Velocity measurements of fiber suspensions in pipe flow by the nuclear magnetic resonance imaging method

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ABSTRACT: Nuclear magnetic resonance (NMR) imaging was used to measure mean velocity profiles of wood pulp suspensions undergoing steady pressure-driven flow through a horizontal circular pipe. Suspensions of hardwood and softwood kraft pulps at different consistencies were studied at mean flow rates up to about 1 m/s. At a given flow rate, the mean velocity profile for a pulp suspension is highly dependent on the stock consistency and the physical characteristics of the fibers. Various flow patterns from plug flow to complex flow were observed for hardwood pulp suspensions of 0.5 wt.% and 0.63 wt.% fiber concentrations, whereas only plug flow was observed for a softwood kraft pulp suspension of 0.86 wt.% fiber concentration. Possible flow mechanisms are presented to explain the observed velocity profiles.

KEYWORDS: Betula, dispersions, fibers, hardwood pulps, nuclear magnetic resonance, pipe flow, profiles, pseudotsuga menziesii, softwood pulps, velocity measurement.

Pulp flow is involved in many unit operations of the papermaking process, such as beating, screening, pumping, and forming. The understanding of flow behavior and microstructure dynamics is therefore important to paper technology *(1, 2)*.

The key to most unit operations is the disruption of the fiber network and the creation of a "fluidized" state by shearing stress *(3)*. Despite extensive studies for nearly half a century *(3–5)*, direct visualization of the fluidization process of pulp suspension at consistencies used in industrial practice remains rather restricted because of the experimental difficulties. We have applied the NMR (nuclear magnetic resonance) imaging technique to observe the flow of cellulose fiber suspensions undergoing steady pressure-driven flow in tubes. Such flow is commonly used in paper mills *(4, 5)*, and its simple geometry can help conceptualize flow patterns in more complicated geometries *(6)*.

NMR imaging is a noninvasive method based on the paramagnetic properties of nuclei. In an NMR imaging experiment, the required signals are obtained by designing radio frequency pulses *(7)* and magnetic field gradient pulses of different waveforms to interact with the spin system positioned in a static magnetic field. Here the phase information of the signals was used to encode the velocity of the fluid. This was carried out by applying magnetic field gradient pulses of bipolar form so that the phase of the ^1H magnetization was sensitive only to the velocity of the spins *(8, 9)*.

Because of the angular symmetry of pipe flow, a joint spatial–velocity, two-dimensional image is sufficient to provide all axial velocity information. The spatial information in the direction perpendicular to the flow was extracted from the frequency spectrum of the NMR signals. This was performed by applying a linear magnetic field gradient pulse during signal acquisition *(10)*.

