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Hydrodynamic Analysis of a High-Consistency Conical Refiner

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This paper aims to help the thermomechanical pulping (TMP) to attain the papermaking quality required for conical refiner. For this purpose, a hydrodynamic model was derived for pulp flow along the plate through analysis and calculation of the forces acting on the pulp in the refining zone of a high-consistency conical pulp refiner. The refiner contains both the conical refining zone and flat refining zone. In the refiner, the forces on the pulp come from two sources: the refiner plates and the interaction among fibres. Then, the author conducted a force analysis on the pulp in the refining zone based on hydrodynamics, and derived a set of equations for high-consistency conical refiner. The research findings greatly simplify the modelling process of pulping in high-consistency conical refiner.

1. Introduction

The thermomechanical pulping (TMP) is an energy-efficient refining method, but it is an ideal refining technique for China, where most pulps contain short fibres. With the advent of high-consistency, energy-saving conical refiner in the last two decades, it is meaningful to find a way to help the TMP attain the papermaking quality required for conical refiner. For this purpose, a hydrodynamic model was presented for the refining zone of the conical refiner.

In the refining zone, the fibres are separated, split, distorted and modified when the pulp and shive pass through the bar patterns of opposing plates with the pulp and the shive (Lu, 2010). Due to the lack of water, the fibres are not in the form of liquid suspension, but blanketed with a fast-moving, high-pressure hot steam produced during the refining process. Due to the high consistency of refining, the steam flow cannot be analysed by the volumetric method (Murton, 2005) widely adopted for low-consistency refiner.

In the refining zone, there is a stagnation point, at which the steam is static. In its upstream, the steam moves forward and pushes the pulp outwards; in its downstream, the steam flows backward and draws the pulp inwards. Miles and W.D. Ma (Miles and May, 1991; Miles et al., 1990) attempted to describe the flow and forces in a refiner mathematically. Liu C.P. and G. Gauca are the few scholars who have created a model for conical refiner (Liu and Rox, 2001). Unfortunately, their models are too coarse to cover all critical factors, such as the stagnation point and the effect of steam flow on pulping.

Adding to the complexity is the emergence of new patterns of conical refiner. Recent years saw the invention of refiner containing both conical and flat refining zones. In general, the diameter of the flat zone is much greater than the axial length of the conical zone, thus extending the effective refining zone without changing the overall size of the refiner. The new trend calls for more hydrodynamic models on refining zones.

2. Assumptions

The hydrodynamic analysis was performed on the following assumptions:

(1) The pulp is fed continuously into the refining zone and distributed evenly across the zone.

(2) The refining pressure and the height of refiner bars are constant; for simplicity, the model is considered as incompressible.

(3) All the dilution water is absorbed by the pulp, and not separated out under the centrifugal force. Any water squeezed out of the pulp by refiner bars is reabsorbed.

As mentioned above, the new refiner, containing both conical and flat refining zones, boasts a larger effective refining zone than traditional conical/flat refiner with the same diameter. The new structure also markedly enhances the pulp quality and saves energy. This is because the fibres are further split and separated horizontally thanks to the extended refining route, and the reversing at the junctions between the flat and conical plates.

Based on these assumptions, the forces from refining plates were divided into the flat zone and conical zone, where *r1* is the maximum diameter of the flat plate, and l is the length of the conical plate (Figures 1 & 3).

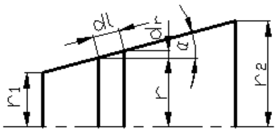

Figure 1: A typical segment (radius: r; width: dr) of conical zone

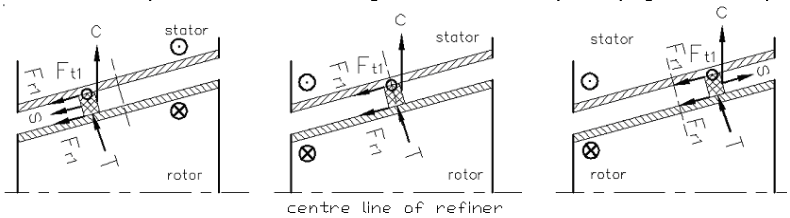

Figure 2: Force analysis of the typical segment in Figure 1

Note: The broken line stands for the stagnation point of the steam flow, at which the steam is static.

3. Modelling

3.1 Forces analysis of conical zone

The conical angle of the refiner plate is denoted as α. The typical segment (radius: *r*; width: *dr*) in Figure 1 was subject to a force analysis (Figure 2).

Owing to the poor fluidity of the pulp in high-consistency refining zone, a screw is often installed to press it across the entrance to the refining zone. When the fibres leave the screw, the initial velocity is rather low. Upon reaching the narrow clearance between the two plates, the fibres continuously pick up speed until getting to the peak velocity at the outer periphery of the refining zone. Then, the fibres are under the joint action of the centrifugal force from the plate movement, and the frictional force from plate compression and fibre interaction.

