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"High Performance Composites"

THE RHEOLOGY OF FIBROUS MATERIALS IN LOW VISCOSITY MEDIA: A Literature Survey

Charlotte M. Bower, Editor

Michael K. Collins

John D. Calfee, Program Manager

March 18, 1966

Monsanto Company/Washington University
St. Louis, Missouri

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FOREWORD

The research reported herein was performed under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-66-C-0045, order number 1001/58(C-65-006).

The prime contractor is Monsanto Research Corporation. The Program Manager is Dr. John D. Calfee (Phone: 314-WY 3-1000, station 3754). The work is done by Washington University, St. Louis, Missouri with Dr. James M. McKelvey (Phone: 314-VO 3-0100, station 4464) as Project Director, and Monsanto Company, Central Research Department, St. Louis, Missouri, with Dr. John D. Calfee as Project Director.

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Prepared for the Advanced Research Projects Agency under Contract N00014-66-C-0045, Order Number 1001/58(C-65-006)

ABSTRACT

The results of a literature search of the field of the rheology of fibrous materials in low viscosity media are presented. Low viscosity was defined as any viscosity less than or equal to that of water. Thirty references with abstracts are given.

TABLE OF CONTENTS

I. INTRODUCTION

Since many composite materials consist of an incorporation of a dispersion of fibers in a continuous matrix phase, it is logical to ask several questions: by what techniques could fiber suspensions or lay-up of fibers from solution be put to advantageous use in facilitating composite fabrication and what rheological properties of such a system could be utilized to produce a desired fiber orientation in the finished structure? It was the desire to elucidate the answers to such questions that generated this search of the literature.

The field divides itself naturally into two areas, fiber flow in high viscosity and low viscosity media. This search encompasses the latter section, low viscosity media being defined for our purposes as those with viscosities in the range from air to those slightly more viscous than water.

In the initial stages of research in any virgin field, the literature is more often useful in telling one what has not been done, rather than the converse. Such is certainly the case in this search. Depending upon the viewpoint taken, the field of rheological behavior of liquid-fiber systems is either dishearteningly barren or refreshingly unsullied by the footprints of previous investigators. For our purposes, the literature cannot truly be said to answer any questions. In some areas of fibrous flow, the literature provides insight and suggests further work; in others, no light is shed.

In consideration of the limited amount of material found, an interested party would be better profited by directly consulting the references given than by attempting to draw conclusions from a superficial survey of the literature content. This paper will therefore present only a brief iteration of the kinds of information to be found in the literature, and it will conclude with an enumeration of those problems to which little or no consideration has been given.

II. GENERAL SUMMARY OF THE LITERATURE CONTENT

The majority of the previously conducted investigations, having been carried out primarily by the paper industry on paper pulp-water systems, are concerned with pipe flow phenomena of dilute systems (0.1-5.0% fiber, by weight). Most of the definitive theoretical work has been extrapolated from idealized studies of suspensions of spheres or short rods, and, because of the ease of observation, the rigorous experimental work has been carried out in high viscosity media, thus falling outside the realm of this search. Also, in view of the difficulty of expressing in statistical terms the large number of physical properties which characterize a given pulp, fiber, or experimental procedure, any correlations of the various experimental data will be of questionable validity.

With respect to knowledge of the various properties of the system under consideration, the state of the art is well summarized in the following statements.

Ideality of the System

Fibrous flow systems are definitely non-Newtonian in character. The velocity profile is much flatter than for corresponding Newtonian flow, the flatness increasing with fiber concentration.

Regimes of Flow

Robertson and Mason (1957) found that "for fiber concentrations above 0.2%, three regimes of flow may exist, which are designated as plug, mixed, and turbulent flow. The mixed flow represents a transition region in which there exists turbulent flow near the wall and plug flow at the center of the tube."

Types of Laminar Flow

Under certain conditions for fibers in pipe flow, Baines (1959) reports two types of laminar flow: (1) the movement of fibers as a solid body with water without internal friction, and (2) a thin film of water near a solid boundary. For pulp stock, the water film was so thin that the rate distribution could be considered linear.

Daily and Bugliarello (1959) came to the same conclusions and proposed a mechanism in qualitative terms for the annulus formation.