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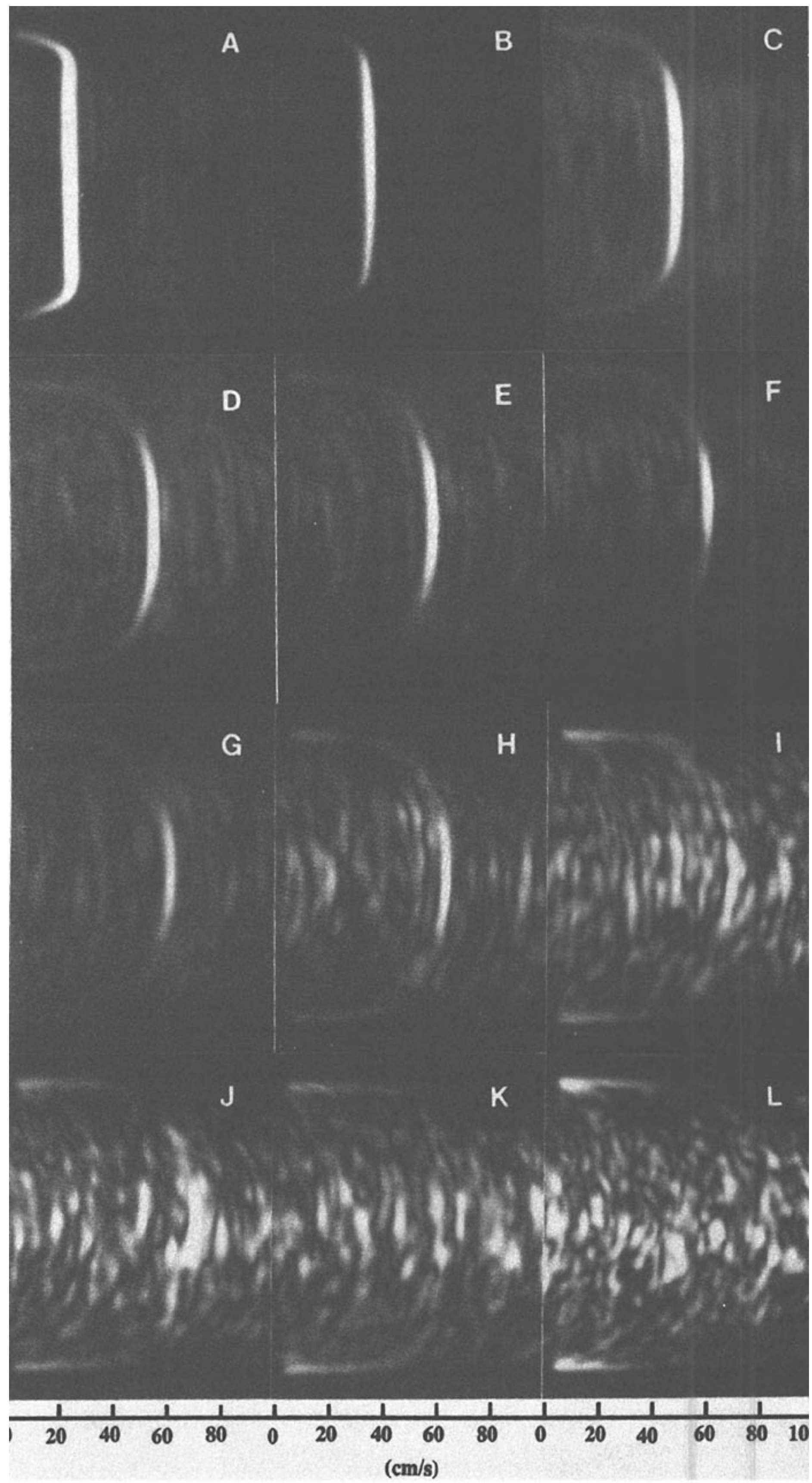
Experimental

The experimental flow system used to study the flow of pulp suspensions in a tube consists of a section of 26.6-mm-ID plexiglass pipe in a flow loop 12 m in length. A portion of the tube was in a 2 T Oxford magnet (corresponding to 85.5 MHz ^{1}H resonance frequency), which was connected to a General Electric CSI-II NMR imaging spectrometer. The length of straight pipe preceding the magnet was approximately 4.5 m (length/diameter =175), providing sufficient length for the flow profile to be fully developed.

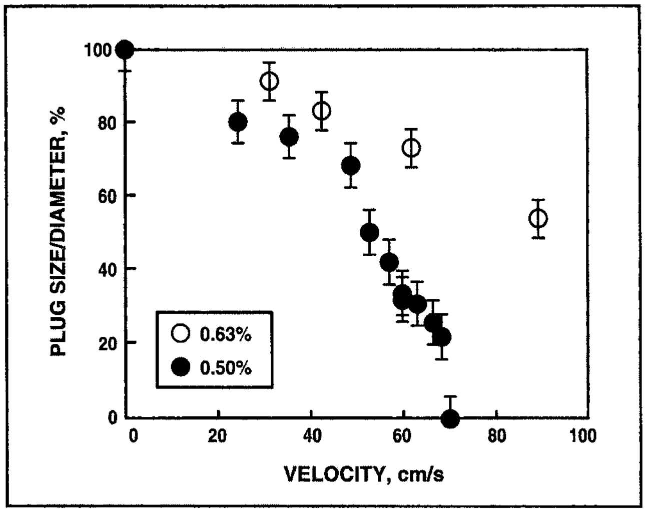
A positive-displacement pump (SPS-20, Orange, USA) was used to pump the cellulose fiber suspensions. Suspensions of 0.5 wt.% and 0.63 wt.% fiber concentrations were prepared from bleached hardwood (birch) kraft pulp (Mörrum, Sweden). A suspension of 0.86 wt.% fiber concentration was prepared from bleached softwood (Douglas-fir) kraft pulp (Weyerhaeuser, USA), which is a relatively long-fibered pulp. Distilled water doped with $CuSO_4$ was used to prepare the fiber suspensions. This doping reduces the NMR relaxation times of the flow medium, which shortens the excitation time of the spin system and allows rapid data acquisition.

