dispersion characteristics of a saline solution, injected concentrically into turbulent pulp suspensions by Kulick et al. [6]. In that work, large effects of the pulp fibers on the mean, spatial dispersion of the saline solution were reported. Specifically, the local concentration of saline was found to decrease rapidly upon injection into the pulp suspensions compared with that injected into pure water. The spectral detail of the turbulent dispersion was not obtained with this method, however, so the effect of pulp fibers on the spectral character of the turbulence was not determined.

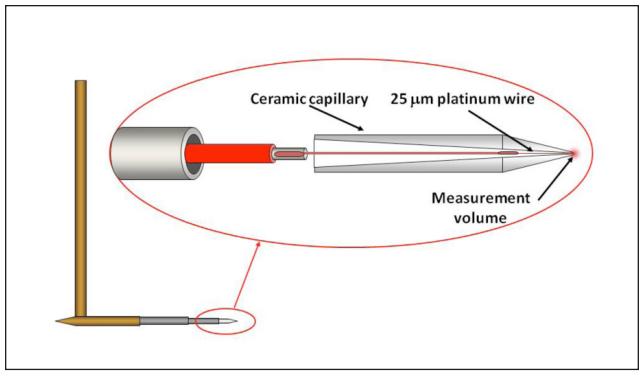
In considering the turbulence of a conductive stream, the spectrum of a fluctuating passive scalar, e.g., conductivity in a turbulent flow, has been shown to have the same wavenumber dependence as the velocity spectrum itself [7]. Therefore, it should be possible to exploit the high-frequency fluctuations in local conductivity as a means to estimate the mixing spectrum resulting from local turbulent fluctuations between two unmixed streams. Strictly speaking, such a technique could only measure fluctuations in the local conductivity gradient resulting from the mixing of two or more streams. In many instances, this measurement would not necessarily represent the exact fluctuations in velocity. This can be realized by considering measurements made in a perfectly mixed turbulent stream, in which instance only a mean shift in conductivity would be observed; however, turbulent velocity fluctuations would go undetected. Nonetheless, the potential exists to characterize simultaneously both the mean and spectral characteristics, which are otherwise extremely difficult to measure. With this in mind, we have implemented a single-tip conductivity probe in conjunction with advanced signal processing to fully characterize mixing quality in semiconcentrated suspensions, including both the mean and spectral characteristics of the mixing. We did so for monodispersed suspensions consisting of 130-µm microspheres and for rayon of 2-mm length and 60-µm diameter (aspect ratio, r = 33) for flow at water-based Reynolds numbers of 57000 and 114000.

EXPERIMENTAL

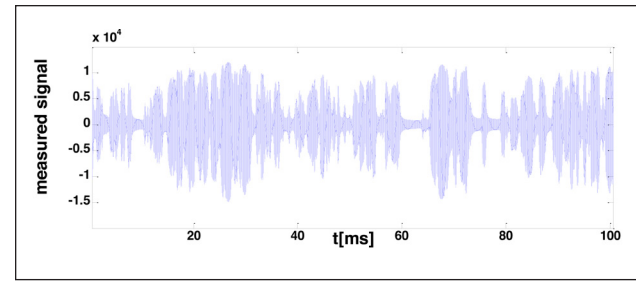
The experiments were performed in the recirculatory pipe flow facility of Innventia AB. **Figure 1** shows a schematic diagram of this facility. The main part of this facility consists of two long sections of cylindrical Perspex pipe, with length of 3 m and inner diameter of 57 mm. The flow loop was constructed in a modular manner so that different piping and experimental setups could easily be studied. The fluid was recirculated from an open reservoir, approximately 1 m^3 in volume, which was mixed continuously with a 40-cm-diam impeller. The bulk suspension flow was driven by an ITT 4.2 kW variable frequency drive centrifugal pump (Flygt pump 3102– 152-mm impeller, ITT Flygt AB; Sundbyberg, Sweden). Flow was measured through the device with an ABB magnetic flow meter (Fisher & Porter model no. 10DS3111, ABB Process Automation; Cary, NC, USA). Pressure sensors were mounted on either end of the pipe (Fuji FKC X22, 6 kPa, and FKC X35, 130 kPa; Fuji Electric Europe, Offenbach, Germany), specifically positioned at 0.25 m and 2.5 m. Velocity profiles can be obtained with a MetFlo DUO ultrasonic Doppler velocimetry profiler (UVP) (HP Products; Indianapolis, IN, USA) with probes mounted 1.0 m downstream from the upper elbow, at an incident angle of 30°. Average conductivity was measured in the reservoir and at the end of the test section using an Hach HQ40D (Hach Company; Loveland, CO, USA) multiparameter measurement probe. Temperature was also monitored with this tool. A long brass pipe (6-mm inner diam, 8-mm outer diam) was used for injection of a high-conductivity saline solution. It was inserted through the center of the 90° elbow and its axial position was adjusted manually. Flow of the salt dosage was controlled manually with pressurized air and monitored with an ABB magnetic flow meter, (Fisher & Porter model no. 10DS2112A). The high resolution conduc-



