

The Photomicrography of Dilute Fiber Suspensions Moving at High Speed

PAPER J-1

By E. L. SCOTT

The development and commercial availability of high-intensity, short-duration lights, such as the Strobolume, and the extremely fast action magneto-optic Rapatronic shutter (0.5 μ sec effective exposure time) has made possible the development of a technique for the stop-motion photography of cellulose fiber suspension in water moving at a speed of 25 to 30 ft/sec.

In order to provide a uniformly illuminated field this technique utilizes a Fresnel field lens between the light source and the suspension, and an auxiliary lens between the Rapatronic shutter and suspension to provide the desired magnification of 1.5:1 on a 4 by 5-in. negative. Kodak Royal Pan Film was found to be well adapted for this type of work inasmuch as normal photographic procedures provided negatives of high quality.

A PAPERMAKING research problem posed some unusual photographic conditions in that cellulose fibers traveling rapidly in suspension were to be completely "stopped" for visual interpretation. The fibers were traveling at high speed in a dilute aqueous suspension under simulated papermaking conditions. For a better understanding of the papermaking terms used, the following brief description of the papermaking process is provided.

For the sake of brevity, several steps of papermaking are by-passed in favor of starting this description with the individual papermaking fibers in aqueous suspension. To form these fibers into a web of paper, the aqueous suspension is pumped into a flow-box, where the suspension is under constant agitation. The flow-box delivers the fiber suspension, by means of a slice opening, onto the Fourdrinier wire as a flat jet having very nearly the same velocity as that of the wire.

The Fourdrinier wire is a woven-wire endless belt, with about 100 meshes/in., which receives the fiber suspension from the flow-box. The speed of the Fourdrinier wire is generally designated as the machine speed, and it is here that paper is first formed as the suspending water drains through the openings in the wire, leaving an interlaced mat of fibers on the surface of the wire screen.

The paper industry is constantly endeavoring to make better paper consistently at higher and higher paper machine speeds. However, the behavior pattern of the individual fiber has not always been predictable under these accelerated conditions. To understand why they react differently was the problem to be investigated.

With the advancement and technical improvement of strobe lights, ultra-high-speed shutters and ultra-high-speed motion-picture cameras, more and more photographic methods have been adapted to research studies of dilute fiber suspensions under high-speed papermaking conditions.

The subject to be studied photographically was a cellulose fiber, brilliant white, averaging 2.5 mm in length and about 0.035 mm in diameter, moving at speeds of 20 ft/sec or greater in dilute water suspension. The problem of photographing these rapidly moving fibers was undertaken as an integral part of a long-term research program and hence has been placed on a continuing investigative basis. This photographic technique

has been of significant help in arriving at a better understanding of the behavior of fibers in a dilute suspension.

Photographic Requirements

Several pertinent points were brought out during preliminary discussions of the problems of completely stopping the motion of these fibers in a rapidly flowing dilute suspension.

(1) The speed at which the fibers move is 1200 ft/min, at a fiber content of 0.25%. At these speeds a fiber will move a distance equal to its diameter in 5 μ sec; and in order to freeze its motion an exposure of 2 μ sec or less would be required.

(2) A shutter with no moving parts would be best suited for this work because of the extremely short exposures required.

(3) In addition to the short exposure requirement a wide viewing angle was necessary; and a system giving high resolution of the image was desired.

(4) Silhouette photography was chosen because of the good contrast that can then be obtained between fiber and background.

The photographic work used a previously made flow box constructed of Lucite which recirculated the pulp suspension at the predetermined velocity of 1200 ft/min. The flow-box can best be described as a large Lucite chest which holds the pulp suspension under conditions of vigorous agitation to provide even fiber distribution in the liquid phase. The fiber suspension leaves the chest through a slit or slice opening and is discharged between two transparent channel walls approximately $\frac{1}{2}$ in. apart. This channel or flume discharges into a large tank and the suspension is recirculated at a steady flow rate at speeds of 20 ft/sec or greater. This model flow-box system holds about 1000 gal of water and for each 400 lb of water 1 lb of pulp is added. Each pound of pulp contains about 700,000,000 fibers.