The forces on the typical segment are illustrated in Figure 2. As the pulp moves around the rotor, a centrifugal force *C* emerges and propels the pulp outwards through the refiner. This motion is opposed by the frictional force along the conical plate *Fr1* and that along the flat plate *Fr2*. There is also a tangential frictional force *Ft1* between the pulp and the stator, which enables the pulp to move at the same tangential velocity with the rotor. In addition, the force *S* originates from the steam flow. Its direction depends on the position of the typical segment relative to the stagnation point. In the upstream of the point, the fast-moving steam moves forward and pushes the pulp outwards; in the downstream, the steam flows backward and draws the pulp inwards.

The net accelerating force on the pulp along the plate direction, denoted as Fa, can be expressed as:

$$F_a = C - F_{r1} - F_{r2} + bS \tag{1}$$

where *b*=+1 means the steam moves forward; *b*=–1 means the steam moves backward; *S*=0 means the steam is static at the stagnation point.

It can be seen from Figure 1 that:

$$dl = \frac{dr}{\sin\alpha} \tag{2}$$

The fibre-plate contact area in the annulus *dA* can be expressed as:

$$dA = \pi(r + r + dr)dl = \frac{\pi(2r + dr)dr}{\sin\alpha} \tag{3}$$

Let *λ* be the modified coefficient of the effective plate bar contact area between rotor and stator. Then, the coefficient can be expressed as:

$$\lambda = \frac{a_s \cdot a_r}{\left(a_s + b_s\right)\left(a_s + b_r\right)} \tag{4}$$

Where *as* and *ar* are the widths of plate bars on rotor and stator, respectively; *bs* and *br* are the width of grooves on rotor and stator, respectively.
Assuming that the plate bar of rotor is the same with that of stator, then the value of *λ* equals 0.25.
Then, combined frictional force of the conical and flat plates can be expressed as:

$$F_{r1} + F_{r2} = (\mu_{r1} + \mu_{r2})T(r) \tag{5}$$

where *T(r)* is the positive thrust on the pulp in the typical segment; *μr1* is the coefficient of the friction between the pulp and the conical plate; *μ r2* is the coefficient of the friction between the pulp and the flat plate.
Hence, the total frictional force along the plate direction can be expressed as:

$$F_r = \mu_r TdA = \frac{2\lambda \cdot \pi(2r+dr)\mu_r P_m(r)dr}{\sin\alpha} = \frac{\pi(2r+dr)\mu_r P_m(r)dr}{2\sin\alpha} \tag{6}$$

where *Pm(r)*is the average pressure over the segment; *μr* is the arithmetic average of the two coefficients of friction along the plate.
The pulp is also under the centrifugal force along the plate direction *C(r)*:

$$C(r) = dM(r)\omega^2 r \cdot \sin\alpha \tag{7}$$

where *dM(r)* is the wet mass of pulp in the annulus;ω is the angular velocity of rotor.
The force of the steam flow on the pulp is (Miles and May, 1991; Miles et al., 1990):

$$S = \frac{1}{2} C_f \rho(r) V(r)^2 A_p(r) dm(r) \tag{8}$$

where C_f is the frictional traction coefficient of the steam on pulp; *ρ(r)* is the steam density at radius r; *V(r)* is the steam velocity at radius r; *Ap(r)* is the aerodynamic specific surface of the pulp; *dm(r)* is the absolute dry mass of pulp in the annulus; *v* is the velocity of the pulp at radius r.
Here, V is assumed to be much greater than v generally, except near the stagnation point. In the steam flow term, the local steam velocity and density *V(r)* and *ρ(r)* are derived by the numerical solution of the steam flow equations proposed by Miles, Dana and May in their theory on the steam flow in chip refiners (Miles and May, 1991; Miles et al., 1990). The aerodynamic specific surface *Ap(r)* of the pulp in a chip refiner has been proved as being independent of the energy applied to the pulp, and thus can be written into the equation as a constant *Ap*.
Under the forces Fa, the resultant acceleration of the pulp dv/dt can be expressed as:

$$dM(r)\frac{dv}{dt} = dM(r)\omega^2 r \cdot \sin\alpha - \frac{\pi(2r+dr)\mu_r P_m(r)dr}{2\sin\alpha} + \frac{b}{2} C_f \rho(r) V(r)^2 A_p(r) dm(r) \tag{9}$$