Effect of Fiber Properties

Very little has been discovered with respect to the effect of various fiber properties. Bugliarello and Daily (1961) have observed that fiber stiffness can account for observed differences in the point of transition to turbulence, the extent of the transition region, and the pressure drops in turbulent flow.

Fiber Orientation During Flow

In the only study primarily concerned with fiber orientation during flow, Baines and Nicholl (1956) found that "for laminar flow there is a definite tendency for the fibers to point in the direction of the streamlines in fully developed pipe flow. For turbulent flow it was found that in the central portion of the pipe random orientation existed, but near the walls there was a definite tendency for fibers to align along the streamlines. In a contracting section of the pipe circuit it was observed that the fibers over the full cross-section were aligned by the fluid acceleration for both laminar and turbulent flow. The resulting orientation at the end of the contraction persisted down the straight pipe until the flow became fully turbulent."

III. QUESTIONS NOT ANSWERED BY THE LITERATURE

Most of the pertinent problems of the employment of rheological systems for composite fabrication remain untouched in the literature. The most obvious of these problems are considered below.

1. Of the flow systems explored, only pipe flow has received appreciable attention. Before final decisions are made, other vehicles of transfer must be investigated.

2. Only cellulose fibers have been considered in depth. It may be found that rheological properties vary widely as other types of fibers are employed.

3. In an effort to retain some approximation of ideality, researchers have studied only dilute fiber suspensions. Since the strength of a composite is proportional to the percent reinforcement, any rewarding "in solution curing" techniques would involve systems of much higher fiber concentration. The characteristics of such a system would be expected to deviate greatly from the dilute case.

4. No studies were found of fibers in a medium of changing viscosity. The effect of changes in this parameter must surely be considered before processes are developed which implement a resin stage change during flow.

5. Composite properties are extremely dependent on fiber orientation and many obstacles must be surmounted before reliable prediction and control of fiber orientation by rheological procedures is possible. The proper control of distribution and consistency of fibers across a flowing system is also far from realization.

IV. SCOPE OF SEARCH

A search such as this is fraught with red herrings, and the number of journals and publications consulted in screening the literature is far too great for individual enumeration. The publications which constituted the main body of the search are listed below.

CHEMICAL ABSTRACTS

INDUSTRIAL AND ENGINEERING CHEMISTRY

PROCEEDINGS OF THE FOURTH INTERNATIONAL CONGRESS ON RHEOLOGY

RHEOLOGICA ACTA

RHEOLOGY ABSTRACTS

TECHNICAL ASSOCIATION OF THE PULP AND PAPER INDUSTRY

TRANSACTIONS OF THE SOCIETY OF RHEOLOGY

The time period from January 1941, through February 1966, has been searched, although several papers published before 1941 which were found in bibliographic references have also been included.

From the nature of the subject and the references found, there is every reason to believe that essentially all of the pertinent literature was unearthed.

V. ABSTRACTS

Aquila, J. O., "Hydrodynamic technology of cellulose pumps," Ion, 19, 233-44 (1959).

The principles of fluid flow are discussed with their application to the flow of pulp suspensions, very dilute fiber suspensions, paper pulp suspensions, and specific conditions encountered in their handling. (from Chemical Abstracts)

Baines, W. D., "Laminar flow of dilute fiber suspensions," Svensk Papperstidn, 62, 823-8 (1959).

The laminar flow of dilute fiber suspensions, pulp stock 5% by weight, primarily in pipes, is discussed on the basis of the viscous-flow theory. Two types of laminar flow were observed: (1) the movement of fibers as a solid body with H_2O without internal motion, and (2) a thin film of H_2O near a solid boundary. For pulp stock, the H_2O film was so thin that the rate distribution could be considered linear. Flow in pipes was discussed in detail, especially friction-loss characteristics. Flow between two rotating concentric cylinders showed the same properties as pipe flow. (from Chemical Abstracts)

Baines, W. D. and Nicholl, C. I. H., "Hydrodynamics of the Fourdrinier wet-end. 1. Fiber orientation in pipe flow," Pulp and Paper Mag. Can. 57 (6), 119 (1956).