1. Overview of the Innventia flow loop facility.



2. The conductivity microprobe with a 25-µm platinum tip measuring electrode.



3. Example of the raw signal as measured by the conductivity probe. The instance shown here is for flow with rayon fibers, 1 m/s, Re_w = 57000.

tivity probe was mounted 50 cm downstream from the upper elbow. It should be pointed out that this distance represented only 10 pipe diameters downstream from the 90° elbow, and therefore there was a high risk of swirl and other asymmetries in the flow. The radial position of the probe could be adjusted manually. A brass reference electrode was flush mounted along the inside of the pipe, approximately 20 cm upstream of the conductivity probe. All data were logged continuously while the facility was in operation using LabVIEW (National Instruments Sweden AB; Kista, Sweden).

Conductivity probe

Local conductivity measurements were made with a single-tip conductivity probe and a copper counter electrode mounted upstream and made flush with the pipe wall. The measurement electrode, which was made by a 25-µm diameter platinum wire, was embedded in a fine ceramic capillary and glued with a UV-curing capsule resin. The platinum wire was cut in level with the resin, leaving a 25-µm-diameter point visible at the probe tip. The ceramic capillary was then glued into a stainless steel tube and fitted into a brass holder that provided strength and a manageable interface with the external equipment. An electrically insulated wire soldered to the platinum wire was run through the probe holder and connected it to the measurement circuit. **Figure 2** is a sketch of the probe design. Complete details of the construction and performance of the probe can be found in [8].

Signal processing

The probe was excited with a 20-kHz sinusoidal analogue signal, ± 2 V, and sampled at a rate of 800 kHz. The small-scale fluctuations in the local conductivity were detected as modulations in the amplitude of the 20-kHz response signal (**Fig. 3**).

Fluctuations in the local conductivity were determined from the modulated amplitude of the sampled signal. To detect the modulated signal, a sine wave, with the same frequency but different phase and amplitude, was fit to each period of the sampled signal (Eq. [1]):

$$A(t) = A_i(t)\sin(\omega t + \varphi_i) \quad (1)$$

where $A(t)$ is the measured amplitude modulated signal, $A_i(t)$ and φ_i are the amplitude and phase shift of the i^{th} 20 kHz sinusoid wave of the response signal. For conductivity measurements to be comparable to each other, the measured values were normalized according to Eq. (2):