The model flow-box is a full-scale section of those used on commercial paper machines, but with the transparent flume replacing the Fourdrinier wire. However, the principal action of the wire is simulated, and web formation in the initial, fluid state can be studied by means of photographs taken through the transparent walls of the flume.

As illustrated (Fig. 1) at speeds of 1200 ft/min through the flume, 5 billion fibers will pass through the selected field of view (which is an area of 4 by 5 in.) in 1 min.

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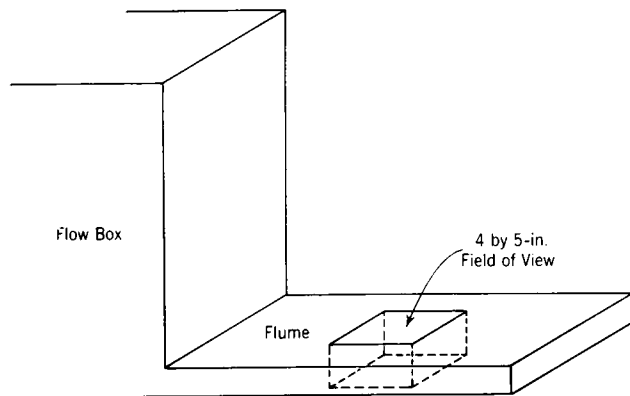


Fig. 1. Diagram of the flume and the selected field of view; 5×10^9 fibers/min pass through this field of view.

Rapatronic Shutter

The very nature of the subject—fibers in a semiopaque suspension and lacking in contrast—dictated that a considerable amount of light must be passed through the suspension if a negative of good subject contrast was to be obtained. Descriptive literature on 1- and 2- μ sec strobe lights quickly revealed that they lack the necessary peak illumination to penetrate the fiber suspension in order to produce negatives of good subject contrast under these conditions.

Attention was directed to the Model 2208 Rapatronic Shutter,* a product of Edgerton, Germeshausen & Grier, which is a rapid-action shutter having a single shutter element with no moving parts, and a nominal exposure of about 0.8 μ sec. The shutter and mountings are designed to take a 4 by 5-in. Graphic View Camera and can be modified to accommodate other types of cameras. The Rapatronic Shutter unit (Fig. 2) employs magneto-optic “light valve” action, and opens by rotating the plane of polarization of light traversing glass in a magnetic field (Faraday effect).

The optical element is a cylinder of extra dense flint glass 1 cm in diameter and 2 cm long with a 5-turn coil around its long axis and placed between two Polaroid polarizers. As shown in the diagram, the P_2 Polaroid element may be rotated 90° to “open” the shutter for focusing purposes. In operation, a high-peak magnetic pulse rotates the plane of polarization 90° as the light passes through the glass cylinder, and the light emerges through the second Polaroid. The nominal exposure time, determined by the length of the magnetic pulse, is 0.8 μ sec. The time delay from photocell pickup to operation is continuously variable up to 100 μ sec. This shutter was originally designed for observation and study of brilliant subjects of short duration, such as high explosives.

Light Sources

When the Rapatronic Shutter and camera are combined, there is in effect a camera with a fixed aperture (in this case $f/18$) and a fixed nominal exposure time of 0.8 μ sec. However, the effective exposure, from “closed” to “open” to “closed,” is likely to be closer to 0.5 μ sec. The factors of a relatively slow lens, an extremely fast shutter and a semiopaque subject through which light must be transmitted point out the sizable problem involved in the selection of a suitable source of illumination.