For the initial phase of a broad study of the transport of fibres in water, observations have been made of very dilute suspensions of artificial fibres. Photographs of various flow conditions have been taken, the discussion of which constitutes this note. The Reynolds numbers, based on pipe diameter, ranged from 2000 to 8000 which are roughly of the same order as those encountered in the paper industry. It has been found that for laminar flow there is a definite tendency for the fibres to point in the direction of the streamlines in fully developed pipe flow. This does not agree with the theory developed for small Reynolds numbers. For turbulent flow it was found that in the central portion of the pipe random orientation existed, but near the walls there was a definite tendency for the fibres to align along the streamlines. In a contracting section of the pipe circuit it was observed that the fibres over the full cross-section were aligned by the fluid acceleration for both laminar and turbulent flow. The resulting orientation at the end of the contraction persisted down the straight pipe until the flow became fully turbulent. While these observations are not directly applicable to problems of the paper industry they should help in understanding the flow in a headbox. (author's abstract)

Baldwin, P. C. and Van den Akker, J. A., "Study of friction between solid surfaces and moving paper stock suspensions," Tech. Assoc. Papers, 22, 317-22 (June 1939).

Apparatus for measuring the "coefficients of friction" between the moving stock and the pipe wall and coefficient of internal friction occurring in the stock at cleavage surfaces is described, and data on these coefficients for different pulps, velocities and consistencies are given. A theory of the flow of paper stock in pipes is presented. (from Chemical Abstracts)

Bobkowicz, A. J. and Gauvin, W. H., "The turbulent flow characteristics of model fiber suspensions," Can. J. Chem. Eng., 43 (2), 87-91 (1965).

The pressure drop of aqueous model nylon fibre suspensions was determined in a vertical 2-in. copper tube in the turbulent range as a function of velocity, fibre length-to-diameter ratio (L/D) and concentration. Fibre diameters ranged from 20.2 to 51.6 microns and length from 0.52 to 1.21 mm. A marked depression below the value for the pressure drop of water was observed at high L/D's and its magnitude increased with the solids concentration. For low L/D values the depression was almost negligible. An explanation is advanced for the depression of pressure drop based on alterations in the turbulence characteristics in the presence of fibres. (author's abstract)

Brecht, W. and Heller, H., "Study of pipe friction losses of paper stock suspensions," Wochlbl. Papierfabr., 66 (14), 264 (April 1935) et seq; Tappi, 33 (9), 14A-48A (Sept. 1950).

A review of the American and European literature on the pipe friction loss of paper-stock suspensions is presented, and the disagreement and inconsistencies in the published data are pointed out. The lack of accurate descriptions of the testing methods and conditions, as well as the absence of complete technical description of the stock used, is particularly emphasized. A testing layout for determining pipe friction loss is described. Test results are presented showing the effect of the following variables on pipe friction loss; velocity, consistency, pipe diameter, pipe roughness, freeness, average fiber length, temperature, load, and various papermaking pulps. The test results are summarized and compared with the results obtained by previous investigators, and the value of the present material as a basis for further investigation is pointed out. (author's abstract)

Bugliarello, G. and Daily, J. W., "Rheological models and laminar shear flow of fiber suspensions," Tappi, Vol. 44, No. 12, p. 881 (Dec. 1961).

After a survey of the existing rheological models, the authors have shown that measured flow characteristics of fibre suspensions cannot be fitted to be models such as Bingham or pseudo-plastic

behaviour, which are suitable for suspensions of particles. Failure of fibre suspensions to conform with existing models is illustrated by the observation that the critical wall shear stress at transition to turbulent flow is approximately independent of pipe diameter, in contrast to the dependence on diameter shown for both Newtonian and non-Newtonian fluids. The authors have been able to show the way in which individual fibre dimensions (i. e. stiffness) can account for observed differences in the point of transition to turbulence, the extent of the transition region, and the pressure drops in turbulent flow. (from Rheology Abstracts)

Buresch, F. M., Nonwoven Fabrics, Reinhold Publishing Corporation (New York, 1962), Library Congress No. 62-21831

A complete discussion of the non-woven fabrics industry, including processes and machinery, fibers used, binders, products and applications, costs and specifications, and research in progress. A patent survey of non-woven fabrics is included.

Several short sections discuss wet and dry lay-up techniques in a qualitative manner.

