Design considerations and engineering characteristics of disc refiners

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Synopsis

With the increased emphasis towards applying disc refiners within the papermill, a study of the current disc refiner design is important. Consideration is given to the refining effects of speed, consistency, refiner plate configuration and pulp qualities. A theory of disc refining is propounded, this being supported by laboratory experimentation using a transparent unit.

Introduction

Much has been published on the theories of beating and refining, but certain principles of disc refiner design and problems encountered by the designer are not so widely known. The first machine employing flat plates or discs was used in 1853; it was not until 1930 that this kind of machine was extensively applied in pulp mills and a few kraft paper mills.

The early disc refiners, crudely constructed, were not built accurately enough for the machine to function satisfactorily. Furthermore, the early designers were not conversant with certain inherent characteristics—

1. High specific loading.
2. Excessively high mechanical forces.
3. The optimum speeds necessary for efficient performance.
4. The importance of plate parallelism.

A successful design today provides short bearing centres, together with a rigid frame, necessary to maintain disc parallelism throughout a wide loading range.

The devices available for load adjustment are—

2. Remote—electro-mechanical, using a fractional horsepower actuating motor, gear reducer unit, screw and nut.
3. Remote—hydraulic actuator, using a piston and high pressure oil system or pneumatic system.

The manual system requires time and labour to wind the machine to the open position for changing the refining plates and does not readily apply itself to modern instrument-controlled refining systems.

The remote, electro-mechanical system of adjustment is positive and automatically 'locks on', once an adjustment has been made.
The single type, consisting of a single stationary plate and a single rotating plate, is the simplest machine. The inlet can readily be provided with a screw feeding device for conveying wood chips or high consistency stock into the refining zone. The main objection to it is that the base must be rigidly constructed or fitted with tie rods to resist axial thrust forces. Some adjusting or trammage device is often fitted to obtain and maintain plate parallelism once the machine has been installed in the papermill. For a given size and manufacturing cost value, this type will absorb only 50 percent of the horsepower absorbed by a comparable twin unit.

There have been various multiple disc designs using up to four stationary and four rotating plates, but the design becomes unwieldy, owing to the widely spaced bearing centres, necessity for an extra large diameter shaft to resist deflection and the requirement of partial dismantling when it becomes necessary to change the plates.

The twin or double rotating disc refiner is a successful design, allowing maximum horsepower absorption for a given size and leaving the designer ample scope to produce a machine capable of maintaining parallelism over a wide loading range by employing straddled bearings at relatively short centres.

Comparison with conical refiners

Many recent statements have been made that the modern disc refiner is more efficient than the conical refiner. There is available a great deal of laboratory and mill data showing that the horsepower consumption to develop fibres to a required stage is considerably lower for a disc refiner than it is for a conical unit. Let us therefore examine the principal differences between the two machines.

Fig. 2 illustrates the important tackle element dimensions of the Hollander beater, high speed conical refiner with wood filling, high speed conical refiner with cast filling and modern disc refiner plates. Comparing these with typical fibre lengths of 2.5 mm shows that the elements of the disc refiner closely approach the fibre length. It is readily apparent that, as tackle elements have become progressively smaller, refining efficiency has increased.

The geometry of the cone, also of the wood packers or fillings in a conical machine, disallow a filling having relatively narrow bars and grooves, though modern foundry practice can produce disc refiner plates having bars and grooves only 1/4 in wide.

For a conical machine, the groove depth diminishes as the filling wears away, but it will be noted that the contact length between the stator bars and the rotor bars also changes as the filling wears away, which can have a marked effect upon the refining performance. In the disc refiner, only the groove depth changes.

Centrifugal force throws the stock into the grooves of channels of the stator filling of the conical machine. With certain conditions, the rotor tends to cavitate. Rounded edges and cavitation pits are often evident in partly worn fillings. The normal complaint from the papermaker is that the machine has lost its ability to emphasise cutting and/or fibre length control.