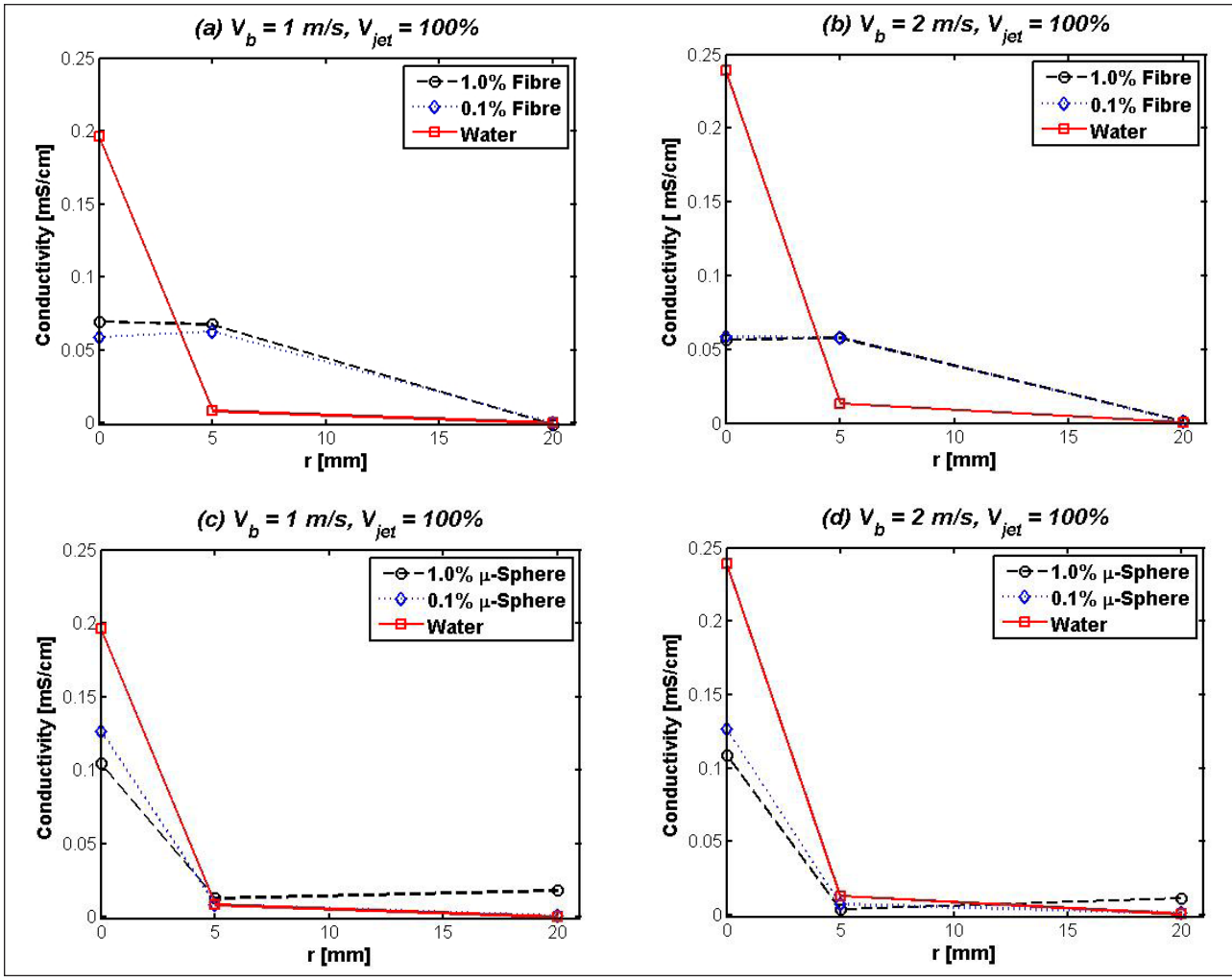
$$\overline{C}(r,t) = \frac{C(r,t) - C_{outer}}{C_{inner} - C_{outer}} \quad (2)$$

where $C(r,t)$ is the local conductivity measured by the microprobe, C_{inner} is the mean conductivity measured by the microprobe placed in a bath of the dosed saline solution, and C_{outer} is the mean conductivity measured by the commercial probe placed at the end of the test pipe. It is further assumed that the conductivity signal can be expressed as a mean and fluctuating signal, C_m and c' respectively, i.e., $\overline{C} = C_m + c'$.

At each measurement point, the mean and fluctuating conductivity measurements were collected for approximately 30 s. The turbulent spectrum, $\Phi(f)$, was then computed from the Fourier transform of the square of the fluctuating signal, c'.