Daily, J. W. and Bugliarello, G., "A particular non-Newtonian flow. Dilute fiber suspensions," Ind. and Eng. Chem., 51 (7), 887 (1959).

Dilute water suspensions of different papermaking fibers in the concentration range between 0.1 and 1.0% were observed with respect to flow properties and friction losses in vertical pipes of two different sizes. The conventional rheological models for Newtonian fluids were not applicable to this system, the laminar flow of which was found to consist of two regions: an entangled fiber "plug" and a very thin peripheral clear-water annulus. A possible mechanism for the annulus formation is suggested, and possible further work is discussed.

Daily, J. W. and Bugliarello, G., "Basic data for dilute fiber suspensions in uniform flow with shear," Tappi, 44, 497-512 (1961).

This is the first of a series of papers reviewing the literature on the characteristics of fiber suspensions, and giving details of some experiments made on the flow in a pipe of suspensions of less than 1 percent. All fibers showed non-Newtonian characteristics, but with a considerable transition range between laminar and turbulent flow. Velocity distributions were measured in pipes up to 2 inches. The presence of fibers gave a flatter velocity profile than for corresponding Newtonian flow, the flatness increasing with fiber concentration. (from Rheology Abstracts)

Durst, R. E., "Flow properties of paper pulp stock. IV. Effect of fittings on pipe systems carrying pulp slurries," Tappi, 42, 713-18 (1959).

Bleached northern kraft pulp slurries of 2.0, 3.0 and 3.8% consistency were pumped through a fully described circulating system at velocities from 1 to 10 ft./sec. The head loss across the fittings was determined. The equivalent length of the fittings decreased with increasing consistency of the pulp stock, over the range studied, and the straight sections following fittings showed decreasing head loss values with increasing velocity. (from Chemical Abstracts)

Durst, R. E. and Jenness, L. C., "The flow properties of pulp paper stocks. I. Relationship of shear value to pipe friction for bleached sulphite pulp slurries," Tappi, 37, 417-422 (Oct. 1954).

Flow data have been taken on a long-fibered bleached sulphite stock of 2.0, 3.0, 4.0, 5.0, and 6.0% consistencies at stock velocities ranging from 1.5 to 10.0 f.p.s. in a flow system of 6-in. spiral welded pipe with test sections of 10, 20, 30, and 40-ft. lengths. Shear studies have been made on the same consistency stocks to obtain empirical shear values over the same range of velocities. A correlation of the data from the two systems has been tested for predicting friction head losses in pipes of 6, 8, 10, and 12 in. diameter with reasonable success. (author's abstract)

Durst, R. E. and Jenness, L. C., "The flow properties of paper pulp stock. II. The relationship of shear value to pipe friction for soda kraft and ground wood slurries," Tappi, 38, 193-198 (April 1955).

A correlation, reported previously, relates the laboratory measured shear value of bleached sulphite pulp to the pipe friction of pulp slurries flowing through a piping system comprised of nominal 6-in. spiral welded steel pipe. The correlation was obtained by defining a dimensionless suspension flow number, N_{SF}, equal to $Dv\rho/S$, calculated from consistent units of pipe diameter, stock velocity, and stock density in slugs per cubic foot and the shear value, S, measured in the viscosimeter also previously described. A friction factor, f, calculated from measured head loss data became a function of the N_{SF} so that a log-log plot of f vs. N_{SF} resulted. The deviation of measured values from the straight line for the sulphite pulp was less than $\pm$ 7%. More recent data show the correlation holds also for the three pulps; bleached soda, unbleached kraft, and unbleached groundwood. The correlation seems to hold equally satisfactorily for the sulphite, soda, and kraft pulps and with only slightly greater deviations for the groundwood pulp. The soda and kraft pulps were pumped at consistencies between 2 and 5%, and velocities from 1 to 10 f.p.s. The groundwood was investigated only in 2 and 3% consistencies. (author's abstract)

Durst, R. E. and Jenness, L. C., "The flow properties of paper pulp stock. III. The relation of shear value to pipe friction for pipes of various diameters," Tappi, 39, 277-283 (May 1956).

