Distribution and Motion of Pulp Fibres on Refiner Bar Surface

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Pulp distribution and pulp motion in the refining zone of a commercial chip refiner were recorded by high-speed photography. A 1865 kW, single-disc refiner in the second stage of a pulp mill was used for the experiments. Cinestroboscopic photography and computer image analysis showed that 50 to 85% of the bar surface, depending on the radial position, is covered with pulp. An image-converting camera operating at 100 000 pictures per second was used to record the movement of pulp during one bar crossing of the refiner plates. The pulp appears in the form of flocs. The flocs move tangentially, driven by the rotor, and change shape and are disrupted in the process. Flocs can also be trapped on bar edges.

INTRODUCTION

Chip refining is an important and sizeable part of the pulp and paper industry worldwide. Currently, close to 30 million tons of mechanical pulp are produced annually using disc refiners. The refining process is more flexible and produces a stronger pulp compared to the conventional groundwood process. Hence, over the past two decades, the incremental capacity in mechanical pulping has come almost exclusively from disc refiners. Over the same period, the throughput of individual disc refiners and the power attached to them has increased approximately 10 times.

Since the earliest days of the chip refining in the mid-1950s, the Pulp and Paper Research Institute of Canada has been actively engaged in determining the mechanistic aspects of the refining process and high-speed photography has been an important tool in its research program.

Results of high-speed photographic studies of the chip refining process were presented at the Ninth (1970) and Sixteenth (1984) International Congresses on High Speed Photography, and at International Mechanical Pulping Conferences in 1983 and 1989 [1-4].

High-speed ciné films of what happens in high-consistency chip refining were obtained by means of a Hycam camera at framing rates of up to 10 000 pps (pictures per second) [3,4]. These studies provided considerable information on the nature of material flow through the refining zone of two industrial single-rotating disc refiners and on the distribution of pulp fibres on the bars of the refiner plates. However, even at the highest framing rate of the Hycam camera [3,4], there was considerable motion blur resulting from the passage of the bars on the rotating disc, and the fibres momentarily stapled to them, past the bars of the transparent stationary plate through which the pulp inside the refiner was photographed. At the highest framing rate of 10 000 pps, the exposure time for the Hycam camera was 40 μs. The linear motion of the bars on the rotating plates, and on the fibres stapled to them, during this time was calculated to be approximately 4 mm. This was somewhat greater than either the bar width or the length of an individual softwood fibre (approximately 3 mm). It was not possible, therefore, to identify fibres or fibre bundles clearly and observe their movement on the refiner bars from such high-speed ciné films. At least an order of magnitude improvement in the framing rate and exposure time was necessary, compared to that available with a Hycam camera, in order to obtain a blur-free image of the fibres on the bars. For the study reported here, we have employed two techniques which produce such blur-free photographs. One of the techniques, described by Miller [5], employs cinestroboscopic photography, and the other employs a high-speed electronic image converter, IMACON, camera.

The objective for cinestroboscopic photography was to obtain blur-free images of pulp distribution on the refiner bars. Using computerized image analysis methods, the average fraction of the bar surface covered with pulp was determined from these photographs. The objective of IMACON photography was to obtain high-resolution images in order to determine the nature of the fibrous material on the bar surfaces, and to record the movement of this material on these surfaces.

EXPERIMENTAL

The trials were conducted on a Sprout-Bauer Model 42-1B single-rotating disc refiner, equipped with 1067 mm diameter discs and a 1865 kW motor. The refiner was one of four such atmospheric discharge refiners, operating in the second stage position of a thermomechanical pulping system at the Domtar Newsprint mill in Donnacona, Quebec. The refiners produce newsgrade mechanical pulp from
spruce and balsam chips. As described previously [2,3], a window was cut in the stationary plate holder between the 10 and 11 o'clock positions and extending approximately 10° circumferentially. A transparent refiner plate segment, machined out of high-temperature polycarbonate sheet stock, was placed in the window and held in position by means of the adjacent metal plate segments normally employed by the mill for the pulping operation. A photograph of the transparent segment and the two adjacent metal plates is shown in Fig. 1. Type D13A-001, Nihard plates with approximately 30 h plate life were used during these trials. The plate has both a coarse and a fine bar section. The transparent plate segment had shallower grooves, of 2 mm depth, but in all other respects the bargroove pattern was similar to the pattern on the metal plate. As shown previously [4], the shallower grooves facilitate the photography of pulp flow in the grooves.