Experimental conditions

Two types of particles were considered, at two different concentrations each. The first suspension consisted of polystyrene microspheres (Dynoseeds), with diameter, d_s = 130 µm, and specific gravity, SG_s = 1.05, suspended in tap water. The second suspension consisted of rayon fibers, with mean length, L_f = 2.0 mm; mean diameter, d_f = 60 µm; and specific gravity, SG_f = 1.50, suspended in tap water. The aspect ratio of these fibers, $r_f \approx 33$, and the tensile and flexural modulus were 1.11 GPa and 1.03 GPa, respectively. In general, these fibers were straight; however, a small fraction (approximately 1.5%) were found to be kinked with a mean kink angle of 44.8°. All fiber properties were measured with a L & W Fiber Tester (Code 912, Lorentzen & Wettre; Alpharetta, GA, USA). Two concentrations were considered for each particle type, namely 0.1% and 1.0% volume fraction. For the fiber suspensions, these concentrations corresponded to crowding factor values of 84 and 840, respectively. The Reynolds numbers considered here, base pipe diameter, D = 57 mm, mean suspension flow velocity and on the density and viscosity of



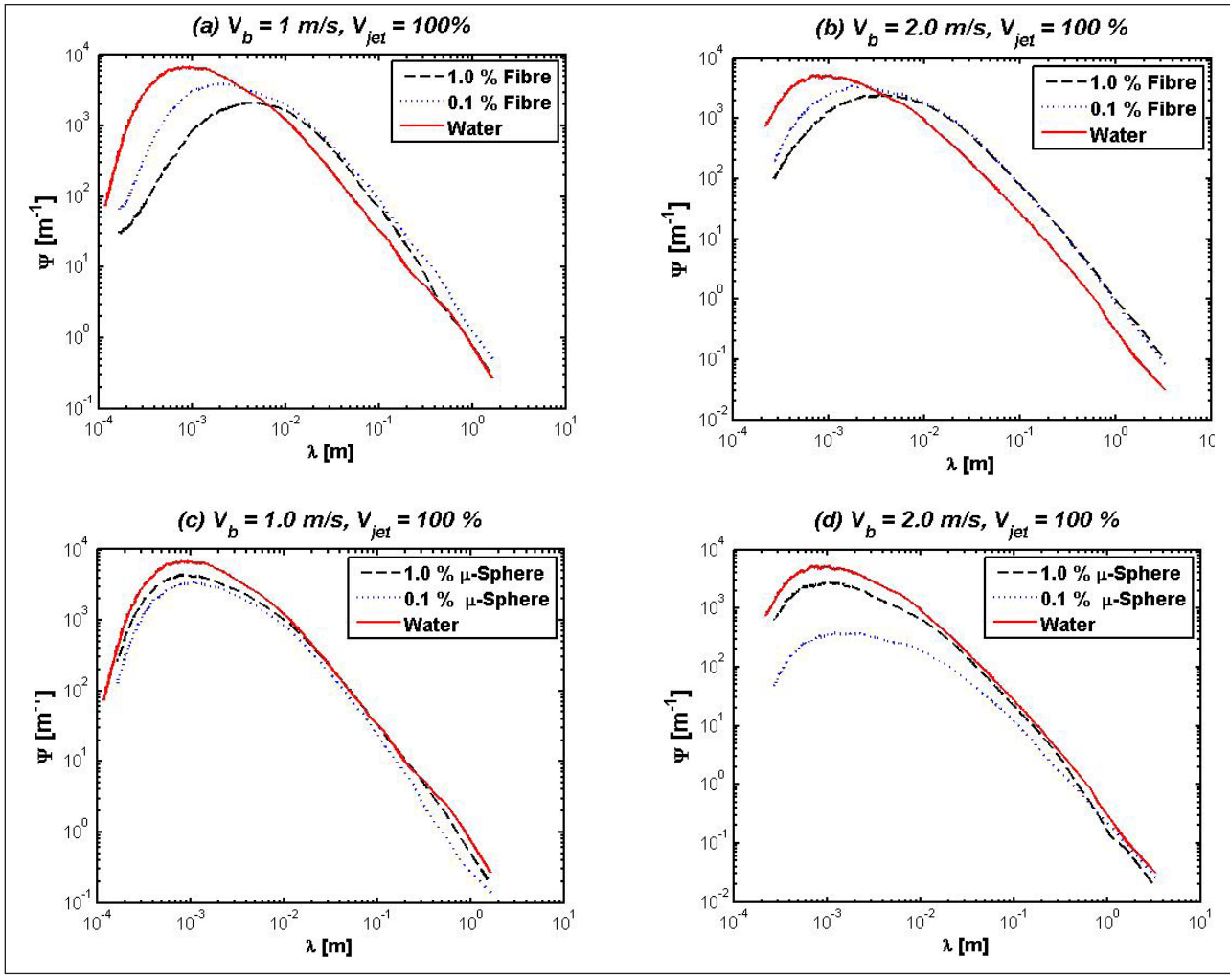
4. Mean conductivity profiles for dosage into (a) rayon fiber suspensions, v_b = 1 m/s; (b) rayon fiber suspensions, v_b = 2 m/s; (c) microsphere suspensions, v_b = 1 m/s; (d) microsphere suspensions, vb = 2 m/s. In all instances shown, the relative dosage velocity equals the bulk suspension velocity, i.e., v_{jet} = 100%.