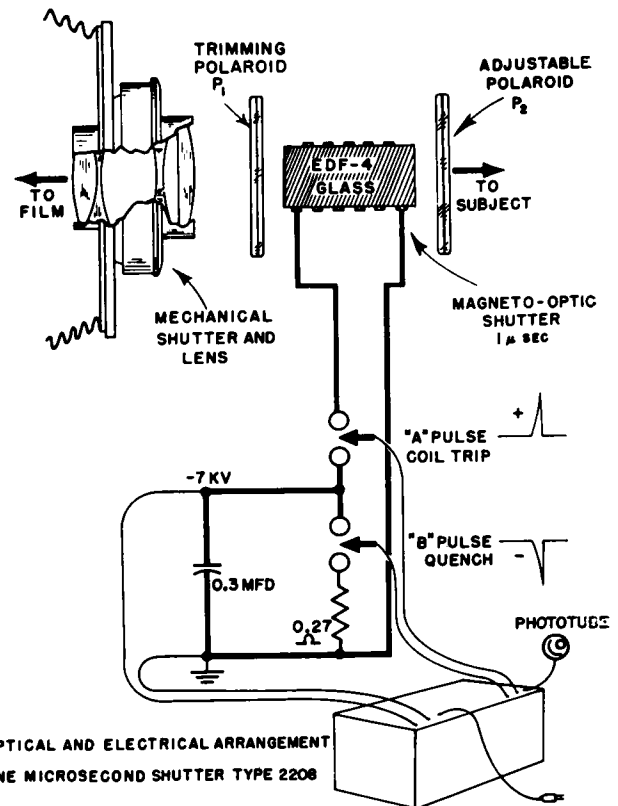


Fig. 2. Schematic diagram of the Rapatronic Shutter.

In order to define the illumination problem better, a number of experiments were conducted using incandescent sources. By employing a Photogenic Spotlight F7750, 750-w lamp and a Lucite cell of the same thickness and gap area as the model flow-box flume, it was found that the amount of light transmitted through the cell walls was of the order of 93%. When the Lucite cell was filled with the fiber suspension at 0.25% concentration, the light transmission fell to 61%.

Further investigation showed that the Rapatronic Shutter allows about 0.001% of the incident light to pass through it in the “closed” position and approximately 10% to pass through in the “open” position. That is, 10,000 times more light passes through the “open” shutter than through the “closed” shutter. However, it is to be noted that with a continuously burning lamp, in a few milliseconds the shutter would pass as much light in the “closed” phase as in one “open” phase; and for this reason strobe illumination was deemed necessary. Twice as much light will pass through the “open” shutter in 1 μ sec as through the “closed” shutter in 1/200 sec. In other words, a slow mechanical shutter, using incandescent lighting, allows too much ambient light to pass through the “closed” Polaroids. This would result in blurred images.

The density of the Polaroids was investigated at the same time as the lighting experiments were conducted, and their numerical density was chosen so that the ambient room lighting did not fog the film during the 1/100-sec exposure time through the “closed” Polaroid elements. A ratio of 1:2 is not acceptable for picture taking. A minimum ratio of 1:10 was found necessary to obtain useful photographic data. In order to fulfill these requirements, it was necessary to find a strobe light source with a high peak candlepower and a short duration.

*Edgerton and Wyckoff, *Jour. SMPTE*, 61: 296, Sept. 1953.

The General Radio type 1532-B Strobolume† has been used successfully in other types of photographic work requiring high-intensity strobe lighting. Previous work with this light had demonstrated that it had most of the features needed for this problem. The Strobolume has an effective peak of 10 megacandlepower and a flash duration of 30 μ sec. It can be "strobed" (through a General Radio Strobotac) for focusing purposes, and can be fired by means of the "X" contacts on a mechanical shutter, or it may be fired manually if desired. The most convenient method of operation was to use the 1/100-sec setting on the mechanical shutter, release the shutter by cable, trigger the light by the "X" contacts, and then use a phototube placed in the light path to initiate the Rapatronic Shutter. The Strobolume reaches peak intensity in about 4 μ sec. The Rapatronic firing delay was adjusted to fire when the Strobolume reached its peak. With the 30- μ sec duration, the light transmission during the "closed" shutter is much less than the 1:10 ratio established to avoid ambient light troubles.