The flow phase encoding gradient was systematically incremented 128 times in each imaging experiment so that a 256 x256 image was obtained after zero-filling. The total experimental times varied from less than 2 min, producing a flow image for steady flow with two coadding signal acquisitions, to a few hours, obtaining a time-averaged flow image for unsteady complex flow with 160-signals coadded. A two-dimensional Fourier transformation (FT) technique was used to reconstruct the joint spatial–velocity ^{1}H spin density distribution image. The receiver/transmitter coil is a handmade 100-mm bird-cage coil. Independent estimates of the area-averaged flow rates were carried out by timed collection of the flow material. The bulk flow rates measured in this manner are consistent with the NMR imaging results within the 90% statistical confidence interval of the timed collection data.

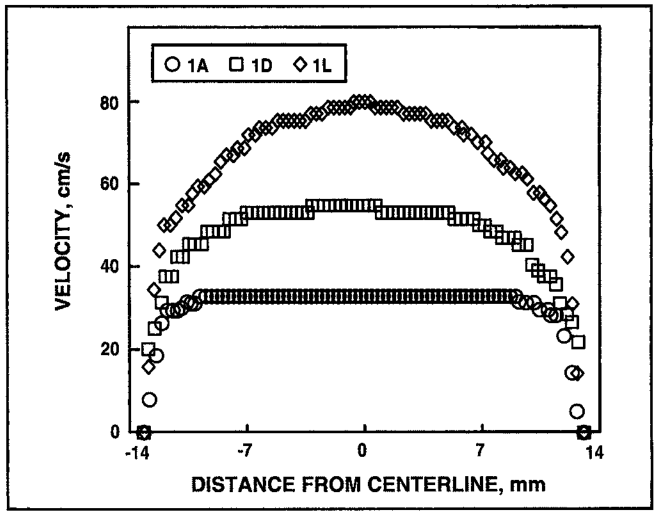
1. Joint spatial–velocity ^{1}H spin density distribution images of a cellulose fiber suspension prepared from hardwood kraft pulp at 12 mean flow rates. Fiber concentration in pulp suspension is 0.5 wt.%.



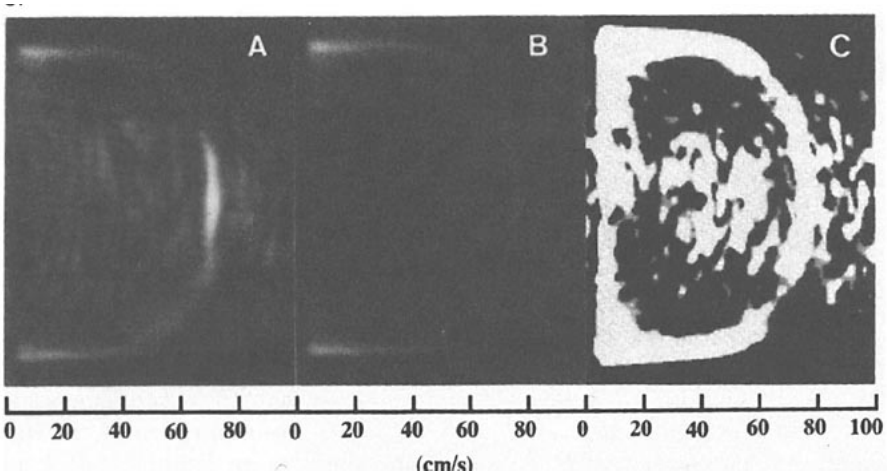
2. Plug size as a function of mean flow rate for hardwood pulp suspensions at two levels of fiber concentration (0.5 wt.% and 0.63 wt.%)



4. Mean velocity profiles for a hardwood kraft pulp suspension (0.5 wt.% fiber concentration) at three mean flow rates. Data obtained from quantitative analysis of the flow NMR images in Figs. 1A, 1D, and 3C



3. Time-averaged flow NMR images of the turbulent flow shown in Fig. 1L. The area-averaged bulk flow rate is 71 cm/s. The number of signals averaged to produce Images A and B are 40 and 160, respectively. A display of Image B with larger brightness contrast is shown in Image C.