water, were Re_w = 57000 and 114000 (corresponding bulk velocities, vb = 1 m/s and 2 m/s, respectively). A saline solution consisting of table salt dissolved in tap water, 50 g/L in concentration, was used as the passive conductive tracer. The saline solution was injected into the suspensions with relative velocities of 80%, 100%, and 120% of the bulk suspension velocity, which was controlled manually by pressurized air and monitored with a magnetic flow meter. In all cases, the saline solution was injected along the pipe centerline, 10 cm upstream from the conductivity probe.

RESULTS

Conductivity measurements were made with the probe positioned at three different radial positions, namely along the pipe centerline, r = 0, and at radial distances r = 5 mm and r = 20 mm from the centerline. **Figure 4** presents profiles of the mean conductivity levels for the different suspension flows. Variations in these measurements represent the mean dispersion of the dosed stream in response to the suspension contents. It should be mentioned that the statistical error in these measurements was extremely small due to the large number of samples collected at each point (approximately 30 s of sampling x 20000 samples/s); therefore, error bars are not included with these plots.

The first observation to be made from the mean conductivity profiles was that the saline stream was highly concentrated around the pipe centerline for both the water and microsphere suspensions. This was clear from the large peak in conductivity at r = 0 and the relatively low and near-constant values in conductivity at larger radial distances. However, with the fiber suspensions, the saline stream was found to disperse to at least as far as r = 5 mm, as indicated by the near-equal and relatively larger values of conductivity at r = 0 and r = 5 mm. This result is interesting and will be commented on further after investigating the turbulence spectra. The general effect of the solids phase was to suppress the mixing of saline solution in the flow direction. A greater suppression of mixing was also noted at higher solids