Photographing Dilute Fiber Suspensions Moving at High Speed

The choice of the best arrangement of light source, auxiliary lenses, shutter and camera was the subject of considerable experimentation. It was desired to produce negatives with approximately 1.5:1 enlargement and with an evenly illuminated field. Several conventional microscope arrangements were tried using lamp and condensing lens systems below the flume, and an auxiliary objective lens and the shutter combination described above. These arrangements produced either very uneven illumination with hot spot images of the source, or insufficient light intensity for photography, even with the fastest rated films and forced development. The addition of diffusers over the lamps did not improve the situation.

The final and successful arrangement used the equipment shown in Fig. 3: Rapatronic Shutter, 4 by 5-in. Graphic View Camera, 14-in $f/3.5$ projection lens, 12 by 12-in. Fresnel field lens, Strobotac, Strobolume and WF326 heavy-duty tripod.

†General Radio Co., Cambridge, Mass.

A step-by-step description of the procedure shows how quickly and easily the fiber photographs are obtained. (1) The Strobolume is placed 12-in. below a previously selected area on the Lucite flume, (2) the 12-in. Fresnel field lens is attached to the bottom of the flume and (3) a corrected 14-in. $f/3.5$ (4-in. diameter) projection lens is placed on the top plate of the flume and coaxial with the Fresnel lens and light source. The Rapatronic Shutter and camera are placed about 14 in. above the projection lens. The quality of the projection lens determines the quality of the final print and it should be free of aberrations. Focusing is accomplished by "opening" the Rapatronic Shutter and strobing the light, by means of the Strobotac unit, for short periods. The depth of field of the combined optical arrangements is approximately 2 mm, so that accurate focusing is important.

Preliminary photographs taken by this method have shown that proper alignment of light source, field lens, projection lens and Rapatronic Shutter is critical. Any of the four main parts that are off as little as $\frac{1}{4}$ in. can cause trouble in that negatives will not be sharp or of good contrast. In spite of the necessity for accurate alignment of the equipment, it requires less than 30 min to put the assembly in position to photograph the fibers. As a matter of record, this equipment was set up and taken down three times a week for many months, photographing being done through the same flume area with reliable accuracy.

Discussion

The speed with which this technique was developed was due, in part, to using Polapan 200‡ film at the very beginning of this work. A very quick check on alignment, magnification, lighting, coverage and other details was available within a few minutes. Past experience showed that a barely acceptable Polaroid picture, if repeated using the Kodak Royal Pan Film,§ with the normal recommended development time, yielded a film negative of the desired density and gamma to produce

‡Polaroid Corp., Cambridge 39, Mass.

§ Eastman Kodak Co., Rochester 4, N.Y.