The relationship between the mass of pulp in the typical segment and its velocity dl/dt and the mass flow rate m can be described by the following equations:

$$\dot{M} = \frac{dM(r)}{dt} = \frac{dM(r) \cdot dv}{dl} \tag{10}$$

$$\dot{M} = \frac{\dot{m}}{c(r)} \tag{11}$$

where *M* is the wet throughput; m is the absolute dry throughput; *c(r)* is the average consistency of pulp in the annulus.
Then, the velocity change of the pump across the refining zone dv/dl can be obtained based on equations (10) and (11):

$$\frac{dv}{dl} = \frac{\dot{m}}{c(r) \cdot dM(r)} \tag{12}$$

In the typical segment, the axial pressure *Pm(r)* can be offset by power dissipation. If the power dissipation per unit area of the refining zone is constant everywhere, the power dissipation *P(r)* in the typical segment can be expressed as:

$$P(r) = \frac{\dot{m}E \cdot \lambda dA \cdot \sin\alpha}{\pi(r_2^2 - r_1^2)} \tag{13}$$

where *E* is the total specific energy applied to the refiner; *r1* and *r2* are the inner and outer radii of the refining zone, respectively.
The power *Pf(r)* dissipated against the tangential friction force in the annulus can be expressed as:

$$P_f(r) = F_{t1}\omega r = \mu_{t1} P_m(r) \cdot \lambda dA \omega r \tag{14}$$

where *μt1* is the coefficient of the tangential friction force between pulp and stator (hereinafter referred to as the tangential friction coefficient).
If the power dissipated in feeding the pulp along the plate direction is so small as to be negligible, then *Pf(r)* equals *P(r)*. According to equations (13) and (14), the following expression is valid:

$$P_m(r) = \frac{\dot{m}E \cdot \sin\alpha}{\pi(r_2^2 - r_1^2)\mu_{t1}\omega r} \tag{15}$$

Then, equation (12) can be rewritten as:

$$\frac{dv}{dl} = \frac{r\omega^2 \cdot \sin\alpha}{v} - \frac{\mu_r}{\mu_{t1}} \frac{Ec(r)}{\omega(r_2^2 - r_1^2)} + \frac{b}{2} C_f \rho(r) V(r)^2 A_p(r) \frac{c(r)}{v} \tag{16}$$

The consistency *c(r)* changes with the radius because of the conversion of water to steam. If the latent heat of the steam is assumed to be independent of steam pressure, the consistency can be approximated as follows:

$$c(r) = \frac{c_i L(r_2^2 - r_1^2)}{L(r_2^2 - r_1^2) - c_i E(r^2 - r_1^2)} \tag{17}$$

where c_i is the inlet consistency; *L* is the latent heat of the steam. An accurate expression for *c(r)* is given in reference (Huhtanen and Karvinen, 2004).
Based on the evidence of numerous experiments, the tangential friction coefficient μt1 can be described by the following empirical equation:

$$\mu_{t1} = \frac{P}{\omega T(r_1 + r_2)} \tag{18}$$

where *P* is the motor load; *T* is the total positive thrust.
The coefficient of friction between the plates and the pulp is not a function of consistency, indicating that μt1 is independent of the consistency. Similarly, μt1 is also irrelevant to the tangential velocity in the refiner, and to the amount of specific energy already dissipated in the fibres. To sum up, the coefficient has nothing to do with r, and is thus assigned the value of 0.75 (Huhtanen and Karvinen, 2004).
The coefficient of friction along the plate *μr* is assumed to be constant, for no contrary information is available. Thus, it is assigned the value of 0.25 (Huhtanen and Karvinen, 2004).

3.2 Forces analysis of flat zone

The flat refining zone is a circular ring with diameter falling in the interval [r1, r1]. The refiner bars are distributed regularly between the maximum and minimum diameters. The typical segment (radius: *r*; width: *dr*) in Figure 3 was subject to a force analysis (Figure 4).

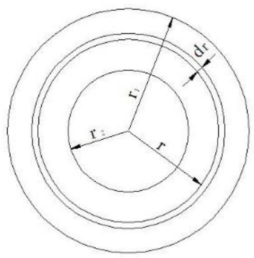

Figure 3: A typical segment (radius: r; width: dr) of flat zone

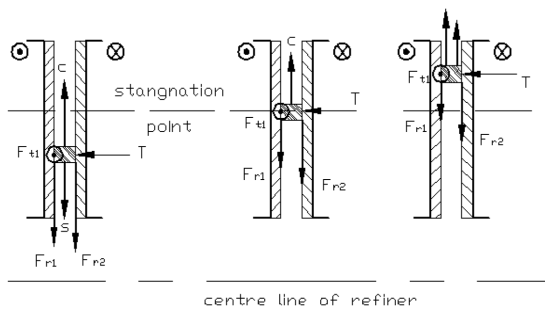

Figure 4: Force analysis of the typical segment in Figure 3

It can be seen from Figure 3 that:

$$dA = 2\pi r dr \tag{19}$$

The centrifugal force along the plate direction *C(r)* can be expressed as:

$$C(r) = dM(r)\omega^2 r \tag{20}$$

The force of the steam flow on the pulp can be expressed as:

$$S = \frac{1}{2} C_f \rho(r) V(r)^2 A_p(r) dm(r) \tag{21}$$

The radial frictional force can be expressed as:

$$F_r = \mu_r T dA = 2\lambda \cdot 2\pi \mu_r r T_m(r) dr = \pi \mu_r r T_m(r) dr \tag{22}$$