In the disc refiner, centrifugal force carries the stock outwardly along the plate channels and smearing of fibres and fibre flocks over the refining surfaces occurs in an efficient manner.

We can conclude therefore that there are significant differences in the flow pattern and refining action within the two machines.

What is refining?

In its broadest sense, the characteristics of the fibres for the paper are interesting, and the combined side this relative separation processes for the band of fibres is upon refiner's temperature a characteristic of the paper. Specific loadings in assessing Milne and Sigg. Specific loadings absorbed in specific loadings will be necessary to produce some fibrous fibre. The physical important role in maximum is determined enough to suit the paper. If this will nullify the modulus of the expression, then the maximum area is a feature.

We can conclude that if the hardwood fibre will sustain then the stock connected in more power will have been achieved (creating muscle...)

paper technology

What is refining?

In its broadest sense, refining is the treatment of fibres for the purpose of developing inherent strength characteristics. Let us consider how this is achieved.

Fig. 4 illustrates the range of treatment in which we are interested. All refining machines will produce degrees of fibrillation and cutting action by virtue of the combined hydraulic and mechanical action. Outside this relatively narrow band are the pulpmill fibre separation processes and the deflaking or defibring processes for broke and waste papers. In which zone of this band the resultant effect appears is dependent upon refiner speed, tackle design, refining consistency, temperature and pH value, specific loading and fibre characteristics.

Specific loading is analogous to, but more accurate in assessing refiner performance than the Samuel Milne and Sigurd Smith measurements of "inch cuts". Specific loadings are relative values of horsepower absorbed in terms of refining bar surface. If the specific loading is relatively high, the fibres and fibrils are macerated and cut.

The physical characteristics of the pulp play an important role. At high specific loadings, to achieve maximum length control, the fibre must be tough enough to sustain a fibre film between the refining surfaces. If this fibre film breaks down, the disc plates will gall together and stall the machine. The rupture modulus of the pulp slurry or, for want of a better expression, the toughness of the fibre determines the maximum absorbed power for a given bar surface area.

We can conclude that, if it is necessary to refine to reach a desired freeness or strength level — say, a hardwood kraft at 4 hp days/ton — and the particular fibre will sustain a fluid film only at 2.3 hp days/ton, then the stock must be treated through two machines connected in series. Furthermore, if application of more power than the stock can sustain in one pass were attempted, the treatment would be over-severe (creating mush) or would at least be detrimental to the ultimate strength to which the fibre could be developed.

Let us now consider the theory of refining. Several research groups have attempted to understand the true fluid mechanics of refining. It has been suggested that shearing and crushing take place at the point of interaction of the rotating and stationary refining surfaces. Other workers suggest that the fibre is shortened, not by a shearing, but by a tensile failure. A further and more probable possibility should not be overlooked and the following hypothesis is offered for consideration.

Refining is considered as a four-step process:

1. There is a localised preliminary removal of water where flocks of fibres gather between approaching tackle elements, the fibres becoming sufficiently compacted that further mechanical pressure expels water together with a few fibres. The consistency at this stage is assumed to be in excess of the general mass consistency.

2. Mechanical pressure of the tackle elements becomes sufficiently high to exceed the structural elastic limit of the fibres composing the particular flock. Further water is expelled at this stage.

3. A shearing movement of the tackle elements as they pass each other takes place, with the flock compressed between the adjacent bars.

4. Release of the mechanical pressure allows for reabsorption of the water into the ruptured fibres and fibrils. This stage is followed by or is coincident with turbulent agitation, which disperses the flock into the general mass flow.

If, in the second stage, the mechanical pressure is insufficient to overcome the elastic limit of the flock, the fibres will deflect, then spring back without any physical change.

The word flock has been used intentionally in place of the more general term fibregage. The latter suggests complete covering of the tackle elements with fibres, whereas this hypothesis assumes a local action. It seems plausible that continuous coverage of the tackle edges does not occur, but only localised, closely spaced areas with flocks between them.