All of the photographs were obtained after the refiner was brought to the normal operating load of 1500-1600 kW. During the time taken to obtain the photographs, up to 30 min, there was no noticeable wear of the transparent plate.

**Cinestroscopic Photography**

The schematic diagram in Fig. 2 and the photograph in Fig. 3 show the arrangement of the equipment used for the cinestroscopic photography. A Doflex-16, 16 mm ciné camera, equipped with a Tamron SP 300 mm lens and 15 mm extension tubes, was employed for these trials. The camera is driven by a variable speed motor and equipped with a specially designed contactor. A signal from the contactor indicates when the camera is ready with its shutter open. This signal is sent to the Flash Delay unit. A second signal, generated by the photo diode sensor when it senses the target on the rotating shaft, is also sent to this unit. When the second signal arrives it triggers the strobe light after a predetermined delay time, and the film frame is exposed for 1 μs. The camera drive then advances the film for the next picture and the cycle is repeated.

Usually one photograph is obtained for each shaft rotation. The Flash Delay unit determines the moment of exposure and thus the relative position of the rotor plate with respect to the transparent stationary plate in the exposed photograph. By selecting an appropriate delay time, a series of photographs was obtained when:

- The bar pattern of a rotor plate was aligned with that of the transparent stator plate.
- The rotor plate pattern was approximately 4° in advance of the pattern alignment position.
- The rotor plate was approximate 4° behind the position of exact pattern alignment.

Photographs were taken at three radial locations on the stationary plate, as indicated by the boxes in Fig. 4A: between 10 and 45 mm from the inner periphery of the refining zone (A); between 45 and 85 mm in the coarse pattern area (B); and between 85 and 125 mm in the area overlapping the coarse and fine patterns near the exit zone (C). At each radial location a separate series of photographs was taken at two adjacent circumferential positions. As illustrated schematically in Fig. 4B, one location was in the region where the bar-groove pattern met to form “Vees”; the second was to the right of the “Vees” where the pattern is parallel. Thus, eighteen separate series of photographs were obtained, namely at six locations on the stationary transparent plate and for three relative plate crossing positions at each location. Ten photographs from each series were analyzed on a Kontron IBAS image analyzer.

**Image Analysis**

The original images from the cinestroscopic photography, captured on the 16 mm film, were transferred directly to the IBAS Image Analysis system by means of a specially constructed light box and a charged couple Diode camera equipped with a 25 mm TV lens, as shown in Fig. 5. The film plane was illuminated by means of a controlled intensity EFR Quartz-line lamp. Light was guided into the box by means of fibre optics. A condensing lens and diffusing mirror were provided in the light path to give even, bright illumination over the entire film plane. A feed and take-up reel transported the film to a film frame mounted on the box. This ensured proper registration of the individual frame for image analy-
sis. No noticeable geometric distortions were introduced by this method of image transfer.

The image processing consisted of several steps. First, a shading correction was applied to equalize any gradual changes in background light level that might be present in the original from one region of the image to another. Such variation is due to uneven lighting resulting from the single light source used to take the original photographs. Next, a binary mask, corresponding to the bar-groove pattern of the transparent plate, was created in order to eliminate image information from the grooves, since the purpose of analysis was to measure only the area of bar surface covered with fibrous material. A single mask for each of the six different plate areas was sufficient, because good registration was achieved by aligning the film initially on the light box. Minor adjustments were then made by using the image transformation function of the IBAS system to achieve exact registration of plate bar-groove pattern and the binary mask of this pattern.

Image segmentation was the next step. Typically, where fibres are in good contact with the bar surface of the stationary plate, the image area is bright. Dark areas were considered to be void of fibres. The grey level discrimination threshold, used to segment the image into areas occupied by pulp, as distinct from void areas, varied very little for any one series of photographs. It did vary somewhat from one series to another, since the camera set-up had to be altered for photographing each of the six different plate areas. However, since a consistent method by a single operator was used for image analysis, the resulting measurements are considered to be a valid comparison of the amount of stator bar area covered by pulp fibres for the different areas of the refiner plate photographed during the trials.