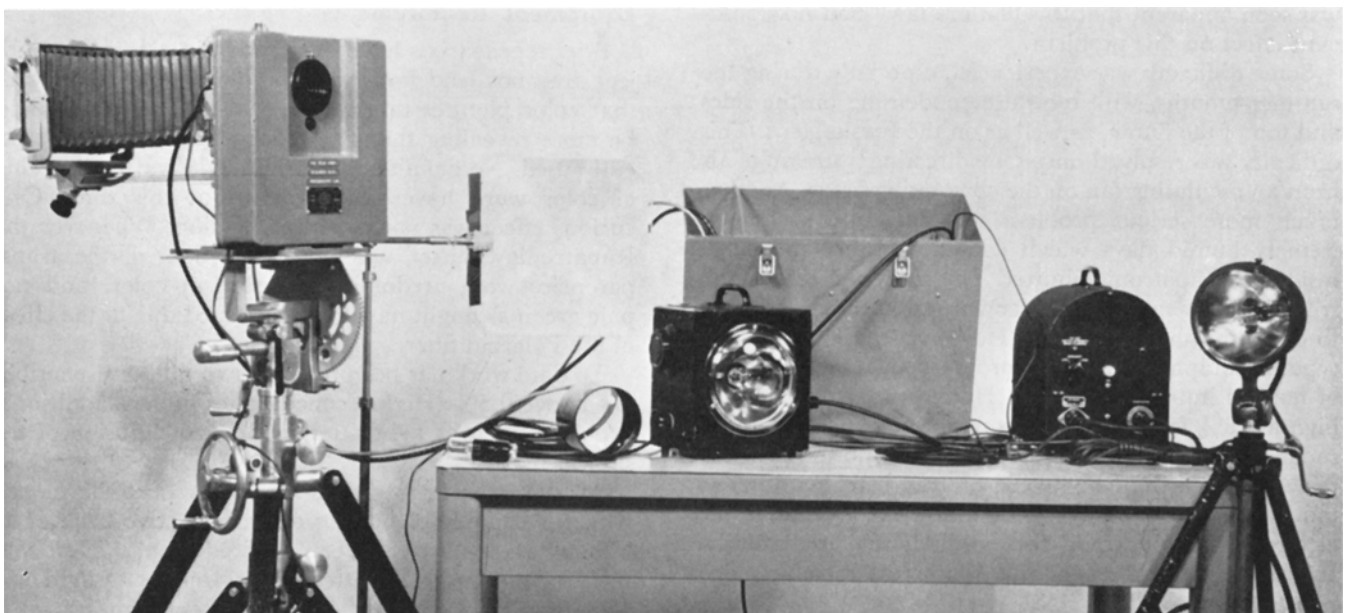


Fig. 3. Photographic equipment.

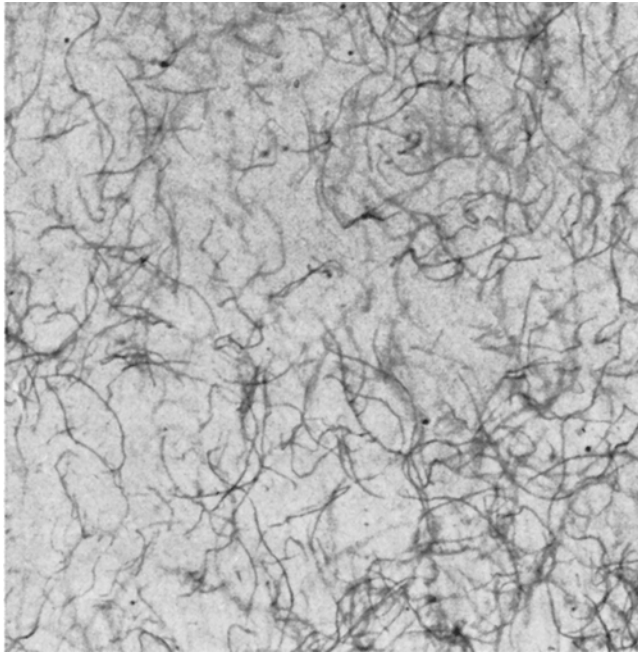


Fig. 4. Ultra-high-speed photography of fiber moving at 1200 ft/min at 0.25% concentration.

quality pictures. It was never found necessary or advantageous, in this work with the Rapatronic Shutter, to use any of the generally accepted procedures to increase the effective speed of photographic films, as Royal Pan film proved to be admirably suited to the needs.

At the very beginning of this program there was some apprehension, and considerable thought was given to the "failure of the reciprocity law." Bunson and Roscoe¹¹ state that "the product of a photochemical reaction is dependent simply on the total energy involved, that is, on the product of intensity and time, and is independent of either of these factors separately. In practice, however, photosensitive materials exhibit the phenomenon known as the 'reciprocity effect' or 'failure of the reciprocity law.' At the very short times involved in high-speed photography, the reciprocity effect may, with some materials, assume such a magnitude that it must be considered in exposure calculations." As work progressed it was soon apparent that this "failure law" had no significant effect on this problem.