Many factors will of course affect the refining action. Those easily controllable are termed the machine factors —

(a) The dwell time within the refining elements for initial water removal.

(b) Centrifugal forces acting upon the pulp suspension.

(c) The dwell time for flock compression.

(d) The characteristics and capabilities of the feeding channels within the refiner.
Mechanical and hydraulic actions imposed upon the flocks are influenced by tackle clearance, face width of the bars and bar edge condition—sharp or rounded.

Those factors not so easily controllable are termed the pulp factors—

(a) Plasticity of the flocks.
(b) Gathering capability.
(c) Resistance to expulsion of water.
(d) Tensile and compressive strengths of the flocks.

To enable a further understanding of the fluid mechanics within the refiner, recent research work has been conducted in our Middletown, U.S.A. laboratory. A transparent disc refiner model and high speed cinematography techniques were employed to study the internal flow patterns and flock formation. Unfortunately, the original pictures provide insufficient definition for general projection and viewing. Fig. 5-7 have therefore been constructed as clear illustrations of the observations.

In Fig. 5, the solid lines represent the stationary bars and the dotted lines represent the rotating bars. Individual fibres A and fibre flocks B lie on the stationary bars and perpendicular to the rotating bars. Fibre flocks generally had a length to width ratio of 2:1 and covered 50-70 per cent of the stationary bar width. The portion of the fibres and fibre flocks that presumably staple over the edges could not be observed. Some fibre flocks remained on the stationary bar for at least one revolution of the rotating bar.

Sections of the fibre flocks were seen to separate away from the master flocks and pass across the stationary bars C (Fig. 6). Immediately following this, the master fibre flocks would again increase in area; following this rebuild-up, further separation occurs. This cycle repeated itself over and over again.

From Fig. 7, a brushing or opening effect D was noticed. Observations also indicated a more pronounced flocking effect towards the disc periphery. By the introduction of coloured tracers, some recirculation and backflow within the disc grooves was observed. This backflow was more pronounced at the disc centre than at the periphery.

Other inconclusive observations were made, but this research work, although limited in scope, is a further step towards understanding the fluid mechanics within the refiner.

**Refiner efficiency**

The most widely used means of expressing refiner efficiency is in terms of horsepower days per ton required to develop a certain physical test or to reach a desired freeness level in the papermaking stock.\(^{(3)}\)

We are concerned here, however, with the purely mechanical efficiency. A proportion of the power applied to any refining machine performs no useful work. Bearing friction, gland friction and pumping action account for most of this power loss. In order to understand further the fluid mechanics of the disc refiner, an attempt has been made to apply standard mechanical and hydrodynamic equations.

The total brake-horsepower (bhp) absorbed can be divided into three groups\(^{(6)}\)—

---

**1. Power absorbed by the water**

\[ H = k \cdot Q \]

in which

- \( H \) = head pressure
- \( Q \) = flow rate
- \( k \) = constant

Therefore, the water head

\[ H = \frac{Q}{k} \]

**2. The disc requires a centrifugal pumping efficiency**

For a centrifugal pump,

\[ H = C \]

in which

- \( H \) = head pressure
- \( C \) = constant

The head pressure of the impeller is determined by

\[ H = \frac{Q}{k} \]

\[ H = C \]

**3. Disc friction**

At a given speed becomes—

\[ H = k \]

or

\[ H = C \]
1. Power absorbed by a whirling disc in a non-Newtonian fluid.
2. Power absorbed by pumping.
3. Power absorbed in useful refining work.

The first two groups must also be considered when the machine is backed off to the unloaded position. The third group can be considered as a pure attrition action analogous to disc friction (a friction clutch or thrust bearing)—

1. A whirling disc has a friction and pumping effect, where $Q$ varies as $D^3$,
   $H$ varies as $D^2$ and
   water horsepower [40] varies as $D^5$;
   in which $Q$ = Rate of flow.
   $D$ = Disc diameter.
   $H$ = Generated head.