**IMACON Photography**

The principle of operation of the IMACON camera may be briefly described as follows. The light radiated from the subject under study is focused through the objective lens to the photocathode of the image converter tube. The photocathode converts the photon image to an electron image which is intensified and focused on the photoanode where it is converted into a higher intensity photon image. Shuttering is performed electronically and framing is accomplished by deflecting each sequential image to a different area of the photoanode. The persistence of the photoanode screen coating allows the image to be transferred to a Polaroid film.

The schematic diagram (Fig. 6) shows the arrangement of the equipment used for obtaining photographs with an electronic camera. An IMACON model 790 camera equipped with Katoptaron LDM-1 "lens" was placed approximately where the Doiflex camera was located previously (Fig. 3). The trigger contacts of the IMACON camera were wired to the Trigger Delay Generator and the Flash Delay Unit. As before, the photo sensor senses the target on the refiner shaft and sends its signal to the Flash Delay unit. The signal is processed by a Multiflash Generator which triggers the Strobotac. Light from the strobe is sensed by a photo sensor attached to a Vivitar long duration flash unit and in turn triggers the flash light. The Multiflash Generator also triggers the IMACON camera shutter via the TRW Trigger Delay Generator at an appropriate moment to synchronize the electronic shutter and the Vivitar flash light. As in the case of cinematographic photography, the Flash Delay unit is used to select the relative position of the rotor plate with respect to the transparent stator plate during picture exposure.

Forty photographs were obtained on Polaroid film from different locations in the refining zone. Each photograph consists of eight sequential pictures taken at a framing rate of $10^4$ pps. The exposure time for the individual frame was $1 \mu$s. Photographs were obtained at two.
Fig. 7. Pictures taken from the IBAS screen show the original images from the "Vee" pattern (left) and the corresponding segmented images (right). The white parts of the segmented images indicate the fibre coverage on the bars.

Fig. 8. Same as Fig. 7, but taken from the area adjacent to "Vee" pattern of the transparent plate. Pictures are arranged from bottom to top in the direction of inlet to outlet of the refining zone.

different magnifications; one approximately spanning the width of one bar and one groove, and the other spanning three bars and three grooves. Attempts to obtain pictures at a rate of 10^7 pps with 10 ns exposure time were not successful because of insufficient light.

RESULTS
Image Analysis of Cinestroboscopic Photography

Figures 7 and 8 show two sets of photographs and the corresponding segmented images obtained from the IBAS screen. They are typical images from the "Vee" pattern and the adjacent parallel bar region respectively of the transparent plate. Photographs from bottom to top correspond to the three radial locations of the plate area photographed, that is, from the inner to outer part of the refining zone. The photographs on the left in each figure are typical of the original image fed to the IBAS image analyzer. The corresponding segmented images are shown on the right. A segmented image is obtained after masking the groove area, which then appears black. The percent bar area covered with pulp, which appears white in the picture, was measured from the segmented image. It was not possible to create a fine mask to cover the grooves in the fine bar region of the refiner plate so that area measurements for this region were not carried out. The bar and groove width in the fine pattern area was 0.8 and 1.6 mm, respectively, and in the coarse pattern area they were 2.6 and 3.8 mm, respectively.

Tables I and II give the results of the percent bar area which is occupied by pulp. Each value is an average of measurements obtained from 10 consecutive images of the same field of view, that is from ten individual photographs similar to the ones shown in Figs. 7 and 8.

It is evident from the segmented photographs, and even from the original images, that there is less pulp present on the bars in the middle of the refining zone than on those at the inner section or near the transition region between the coarse and fine pattern. A similar finding was reported in the HYCAM cine photographic studies [2,3]. This visual assessment is quantified by the IBAS measurements, shown in Tables I and II.

The percent bar area covered with pulp is between 50 to 70% for the mid-region compared to between 70 to 80% for the inner section of the refining zone and between 80 to 87% near the transition zone. Pulp coverage seems to increase as the pattern crossing angle changes from negative to positive, that is along the direction of motion of the rotor, for pictures obtained from the mid region of the parallel pattern (45–85 mm, Table II). The mid-region of the "Vee" pattern shows an opposite trend (45–85 mm, Table I), while there appears to be no systematic trend for any of the other plate regions. It is not possible from the available data to determine if any systematic relationship exists between the pattern crossing angle (the angle between the bar crossings of the stationary and the rotating plates) and the extent of pulp coverage.