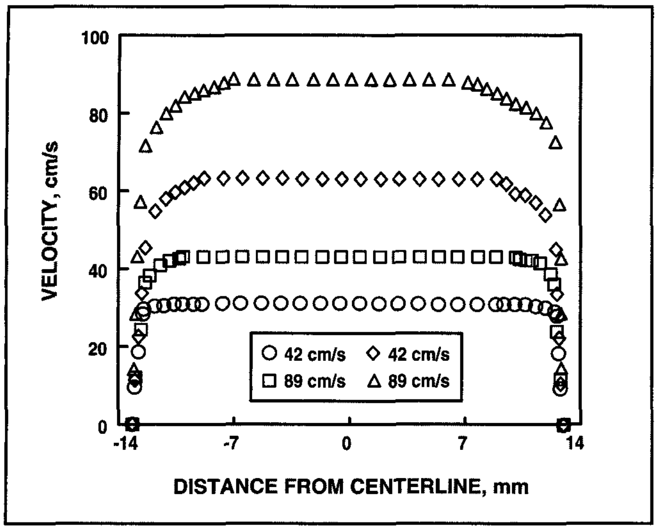
Results and discussion

NMR imaging allows direct determination of the velocity profiles throughout the opaque cellulose fiber suspensions *(11)*. **Figure 1** shows flow NMR images for a 0.5 wt.% hardwood pulp suspension at different mean flow rates. As expected, the pulp suspension exhibits three basic types of shear flow as mean flow rate is increased: plug flow (Figs. 1A and 1B), mixed flow (Figs. 1C–1H), and turbulent flow (Figs. 1I–1L). These basic flow patterns for pulp suspensions were originally suggested by Robertson and Mason based on their experimental studies on the flow of dilute pulp suspensions (0.05 wt.%) in tubes *(3, 12)*. Similar qualitative descriptions have also guided much of the discussion regarding rheological properties of fiber suspensions at higher consistency *(13, 14)*.

Although inferences about bulk flow observations near a wall or indirect measurements in specialized rotational devices *(5, 13)* support such descriptions, direct visualization of the flow has not been available for pulp suspension with fiber concentrations up to 0.5 wt.%. Here the flow patterns for opaque pulp suspensions are directly visualized with the advantage of the NMR imaging technique. Detailed analysis of the flow NMR image reveals the complex interactions between the microstructures of suspensions and the flow. At low bulk flow rates (Figs. 1A and 1B), there is a thin sublayer adjacent to the pipe wall, where the velocity distribution is nearly linear. The thickness of this sublayer is the same order of magnitude as that of the laminar sublayer for pure water at the same bulk flow rate. This suggests that the layer next to the pipe wall is fiber-depleted.

NMR imaging is an averaging method. The time resolution of an ordinary phase flow encoding NMR imaging experiment is about 100 ms, which is the same order of magnitude as the time scale of turbulent fluctuations. The NMR signals for turbulent flow are therefore "partially averaged," which leads to intensity attenuation of the reconstructed flow NMR image. This allows us to distinguish the region of steady plug flow from the region undergoing unsteady complex flow and to estimate the plug size. In

5. Mean velocity profiles for a hardwood kraft pulp suspension (0.63 wt.% fiber concentration) at four mean flow rates. Data obtained from quantitative analysis of the flow NMR images at the corresponding mean flow rates.



6. Velocity distributions for a softwood pulp suspension (0.86 wt.% fiber concentration) at two mean flow rates

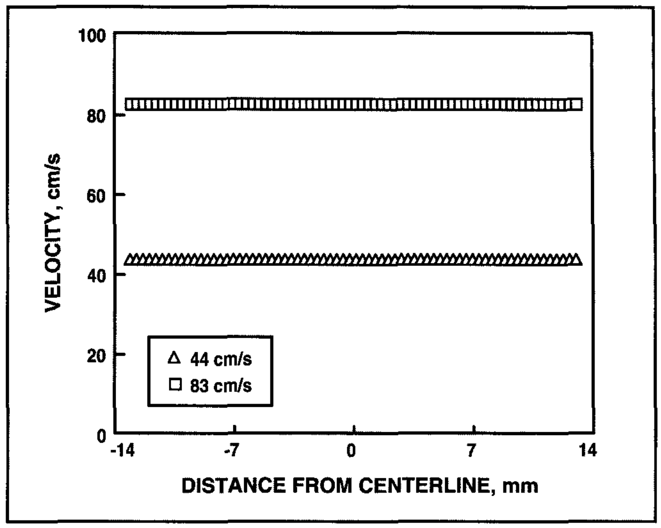


Fig. 2, the plug size—estimated from the lengths of the bright regions in the flow NMR images—is presented as a function of the average flow rate for hardwood pulp suspensions of two concentrations. In both cases, the radius of the plug decreases as the mean flow rate is increased.