Therefore, the whirling disc horsepower can be written as $AD^3N^3$ or $D^2N^3$ or $kD^5N^5$ for pulp slurries,
in which $A$ = Disc area.
$k$ = Fluid constant.
$N$ = Rotational speed.

2. The disc refiner has the inherent characteristics of a centrifugal pump of low specific speed and low efficiency.

For a centrifugal pump [41],
\[
\text{bhp} = \frac{QH \times 100}{3300 \times \text{efficiency}}
\]
or
\[
\text{bhp} = k_2QH,
\]
in which $Q$ = Rate of flow.
$H$ = Generated head.
$k_2$ = Fluid constant.

The head produced by a centrifugal pump varies as the square of the speed, also as the square of the impeller diameter. Therefore, if—
\[
k_2QH = \text{bhp},
\]
\[
\text{bhp} = k_2D^2N^2.
\]

3. Disc friction turning moment is expressed by [42],
\[
M = \frac{3}{2}\omega W_r^2,
\]
At a given speed and constant loading, this expression becomes—
\[
M = \frac{3}{2}W_r^2N
\]
or
\[
\text{bhp} = k_3D^2N,
\]
in which $M$ = Turning moment.
$\omega$ = Friction coefficient.
$W_r$ = Axial thrust.
$r$ = Disc radius.
$N$ = Rotational speed.

We can summarise these formulae by the following statements—

(a) The power losses due to the whirling disc in the stock suspension are proportional to the cube of the speed.

(b) The power losses due to the pumping effect are proportional to the square of the speed and directly proportional to the flow quantity.

(c) The horsepower absorbed in useful attrition work is directly proportional to the speed of rotation.

One can conclude therefore that the lowest possible speed should be chosen permissible with meeting a desired set of refining characteristics.

**Effect of speed**

WITH ANY machine, the manufacturer is confronted with the problem of recommending the correct speed of rotation. We have already seen how, from a purely mechanical standpoint, the lowest possible speed is the most efficient.

We must reconsider the earlier remarks, however, when discussing the refining spectrum (Fig. 4). What is the most efficient speed to produce predominantly fibre length control or for that matter predominantly fibrillation without extreme cutting? The test work to produce the answer to this question can be a costly and arduous procedure.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Kraft pulp</th>
<th>Bleached sulphite pulp</th>
<th>Bleached hardwood pulp</th>
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</thead>
<tbody>
<tr>
<td>Power n. freeness</td>
<td>700</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>Power n. burst (Mullen)</td>
<td>900</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Power n. tensile strength</td>
<td>700</td>
<td>700</td>
<td>900</td>
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<tr>
<td>Power n. tearing strength</td>
<td>900</td>
<td>1200</td>
<td>900</td>
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<tr>
<td>Power n. shrink</td>
<td>900</td>
<td>900</td>
<td>700</td>
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<tr>
<td>Power n. flit</td>
<td>900</td>
<td>900–1200</td>
<td>1200</td>
</tr>
<tr>
<td>Power n. density</td>
<td>700</td>
<td>700</td>
<td>700</td>
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<tr>
<td>Power n. fold</td>
<td>700</td>
<td>700</td>
<td>1200</td>
</tr>
<tr>
<td>Freeness n. tearing strength</td>
<td>900</td>
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<td>900</td>
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<td>1200</td>
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<td>Freeness n. density</td>
<td>900</td>
<td>700–900</td>
<td>720</td>
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<td>Freeness n. shrink</td>
<td>900</td>
<td>900</td>
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<tr>
<td>Freeness n. fold</td>
<td>900</td>
<td>900</td>
<td>1200</td>
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Table 1 shows the final analysis from one such series of tests to cover one plate configuration: the best general performance on hardwood pulps is in the higher speed range. On the kraft and sulphite pulps, the lowest possible speed produced the maximum freeness change, whereas the mid-range speed appears to give the best fibre length reduction generally. The results of many such tests show that generally—

(a) At speeds around 4,000 ft/min, the predominant characteristic is fibre length control.
(b) At speeds around 5,000 ft/min, there appears to be a good balance between fibrillation and fibre length control.
(c) At speeds of 6,000 ft/min, a predominance of fibrillation with very little cutting occurs.
(d) At speeds in excess of 7,000 ft/min, good defibring or deflaking characteristics occur.