A correlation was found and previously reported, which related the laboratory measured shear value of four "type" pulps to the pipe friction of those pulp slurries flowing through a piping system comprised of nominal 6-in. spiral welded steel pipe. The flow system was modified to include test sections of the same pipe in 8 and 12-in. diameters. Friction head loss curves were determined for bleached sulphite and bleached hardwood sulphite pulp slurries in the new test sections. A new empirical correlation based on data from the above pipe diameters is proposed which makes possible the calculation of pipe friction in flow systems of various pipe diameters, for any stock on which the shear stress velocity rheogram has been determined. The accuracy of the calculated pipe friction appears to be of a much higher order than that given by any previously proposed method of calculation for a variety of stocks and for a number of pipe diameters. (author's abstract)

Emmons, H. W., "The continuum properties of fiber suspensions," Tappi, Vol. 48, No. 12, p. 679 (Dec. 1965).

The general properties and equations of motion of a paper fiber slurry in water are derived, and a number of settlement, compression, and filtration problems are solved. A few cases are compared with experiment and show encouraging agreement. (author's abstract)

Erwall, L. G. and Ljunggren, K., "Radioactive tracers in the cellulose and paper industry," Tek. Tidskr., 89, 877-84 (1959).

Flow measurements and studies by means of tracers are described, i.e., pulp and water flow; circulation in digesters; mixing in bleaching towers; continuous cooking; flow behavior in a saveall; flow pattern in streams; fiber flow measurement on papermaking machines with labeled fibers; the performances of a centrifugal cleaner; and the rosin in paper manufacture. (from Chemical Abstracts)

Guenter, T. E. and Ceaglske, N. H., "Friction pressure drop in the flow of paper pulp stock," Tappi, Vol. 34, No. 3, 140-144 (March 1951).

Data were obtained in a 1-inch smooth copper pipe for velocities ranging from 1 to 15 feet per second and for pulp consistencies of 1.16 to 2.73%. The method of correlation used depends on the validity of the Fanning friction factor plot for non-Newtonian fluid flow. Results show that the effective viscosity of the pulp goes through a maximum at fluid velocities in the range of 2 to 5 feet per second and then decreases sharply with increasing velocity. The consistency has a large effect on the viscosity and pressure drop. The viscosity of the lowest consistency (1.16%) showed a

decided tendency to approach a constant value at high velocities; this stock also demonstrated behavior similar to water and different from other consistencies. The pressure drop versus velocity plots showed the same maxima and minima as indicated by Brecht and Heller, and Forrest and Grierson. The data from this investigation fill out regions not covered by the aforementioned articles. The flow nozzle, employed to give a continuous indication of flow rate, worked very well and lent advantageous flexibility to the operation. (author's abstract)

Hubley, C. E., Robertson, A. A. and Mason, S. G., "Flocculation in suspensions of large particles," Can. J. Research, B28, 770 (1950).

Based upon an assumed mechanism of particle aggregation by shear-induced interparticle collisions, a new method of studying flocculation in suspensions of large particles is described, and representative results obtained with cellulose-fiber suspensions are presented. The method consists of subjecting the suspension to a reproducible condition of shear motion and analyzing the fluctuations in optical transmission coefficient electronically. An approximate statistical theory is presented on the basis of which a flocculation index (σ/N_0) appropriate to the method is proposed. The index is a function of both the number and size of the aggregates. The flocculation index was found to decrease with increasing rate of shear and decreasing fiber length. The effect of concentration and of additives was investigated. Alternative experimental techniques are outlined and limitations to the present method are pointed out. (author's abstract)

Ippen, A. T., Daily, J. W. and Bugliarello, G., "Pertinent factors in flow research on dilute fiber suspensions," Tappi, 40, 478-484 (June 1957).

The desirable hydraulic characteristics of the diluted paper stock as it is deposited on the wire of the paper machine are briefly reviewed. The various hydraulic aspects and problems of the paper making process from the beater to the slice are examined. The problems are then rearranged in basic categories involving fundamental aspects of the flow. This classification is for the purpose of leading to a clearer understanding of the processes involved in imparting the desired characteristics of the suspensions. Recommendations are made for a research program covering especially the influence of fibers and fiber aggregations on the turbulent characteristics of shear and nonshear flows. (author's abstract)

Karnis, A., Goldsmith, H. L. and Mason, S. G., "Axial migration of particles in Poiseuille flow," Nature, Lond., 200, 159-160 (1963).