The segmented IBAS images from the inner and middle regions of the refining zone (i.e., A and B in Fig. 4A) were further subdivided into four equal parts, and measurements were carried out for these smaller radial sections. While there was no systematic change in the values of coverage for the inner (A) zone, there was some evidence that the coverage changed systematically with increasing distance for the mid-region. Pulp coverage on the bar surface in the mid-region (B) increases with increasing radial distance (Table III).

A possible explanation of this is as follows. Steam generated in the refining zone flows forwards towards the refiner discharge and also backwards towards the feed end. This results in a considerable backflow of pulp in the grooves of the stationary plates and pulp recirculation in the inner half of the refining zone [2,3].
Thus, there is a considerably greater amount of pulp between the refiner plates at the beginning of the refining zone (more than the nominal throughput) than in the region further downstream (equal to throughput). This could account for the higher values of pulp coverage observed for the inner zone. The higher coverage near the transition region is probably caused by the restriction to radial pulp flow by the fine plate pattern. Note that the values reported here are for a second-stage atmospheric discharge refiner operating at approximately 1500 kW, 35% discharge consistency and 45 t/d throughput. Larger refiners operating at much higher ratios of throughput to plate area may have even higher values of bar coverage.

May and coworkers have described a different method for determining the percent bar occupied by the pulp pad in an operating refiner [6]. For a Bauer 400 atmospheric discharge double-disc refiner operating as a second-stage refiner, they obtain a value of 5%, on average, at a feed rate of 4 t/d. Considering that the feed rate is less than one tenth of that through the 1500 kW refiner of our experiments, and that the refiners are so different in size, the low value obtained by May et al. appears to agree fairly well with those shown in Tables I and II here.

**IMACON Photographs**

A series of photographic sequences, each containing 8 images (frames) were obtained at two magnifications by means of the IMACON camera. Figures 9 and 10 show examples of two such sequences obtained at the lower magnification. One image field was
at a radial distance of approximately 80 mm from the inner periphery of the refining zone in the ‘Vee’ pattern area (Fig. 9) and the other was an adjacent parallel bar region to its right (Fig. 10). It was not possible to tilt the IMACON camera and the Katopian lens at an angle to the vertical, so that the stationary transparent plate had to be photographed in the position it was mounted in the refiner, between the 10 and 11 o'clock positions. The radially outward direction of the refining zone, as defined by the bar-groove pattern of the stationary plate in each frame, is therefore inclined at 45° to the vertical and the tangential direction of the rotating element is perpendicular to it. The order in which the frames were taken, at intervals of 10 μs, is identified by the numeral under the frame. The rotor bar moves through a distance approximately equal to the width of one bar and groove in a time interval of 68 μs. As seen from the photographs (Fig. 10), the trailing edges of the bars on the rotor reappear in approximately the same position after seven frames. Thus, the eight picture sequence records the passage of slightly more than one rotor bar with respect to a fixed point on the stationary plate.

Let us turn our attention to what can be seen through the bar elements of the stationary plate. The pulp fibres scatter light and appear bright while the areas void of pulp appear dark. It is assumed that the rotor grooves appear black (left of the trailing edges, Fig. 10, frame 1, and right of the leading edges Fig. 10, frame 4) because sufficient light does not reach the material in the grooves, since it is very unlikely that there is no pulp present in the rotor grooves. This assumption also implies that the material in the rotor grooves is at some depth below the material on the bars. Considerably more material can be seen through the transparent rotor bars when they are aligned with rotor bars (Fig. 9, frame 4, and Fig. 10, frame 6) than when they are aligned with rotor grooves (Fig. 10, frame 8, and Fig. 10, frame 3). This implies that pulp is carried around on the rotor bars and brought over the stator bars. It is possible to identify some common features in two or three successive frames, such as the size and shape of pulp flocs (particularly in Fig. 10). The size and shape of these identifiable flocs even changes to some extent in each successive frame and there appears to be a continuous and almost complete change of material seen through the stationary bars (and therefore on the stationary bar) during the passage of one rotor bar in an eight frame sequence. The pulp flocs appear to move in the direction of motion of the rotor, that is, across the bar width. Although it is not possible to identify fibres at this magnification, it seems likely that the material on the bars is aligned in the tangential direction, as observed from the high-speed ciné films [2,3].