Under the radial forces Fa, the resultant acceleration of the pulp dv/dt can be expressed as:

$$dM(r)\frac{dv}{dt} = dM(r)\omega^2 r - \pi \mu_r r T_m(r) dr + \frac{b}{2} C_f \rho(r) V(r)^2 A_p(r) dm(r) \tag{23}$$

The relationship between the mass of pulp in the typical segment and its velocity dl/dt and the mass flow rate m can be described by the following equations:

$$\dot{M} = \frac{dM(r)}{dt} = v\frac{dM(r)}{dr} \tag{24}$$

$$\dot{M} = \frac{\dot{m}}{c(r)} \tag{25}$$

Then, the velocity change of the pump across the refining zone dv/dl can be obtained based on equations (24) and (25):

$$\frac{dv}{dr} = \frac{r\omega^2}{v} - \frac{\pi \mu_r r T_m(r) c(r)}{\dot{m}} + \frac{b}{2} C_f \rho(r) V(r)^2 A_p(r) \frac{c(r)}{v} \tag{26}$$

The power dissipation *P(r)* in the typical segment can be expressed as:

$$P(r) = \frac{\dot{m}E \cdot \lambda dA}{\pi(r_2^2 - r_1^2)} \tag{27}$$

The power *Pf(r)* dissipated against the tangential friction force in the annulus can be expressed as:

$$P_f(r) = hF_{t1}\omega r = h\mu_{t1} T_m(r) \cdot \lambda dA \omega r \tag{28}$$

where h=1 (Huhtanen and Karvinen, 2004).
If the power dissipated in feeding the pulp along the plate direction is so small as to be negligible, then *Pf(r)* equals *P(r)*. According to equations (27) and (28), the following expression is valid:

$$T_m(r) = \frac{\dot{m}E}{\pi(r_2^2 - r_1^2) h \mu_{t1} \omega r} \tag{29}$$

Then, equation (6) can be rewritten as:

$$\frac{dv}{dr} = \frac{r\omega^2}{v} - a\frac{\mu_r}{\mu_{t1}} \frac{Ec(r)}{\omega(r_2^2 - r_1^2)} + \frac{b}{2} C_f e_s(r) U(r)^2 A_p(r) \frac{c(r)}{v} \tag{30}$$

where a=4 (Huhtanen and Karvinen, 2004).
Fibre interaction:

Compared with low-consistency refining, high-consistency refining is not only influenced by the refiner plate, but also affected by the friction, extrusion, kneading and distortion among fibres. An accurate expression for the forces among fibres is given in References (Li, 1996; Dong and Gu, 2006).
Therefore, the dynamic model of a conical refiner for high-consistency pulping is established as:

$$F = Fa + \sum(\sigma f_n + \tau f_m) \quad (31)$$

where σ and τ are coefficients of shear and friction among fibres in high-consistency pulp, respectively. $\sum \sigma f_n$ is resultant stress (changing alternatively between pressure, tension and shear) and $\sum \tau f_m$ is frictional force.
The centrifugal force *C* is essential to the force *Fa*. Despite the decrease in refiner size, the rotor velocity is on the rise, revealing little variation in *Fa*. In high-consistency refining, however, the forces among fibres occupy a large portion in the total force *F*. The unique trait is fully taken into account in our model.

4. Conclusions

Considering the forces acting on the pulp, the author derived an equation for the pulp flow along the plate in a high-consistency refiner. The forces include a centrifugal force, the frictional forces between the pulp and the refiner plates, the traction force of the steam flowing through the refining zone, and the forces among the fibre. For simplicity, the forces from refining plates were divided into the flat zone and conical zone.
It is concluded that the centrifugal force can be controlled by the local consistency, size and speed of the refiner; the frictional forces depend on the size and speed of the refiner; the coefficient of friction along the plate and tangential friction coefficient are constant; the traction of the steam relies on the local steam velocity, and thus on the motor load and the relative position to the stagnation point.
The forces on the pulp in the high-consistency refining zone are influenced by multiple factors, including but not limited to rotor speed, plate size and pattern, friction coefficient, pressure, resultant stress, friction among the fibres, and shear coefficient.
The forces acting on the pump can be improved by changing the contact area ratio of the refining plate without altering other conditions. The improvement of plate design will rationalize the forces on pulp and save energy.

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