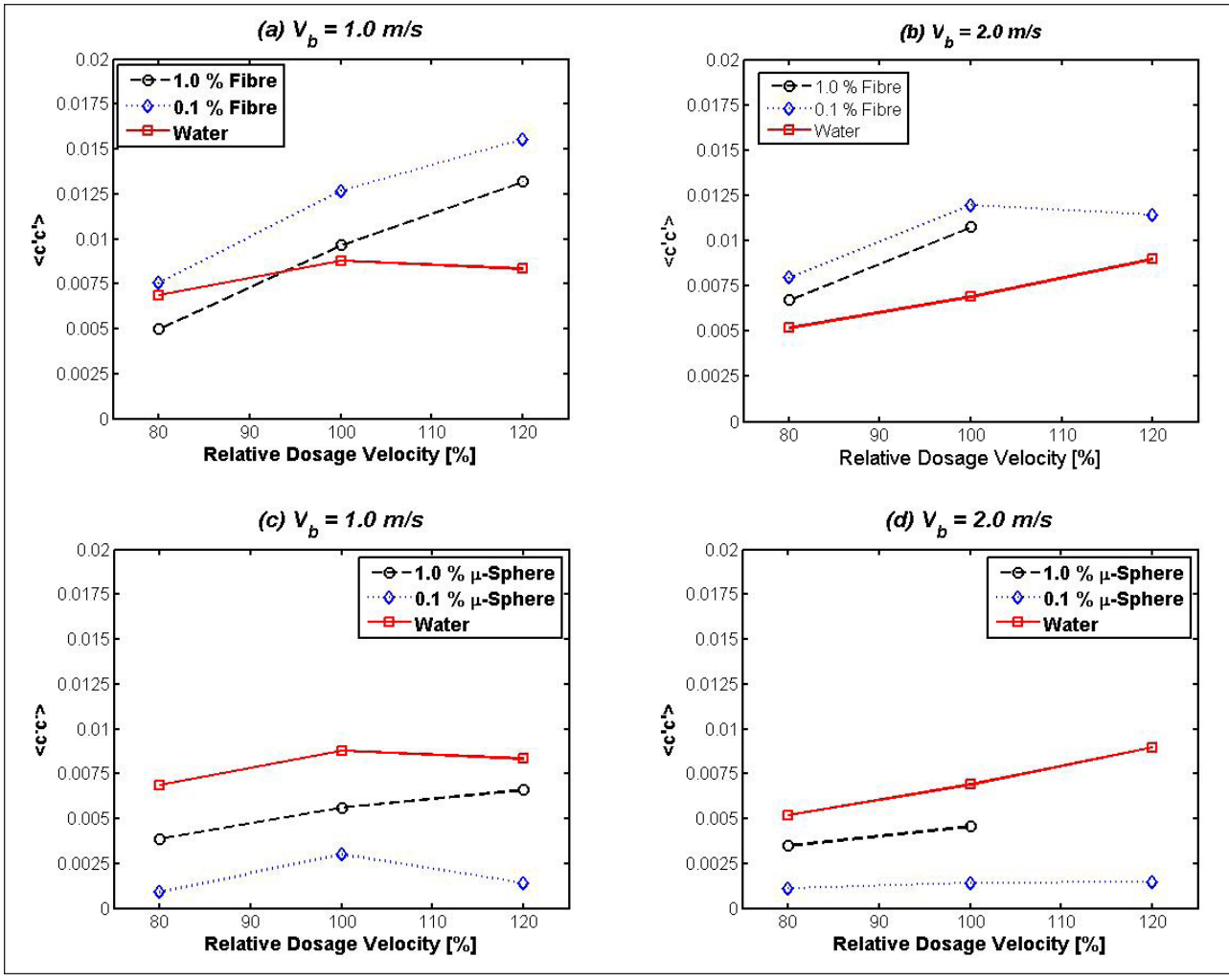
5. Estimates of the turbulent spectra along the pipe centerline for dosage into (a) fiber suspensions with bulk velocity, v_b = 1 m/s; (b) fiber suspensions with bulk velocity, v_b = 2 m/s; (c) microsphere suspensions with bulk velocity, v_b = 1 m/s; and (d) microsphere suspensions with bulk velocity, v_b = 2 m/s. In all instances, the relative dosage velocity is v_j = 100% of the bulk suspension flow.

concentration; that is, lower conductivity levels were measured along the centerline at higher solids concentrations. Also, the suppression of mean conductivity was far greater in the fiber suspensions than in the microsphere suspensions. An increase in the conductivity along the centerline was also noted at higher bulk suspension velocity. This was an effect of increased convection at higher velocity, which therefore led to better transport of the saline solution.