Figure 11 shows a single frame taken from a sequence of the high-magnification photographs and identifies the main features seen in the following figures.

Figure 12 shows two representative photographic sequences (a, b) containing four of the original eight sequence series, four intermediate frames having been omitted. Thus, the time interval between successive frames is 20 μs. The photographs were taken at the higher magnification near the inner section of the refining zone. Each frame covers the width of one stationary bar, aligned at 45° and parts of the adjacent groove to its left and right. Figure 13 gives similar examples from the middle of the coarse pattern area (approximately 70 mm from the beginning of refining zone). The circle is an identification mark placed on the bar surface. Figure 14 gives two examples from the fine bar region, each frame spanning two bars and three grooves.
Fig. 14. Examples of high-magnification IMACON photographs taken from the fine bar region of the refiner plate.

Figures 12 to 14 generally confirm the observations made previously from Figs. 9 and 10. While the general nature of pulp material on the bar surface appears to be in the form of flocs, the presence of thread-like fibres can also be identified. These fibres are aligned across the bars, that is, in the direction of motion of the rotating element. These pictures support the refining mechanism described previously [7], namely that refining is accomplished by a moving bar working along the length of fibres trapped momentarily on the stationary bar.

The four frames in Fig. 13a show a fibre floc trapped on the leading edge of a stationary bar. It remains practically in the same position throughout the four-frame sequence. Thus, it is possible that fibres may be trapped on the edge of the stationary bar and are not docketed off immediately by the moving bar. On the other hand, Fig. 13b shows a similar fibre floc moving from the leading edge almost to the trailing edge in four sequential frames. From the limited number of photographs it is not possible to conclude which event is more frequent. Let it suffice to indicate that both do occur.

CONCLUSIONS

The high-resolution high-speed photographs of the refining zone obtained with the techniques employed in this study do not exhibit any motion blur.

The cinestroboscopic pictures showed that there was significant variation in the amount of bar surface covered by the pulp. For the refiner examined, more than 50% of the bar area was covered by pulp, and the coverage was 80% or more over a considerable portion of the refining zone.

The pulp on the bar surface appeared to be predominantly in the form of "flocs" or blobs of pulp, which can be characterized in greater detail from the high magnification IMACON photographs as fibre bundles. These fibres were draped across the bar width; that is, the fibres were aligned in the direction of motion of the rotating element. It is fair to assume that flocs which could not be resolved in greater detail also contained similar fibre bundles. Moreover, several photographs showed fibres stapled to the leading edge of the stationary bar which remained stapled during one pass of a rotor bar. The tangential motion of fibre flocs, change of floc shape, and floc disruption were also observed during a bar passage.

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REFERENCES


ABSTRACT: Pulp distribution and pulp motion in the refining zone of a commercial chip refiner were recorded by high-speed photography. A 1865 kW, single-disc refiner in the second stage of a pulp mill was used for the experiments. Cinestroboscopic photography and computer image analysis showed that 50 to 85% of the bar surface, depending on the radial position, is covered with pulp. An image-converting camera operating at 100 000 pictures per second was used to record the movement of pulp during one bar crossing of the refiner plates. The pulp appears in the form of flocs. The flocs move tangentially, driven by the rotor, and change shape and are disrupted in the process. Flocs can also be trapped on bar edges.

RÉSUMÉ: Au moyen de la photographie ultra-rapide, nous avons enregistré la répartition et le mouvement de la pâte dans l'aire de raffinage d'un raffineur de copeaux industriel. Un raffineur monodisc de 1865 kW au second stade d'une usine de pâte a été utilisé aux fins des expériences. La photographie cinéstroboscopique et l'analyse des images par ordinateur ont montré que 50 à 80% de la surface des barres, selon la position radiale, étaient couvertes par la pâte. Nous avons employé un appareil photographique à conversion d'images à 100 000 prises de vue à la seconde pour enregistrer le mouvement de la pâte durant le passage d'une barre sur les plaques du raffineur. La pâte apparaissait sous la forme de flocons qui se déplaçaient tangen¬

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