In order to obtain the mean velocity profile for turbulent flow, a statistically averaged stationary signal must be recorded. This is achieved by extending the experimental time in each phase flow encoding step to the order of a few seconds. **Figure 3** shows the time-averaged flow NMR images for the turbulent flow shown in Fig. 1L. The intensity of the image is unevenly distributed (Figs. 3B and 3C). Intensity losses are greatest in the outer regions of the viscous sublayer, where the turbulent intensity (root-mean-square value of the velocity fluctuation) is highest. The turbulent intensity distribution can be evaluated from the intensity distributions of the time-averaged image. The mean velocity profile for the turbulent flow (Fig. 1L) is shown in **Fig. 4**, together with the typical velocity profiles for plug flow (Fig. 1A) and mixed flow (Fig. 1D).

As discovered in previous studies *(1, 3, 15)*, the flow behavior of the suspension varies with the fiber concentration in the suspension as well as with the characteristics of the fiber. **Figure 5** shows the velocity profiles for a hardwood pulp suspension of 0.63 wt.% at different average flow rates. These data were obtained by a quantitative analysis of the corresponding flow images. Compared with the velocity profiles for the pulp suspension of 0.5 wt.% at the same mean flow rate (Fig. 4), the difference is obvious. The difference in flow behavior between these two suspensions is also clearly demonstrated by the dependence of plug size on the mean flow rate.

As shown in Fig. 2, a much higher average velocity is needed to fully fluidize the suspension of 0.63 wt.%, although the fiber concentration is only slightly higher. The influence of fiber properties on flow behavior is even more dramatic. **Figure 6** shows the velocity profiles of a softwood pulp suspension of 0.86 wt.% at two mean flow rates. In both cases, the velocity profile is a horizontal line, indicating that there is little variation in velocity across the tube and that the suspension is undergoing plug flow. At the highest velocity achieved in the experiment (up to 83 cm/s), the plug is still intact, and the thickness of the fiber-depleted water annulus next to the tube wall is much thinner than the spatial resolution of the flow NMR image, which is 196 μm/pixel.

The differences in flow behavior among the pulp suspensions are directly related to the microstructure of the suspensions. Quiescent cellulose fiber suspensions are macroscopically heterogeneous, containing regions of relatively high fiber concentration, called flocs. Above a critical concentration—depending on such fiber physical properties as aspect ratio, modulus, and surface chemistry—flocs tend to form a continuous network structure throughout the suspension. The strength of the network increases with fiber concentration of the suspension at a rate that is characteristic of the pulp *(2, 3)*. The typical length of the American Douglas-fir fiber (2–5 mm) is twice that of the Swedish birch fiber (1–2 mm). Longer fibers provide more contacting points between fibers, resulting in greater mechanical entanglement and hence a stronger fiber network *(1, 2)*.

Classical correlations *(2)* suggest that such physical differences should account for the observations reported here. We expect that at higher mean flow rates, various flow patterns from plug flow to full turbulence will be observed for the relatively long-fiber suspension. However, the accessible mean flow rate is currently limited by the capacity of the pump being used. Finally, by combining NMR imaging measurements with independent measurements of pressure drop, it will be possible to directly infer rheological parameters, such as the yield stress of a pulp suspension *(11, 16)*.

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CORRECTION

Figure printed incorrectly

The four-color segment of a figure was inadvertently ommitted in Figure 2 of a paper by Age Hansen, Pal Moestue, Klaus Moller, Bjorn Themassen,and Harald Nostdal in the January 1994 issue of *Tappi Journal* ("The *Dagbladet* full-scale printing trials, p. 139). The corrected figure appears below.

2. Test form. (Color identifications and percentages are for reference only. This information was not printed on the test form.)