Presented here are estimates of the turbulent mixing spectra measured with the high-frequency conductivity probe for the different suspension flows. All measurements were collected along the pipe centerline. The spectral function, $\Phi(f)$, is defined as the Fourier transform of the square of the modulated conductivity signal, computed in frequency space, f. For convenience, we mapped the frequency-based spectral function to wavelength space, where the wavelength, $\Phi(f)$, is defined in terms of the frequency and bulk suspension velocity, i.e., $\lambda = v_b/f$. Using this definition of wavelength, the wavelength-based spectral function, $\Psi(\lambda)$, can be defined as follows [9] (Eq. [3]):

$$\Psi(\lambda) = \frac{f^2}{v_b}\Phi(f) \qquad (3)$$

Estimates of the turbulent spectra for relative dosage velocity, v_j = 100%, of the bulk suspension velocities v_B = 1 m/s, and 2 m/s, along the pipe centerline are shown in **Fig. 5**. In general, the turbulent spectra were found to be clustered around a definite wavelength value and decayed exponentially at both higher and lower wavelengths. The wavelength spectra were also noted to be skewed toward small wavelengths. However, the character of turbulent spectra was found to be highly dependent on the solids content. For example, with the rayon fiber suspensions, the large wavelength (low frequency) fluctuations were enhanced, while the small wavelength (high frequency) fluctuations were in fact damped. Also observed was a significant shift in the wavelength, corresponding to the spectral peak, to a larger



6. Plots of the pseudo-kinetic energy versus relative dosage velocity for dosage into (a) rayon fiber suspensions, v_b = 1 m/s; (b) rayon fiber suspensions, v_b = 2 m/s; (c) microsphere suspensions, v_b = 1 m/s; and (d) microsphere suspensions, v_b = 2 m/s.

wavelength value than that observed with pure water. These finding suggest that, in fiber suspensions, mixing predominantly takes place over large-wavelength/low-frequency scales, while the small-wavelength/high-frequency mixing eddies are damped by the fiber phase. This observation supports the character of the mean conductivity profiles measured in the fiber suspensions. Recall from Fig. 4, where we noted near-equal mean conductivity levels at the position r = 0 and r = 5 mm; in light of the turbulent spectra, it would appear that the enhanced large wavelength mixing scales were able to better advect the saline solution radially in the fiber suspensions. However, these results might have implications for mixing in papermaking fiber suspensions, where it would be desirable to achieve mixing at all scales. In particular, the high-frequency mixing (small length scale) is believed to be of great importance, because these are the scales most likely to penetrate into fiber flocs and create dispersion at scales at or below that of the fiber length, e.g., when dosing a stock flow with retention aid polymers. Therefore, from a papermaking perspective, additional means may be necessary to enhance the high-frequency scales of turbulence during concentric mixing. As an added observation, the higher concentration suspensions were found to result in slightly lower overall turbulence levels.

The microspheres were found to have a rather different effect on the turbulence spectra. Specifically, the microspheres were found to damp the overall turbulent fluctuations at all scales and to have a negligible effect on the wavelength associated with the spectral peak. In general, the overall level of turbulent fluctuations tended to be lower with low-concentration microsphere suspensions, opposite to what was observed in the fiber suspensions. In general, the behavior of the turbulent spectrum in the microsphere suspension appeared to be preferable to that in the fiber suspensions. From an industrial viewpoint, this result would suggest it may be possible to improve mixing quality if mixing is performed before introduction of the fiber phase.

To investigate the effect of relative dosage velocity on turbulent mixing, we considered the mean-square of the fluctuating conductivity signal, c', which we henceforth refer to as

the pseudo-turbulent energy, E, defined as follows in Eq. (4):

$$E = \langle c' c' \rangle \quad (4)$$

Figure 6 presents plots of the pseudo-turbulent kinetic energy. Of note, the measurement data were determined to be corrupt for $v_b = 2.0$ m/s, $v_j = 120\%$ in the 1.0% fiber suspensions and are not presented. Unfortunately, this was realized after the signal processing routine was completed and the costly resources, including fiber and personnel, were no longer available to remeasure this trial point. However, based on the consistency between the 0.1% and 1.0% fiber suspensions in all other measurements, we assumed that trends with the pseudo-kinetic energy were also similar.