Some difficulty was experienced, especially during the summer months, with moisture condensing on the sides and top of the flume, as well as on the Fresnel lens. This difficulty was resolved simply by directing a stream of air from an oscillating fan on the condensing areas. Another much more serious problem was encountered on extremely humid days which caused moisture to collect inside the Rapatronic Shutter. This shutter is sealed and will not allow moisture under normal humid conditions to enter the shutter proper. However, the location and type of equipment was not ordinary in the usual sense of normal humid conditions. Humidity would range as high as 98% for hours and, as might be expected, under such extreme conditions some of this moisture would penetrate into the Rapatronic Shutter case. At times so much moisture would collect inside the case that the electronic circuit would fire or discharge prematurely. It was then necessary to wait 1 min (as recommended

by the manufacturer) for the circuit to come to its proper full charge before firing it again.

The manufacturer of the shutter suggested that the shutter be returned for a special sealing of the shutter against the extremely humid conditions encountered in this work. It was further suggested that space heaters be added to the inside of the shutter. However, it was agreed that if it was properly sealed the shutter should function correctly under high humidity conditions. After repeated usage of the shutter, and at times inadvertent rough handling, it appears that another resealing is indicated, along with added space heaters.

Photographic Proof of the Technique

With the equipment aligned in the desired positions, an easy, quick and positive way of focusing at various depths in the flume was needed. For exact measurement of the magnification of the fibers, a transparent scale was selected for use in all tests. This scale was taped to a precision-ground step wedge (2-mm steps), inserted in the flume at the preselected depth and photographed in the same manner as the fibers, i.e., closed Polaroids, 0.5- μ sec exposure. Each series of fiber photographs taken by this method starts off with a scale photograph because both accurate focusing in the correct plane and exact magnification of the fiber at this preselected depth in the flume are determined from this scale negative.

Figure 4 is a typical fiber photograph and satisfies three of the required conditions.

First, the fibers are "frozen." There is no measurable motion among the focused fibers in the photograph.

Second, a large field of view has been obtained. There are about $1\frac{1}{2}$ million fibers on the negative, but only a portion of the negative is printed, since only a representative area of fibers is needed for an accurate statistical analysis of the results. These fibers were moving at 1200 ft/min when photographed, at a concentration of 0.25%.

Third, good resolution of the subject matter was obtained. The illustration proves this point. The final prints are 6 \times enlargements, in order to retain a good representation of fibers from the negative.

Contemplated Future Studies and Equipment Requirements

Brief repeat trials have been made in color. The subject does not lend itself well to color; nor is it certain that color pictures taken under these conditions would be more revealing than the black-and-white films presently used. No definite conclusions relative to the value of color work have been reached at this time. One curious effect was noted with color film. Whenever the Rapatronic Shutter was not fully charged, the transparencies were predominately blue in color, and not pale green as might have been expected due to the effect of the Polaroid filter.

To date work has been restricted to dilute suspensions not above 0.5%. Higher concentrates present additional problems such as light attenuation and diffusion of the subject itself.

At this writing a strobe light has been developed which is capable of putting out an effective peak of $4\frac{1}{2}$ billion candlepower and can be fired by the "X" contacts on mechanical shutters. This amount of light will require further changes in the present lighting setup when used with the Rapatronic Shutter.

¹¹Kodak High-Speed Films for Short Exposure—Time Applications, Kodak Pamphlet No. P-32.

This work was carried out as a part of the paper manufacturing research program at The Mead Research Center, Chillicothe, Ohio.

Conclusions

(1) Ultra-high-speed photographic techniques can be used to study the behavior of rapidly moving fibers in a dilute suspension.

(2) Present electronic flash equipment provides sufficient illumination when used with the Rapatronic Shutter for stop-motion photography of rapidly moving fibers in suspensions up to 0.5% fiber content.

(3) Analysis of the photographs has been of significant help in arriving at a better understanding of the behavior of fibers in a dilute suspension.

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