**Effect of plate design**

We have seen from Fig. 2 how refining element dimensions have progressively decreased, whereas the efficiency of refining performance has increased. Refining must fortunately be a compromise: it is undesirable to have each and every individual fibre treated alike. Non-uniform fibres are a prerequisite for making a satisfactory paper sheet and it is not anticipated therefore having to reduce the bar widths of refining plates below the limits set by the mechanical strength of the bars. A modern plate pattern can have bar widths of 4 to 1 in, which gives a good range for varying the desired treatment results. The smaller dimension would be chosen where a predominance of cutting is required and 5 to 1 in or ¾ in if hydration is to be the predominant characteristic.

Relatively wide grooves will not produce a good proximity factor. The grooves must be sufficiently narrow to present the fibre flocks to the bar edges and faces. The groove must not be so narrow that it restricts flow-through or causes excessive water removal. A compromise is again necessary. Practical results to date indicate that, when stock entering the refiner is well defibred, groove widths of 1 to ½ in can be used.

The groove depth is also important, but again there has to be a compromise. Shallow grooves would limit the throughput rate and give short plate life. Deep grooves, although providing a relatively longer plate life, will considerably reduce the proximity factor. A groove depth of ¾ in (using modern plate materials) will give sufficient plate life comparable with replacement costs.

**Further considerations**

**Consistency**—The setting and control of consistency is determined by the papermaker. Experience with conical machines has shown a general tendency to refine for physical development of the fibre at 5 to 6 per cent consistency and to machine jordan for fibre length control at 3 to 3.5 per cent consistency.

Insufficient laboratory testing has been carried out so far to establish whether or not this requirement holds good for the disc refiner. If practicable, relatively high consistencies should be used at the refining stage, otherwise power is expended unnecessarily in pumping large volumes of water. The consistency after refining must be dropped to obtain final consistency control before machine jordaning. The process itself therefore probably demands two different consistencies—higher for refining and lower for jordaning.

Fig. 8 and 9 show the results of mill trials in which a 36 in single machine was run at consistency levels of 3.2 and 4.3 per cent. The incoming consistency was controlled by an in-line regulator and the throughput rate by a magnetic flow meter. The rate of freeness change (Fig. 9) is the same at both consistencies, but Fig. 8 shows higher burst and breaking length levels in the paper for a given stock freeness value run at the higher consistency.

We can generally conclude that consistencies much below 3 per cent would provide insufficient solids concentration to maintain a fibre film at high specific loading values.

**Refining surface**—It is interesting to question whether the total disc surfaces are doing useful work in developing the fibre physical properties—a question
also applicable to the conical refiner. Towards the inlet, in both machines, the surface speed of the rotor is less than at the periphery of the disc or the cone large end. We have removed 66 per cent of the bar length from a conical refiner operating on an all-rag furnish without producing any adverse effect on the refining performance. We have also removed the complete centre section from several disc refiners operating on woodpulps without producing any marked change in refiner performance. Both evaluations were made on the basis of physical strength tests and not on total refiner efficiency. These results confirm our work with the laboratory transparent model (Fig. 7), when a pronounced flocking effect was observed towards the periphery of the discs.

Future designs

Past refiner designs have been based upon the particular whims of the designer, empirical data and, in some cases, trial and error methods. The lack of absolute data and positive knowledge on what happens within a refining machine has limited the efficiency of existing refining processes, though it is essential for designs of the future. We have a great understanding of the fibre cell wall structure; it now remains to evolve refining machines and processes to supplement this knowledge.

References

4. Eschenmiller, H., Private communications