Observations of the radial movements of particles in liquids flowing through straight circular tubes are reported for both high ($Re_p > 10^{-4}$) and low ($Re_p < 10^{-6}$) particle Reynolds numbers. In Newtonian liquids at high Re_p the rigid particles (spherical, rod or disk-shaped) migrated towards an equilibrium radial position of one half the tube radius and the rods and disks assumed rotational orbits with their long axes or faces oriented in planes passing through the axis of the tube. At low Re_p, the radial positions and orbits did not change from the initial value. Deformable particles (liquid droplets and elastomer filaments) moved steadily towards the centre of the tube at all Re_p values. (from Rheology Abstracts)

Mason, S. G., "The flocculation of pulp suspensions and the formation of paper," Tappi, 33, 440 (1950).

The mechanisms whereby pulp fibers aggregate to form flocs which may persist as irregularities in the sheet structure are briefly discussed. Of several possible mechanisms indicated by the experimental evidence, it is concluded that the most important in conventional papermaking is by mechanical entanglement. The extent to which aggregation occurs is determined by a number of factors, the most important of which are the concentration,size, and shape of the fibers, and the type of motion to which the suspensions are subjected. (author's abstract)

Mason, S. G., "The motion of fibers in flowing liquids," Pulp Paper Mag. Can., 51 (5), 93-100 (1950).

The equations of Jeffery (Proc. Roy. Soc. (London) A102, 161-79 (1922)) are applied to the motion of papermaking fibers in a simple shear field. Fiber orientation in the direction of flow is calculated as a function of the axis ratio r, where $r = (\text{length})(\pi/2)/(\text{width} \times \text{thickness})^{1/2}$. For r = 40, 82.2% of the fibers are oriented within 5° of the axis of flow. Calculation of the frequency of particle collisions in shear fields shows that free rotation is impossible above a concentration of 0.031 g./l. for r = 40. Increased velocity will not reduce the tendency of the rotating fibers to interlock and mechanically flocculate. (from Chemical Abstracts)

Morrison, S. R. and Harper, J. C., "Wall effect in Couette flow of non-Newtonian suspensions," Ind. Eng. Chem. Fundamentals, 4, 176-181 (1965).

Suspensions of fibrous particles in Couette flow exhibited yield stresses, apparent wall slip, and time-dependent behavior. The behavior exhibited cannot be observed in a narrow-gap viscometer, and data from such instruments should be used with caution. (from I and E. C.)

Nawab, M. A., et.al., "The viscosity of dilute suspensions of thread-like particles," J. Phys. Chem., 62 (10), pp. 1248-1253 (1958).

The viscosity of dilute suspensions of thread-like rayon particles has been measured for various values of the axis ratio r, and the intrinsic viscosity a_o compared with various theoretical equations. No good agreement with theory was found, but evidence is presented

to show that the intrinsic viscosity is sensitive to a mean particle-orientation factor which is in turn sensitive to permanent and recoverable deformation of the particles by the velocity gradient, and that Burgers' equations probably could be corrected for this effect as to give agreement of a_o with experiment.

Nissan, A. H., Higgins, H. G. and Lagani, A., "The significance of rheology in the making and using of paper," Trans. of the Soc. of Rheology, IV, 207-232 (1960).

A brief review of paper making indicates that rheology is an important factor at many points. The most significant are (1) rheology of fiber suspensions, (2) rheology of wet webs of fibers with 1:4 to 1:2 solid to water ratios, and (3) rheology of air-dry paper in use. The first two subjects are briefly reviewed. Attempts to represent paper behavior in terms of mechanical models of springs and dashpots are summarized and reasons for their rejection advanced. Instead, support is given to interpretations based on molecular and thermodynamic parameters as a basis for a theory of the rheological behavior of hydrogen-bonded solids. Predictions of the theory appear to be confirmed not only by paper but also by ice, cellulose sheets, nylon and other hydrogen-bonded materials. Attempts are made to explain by means of this theory the influence of water, chemical modification of the fibers, and other factors on the rheological constants of paper, and to account for its time-dependent behavior. The essential contribution of the theory is that it relates the variations in behavior to an important parameter, n, the number of hydrogen-bonds per unit volume of material. Thus, changes in rheological behavior reflect changes in n; these changes can be treated by methods of chemical kinetics. (author's conclusion)

Prevorsek, D. and Tobolsky, A. V., "Determination of non-flow shrink ratio in oriented fibers," Presented at the Society of Rheology Meeting, October 29-31, 1962. Abstract: Trans. of Soc. Rheology, VII, 420, (1963).