Figure 6 shows that the pseudo-turbulent energy increased with saline dosage velocity in all instances. This relationship was generally found to be monotonic yet slightly nonlinear. The effect was also shown to be highly dependent on particle type. For example, with the fiber suspensions, *E* increased significantly with dosage velocity. However with the microsphere suspensions, *E* increased gradually with dosage velocity. The case with pure water represented an intermediate region between the fiber and microsphere suspensions. The pseudo-turbulent energy was also found to decrease as the solids concentration increased in the fiber suspensions, whereas it was found to increase with solids concentration in the microsphere suspensions.

The effect of dosage velocity on the pseudo-turbulent energy observed in this study was similar to those presented by Norman and Tegengren [2], where the effect of relative dosage velocity of a dyed fiber suspension, mixed into water, was studied through high-speed imaging. They showed a similar trend, i.e., improved spatial mixing with increased relative dosage velocity. Comparison of the results from Norman and Tegengren [2] with the results of this work would suggest that the pseudo-turbulent energy, as measured with these conductivity probes, might serve as a useful global measure of mixing quality in high-concentration suspensions.

CONCLUSION

A new method for fully characterizing turbulent mixing and dispersion of a dosage stream in semiconcentrated suspension flow was presented. A high-frequency conductivity probe was used in conjunction with advanced signal processing to measure the turbulent fluctuations of a saline solution injected into semiconcentrated, monodispersed fiber, and microsphere suspensions. The mean conductivity signal gathered with this tool was used to estimate the local concentration of the added saline stream at a given point in the flow; that is, the mean spatial dispersion of the dosed stream. Analysis of the high-frequency fluctuating conductivity signal allowed for characterization of the local mixing energy and turbulent

ABOUT THE AUTHORS

Turbulent fiber suspensions is a complex and therefore fascinating subject that presents one of the greatest challenges to the paper forming process. We believe a breakthrough in this area would be a huge benefit to both industry and science.

Previous research has been focused largely on understanding the coupling between solids phase and turbulence, rheology and flow properties during processing and forming. Much work has been dedicated to this research area from a fundamental, modeling perspective, although measurements in these flows and under process conditions are difficult to obtain. This work sheds light on previous modeling and experimentation with respect to stock mixing, chemical addition, and headbox flows.

Probably the greatest difficulty in this work related to calibration of the measurement probe combined with verification of the measurements and results. A great deal of effort was spent ensuring the measurements we collected were in fact what we wanted to measure and not just noise, interference, or other garbage signals.

The most interesting finding was the different effect of different solids types (for example, spheres versus fibers) on turbulence properties. The finding that fibers enhance large-scale (low frequency) mixing scales can be misleading if only the mean conductivity signal is collected. In fact, both mean and spectral information are needed to accurately characterize mixing quality.

Mills should consider the approach they take to chemical addition; for example where, when, and how they add chemicals. Steps should be taken to enhance small-scale (high frequency) turbulence during mixing.

For the next step, we would like to install this probe in an actual approach flow pipe of a mill, or perform studies in an industrial headbox to improve, for example, the design of the turbulence generators, tube banks, and nozzle vanes. Other studies might include dosage of retention aid polymers into a papermaking stock flow, i.e., consisting of cellulose fiber, fines, and filler.

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spectrum, i.e., the spectral mixing scales available in the suspensions for a given set of flow conditions.

The fiber phase effectively increased the low-frequency turbulence in the suspension, attenuated the high-frequency turbulent scales, and had the general effect of increasing the overall turbulence energy in the dosed saline stream. The microspheres were shown to effectively damp the overall turbulence in the saline stream at all scales, and the effect of concentration was shown to be opposite in the fiber suspensions and microsphere suspensions. The overall turbulence in the saline stream was characterized by the pseudo-turbulent kinetic energy, which was shown to increase monotonically with dosage velocity in all suspension and in pure water. **TJ**

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