A method for the determination of non-flow shrink ratios of oriented fibers is described. The dimensional changes accompanying the transition of an oriented semi-crystalline structure into an amorphous random coil state are shown for various polymers. The average number of segments per crystalline sequence, calculated by means of expressions derived by Tobolsky, is in good agreement with the estimates of crystallite sizes obtained by x-ray methods. Irradiation and fatiguing have a pronounced effect on fiber shrinkage, both in the magnitude of shrinkage and in the temperature range where the shrinking process terminates.

Robertson, A. A., "Flow of dilute fiber suspensions. Summary of Tappi-sponsored research," Tappi, Vol. 48, No. 4, p. 98A (April 1965).

A research program sponsored by the Fluid Mechanics Committee of Tappi during the years 1956-62 is described and evaluated in a qualitative manner. The objective of this research was to "investigate the hydrodynamic properties of dilute fiber suspensions -- below 1% consistency -- as a step toward achievement of optimum hydraulic conditions at the paper machine slice." Ten references.

Robertson, A. A. and Mason, S. G., "The flow characteristics of dilute fiber suspensions," Tappi, 40, 326-334 (May 1957).

The flow of dilute (0 to 1%) suspensions of fibers in a long 7/8-in. I.D. glass tube has been investigated as the first step in a study of the flow characteristics of pulp suspensions with particular reference to the mechanisms of flow and the role of fiber properties. It has been found that, at concentrations above 0.2%, three regimes of flow may exist, which have been designated as plug, mixed, and turbulent flow. The mixed flow region represents a transition from plug to turbulent flow in which there is turbulent flow near the wall and plug flow at the center of the tube. Transition points are evident in the pressure loss versus velocity data. The variation of transition velocities and of the pressure-velocity relations, with concentration, pulp type, mechanical treatment, and the presence of additives are discussed. In addition, fiber flocculation in the suspension was measured by an optical method, and discussed. (author's abstract)

Trevelyan, B. J. and Mason, S. G., "Particle motions in sheared suspensions. I. Rotations," J. Colloid Sci., 6, 354 (1951).

Observations of the rotational motion of single rigid spheres and cylinders suspended in a liquid subjected to a velocity gradient have been compared with Jeffery's theoretical equations for ellipsoids of revolution.

The constant angular velocity of spherical particles is proportional to the shear rate, is independent of particle size, and is in excellent accord with theory.

The orbits of cylinders are in good agreement with Jeffery's predicted spherical ellipses. The period of rotation is independent of the orbital constant, and is approximately two-thirds that predicted for a prolate spheroid of the same axis ratio. The latter effect is to be expected from the difference in particle geometry. (author's abstract)

Van den Akker, J. A., "Flow in fiber suspensions and the effects of turbulence," Tappi, 37, 489-494 (Nov. 1954).

Because of the strong bearing of theory and observational phenomena of aero- and hydrodynamics on the flow of low-consistency fiber suspensions, the nature of the flow of fluids around bodies and through ducts is reviewed. Special attention is given to the way in which turbulence is generated in boundary layers and to the velocity distribution across a duct. The dependence of the "critical" Reynolds number on the nature of the system in which flow occurs is described. Reference is made to modern methods for characterizing and measuring turbulent motion. The probable effects of the presence of fiber on turbulence and of the effects of turbulence on fiber motion are discussed. Theory and numerical calculations are given to demonstrate that, in consideration of the motion of individual fibers viscous forces strongly predominate over inertial forces. (author's abstract)

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13. ABSTRACT

The results of a literature search of the field of the rheology of fibrous materials in low viscosity media are presented. Low viscosity was defined as any viscosity less than or equal to that of water. Thirty references with abstracts are given.

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	ROLE	WT	ROLE	WT	ROLE	WT
rheology	8,9	3				
fibers	9	2	9	2		
liquid	9	0	9	0		
low viscosity	0	0	0	0		
orientation			8	3		

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