

Modelling of agitation in the disintegration process of pulp suspensions

B. Fabry*, M. Renaud**, J.C. Roux**

Introduction

In the paper industry, the pulp disintegration process occurs in the first stages in the case of a non-integrated mill. A physical description of the phenomena encountered in a disintegrator is given and applied for a laboratory-helical disintegrator with a mixture of water and glycerol. Then, this description is extended to the pulp suspensions in the low consistency range of mass solid fraction (0 % to 8 %). The differences between the volumetric powers consumed to rotate a pulp and just water are studied as a function of the rotation speed and the mass solid fraction. A global relation is given for the power ratio and a critical volumetric power is determined.

1. NEW APPROACH PROPOSED

1.1 - How to decompose the power consumption ?

The pulp disintegration process is a complex operation where agitation by bulk motion, mixing and dispersion of a solid phase (vegetable fibres) in a water medium occur

simultaneously [1]. In the low consistency range (0 % to 8 %), which is typically used in the paper industry the effective power required to rotate and agitate a suspension can be analysed taking into account the physical phenomena. This effective power is supposed to have different contributions to dissipation, among which :

- inertial
- viscous
- solid/solid friction.

The mathematical description chosen for the power dissipation is a second order function of the rotation speed where the constant term expresses the global solid-solid friction, the linear term reveals the importance of the viscous power and the quadratic term reflects the inertial dissipation :

$$\frac{P}{\rho} = a.n^2 + b.n + c \quad (1)$$

The choice of a second order function for the power versus the rotation speed may be justified by application of the mixing theory for the case of Newtonian fluids in the laminar regime [2]. In this regime, the power number is a function of the reciprocal of the Reynolds number leading to a

AUTHORS : B. Fabry*, M. Renaud, J.C. Roux****

*Centre Technique du Papier, B.P. 251, 38044 Grenoble Cedex 9, France

**EFG, 461 rue de la Papeterie, B.P. 65, 38402 Saint-Martin d'Hères Cedex, France

quadratic term between the power consumed and the rotation speed.

When there are no solid particles in the mixture studied, the term c is obviously equal to 0.

1.2 - Application to water-glycerol mixtures [3]

In order to verify the validity of equation (1), experiments were performed in a laboratory-helical pulper with mixtures of water and glycerol in different proportions. These mixtures are known to be Newtonian fluids and do not include solid particles. For a given mixture, the rotation speed was varied from 5 to 60 s^{-1} (revolution per second) and the corresponding power consumed was measured. Some typical results are given in table 1. The first two columns characterize two physical quantities of the mixture, namely its density $\rho(kg.m^{-3})$ and its kinematic viscosity $\nu(m^2.s^{-1})$. In the third and fourth column, the constants $a(m^5.s^{-1})$ and $b(m^5.s^{-2})$ were determined for each set of experiments.

$\rho(kg.m^{-3})$	$\nu(m^2.s^{-1})$	$a(m^5.s^{-1}).10^{-4}$	$b(m^5.s^{-2}).10^{-3}$
1252	$7,24.10^{-4}$	2,14	6,71
1233	$1,81.10^{-4}$	1,71	6,52
1203	$5,15.10^{-5}$	1,74	4,82
1165	$3,43.10^{-5}$	2,34	3,81
1000	$1,00.10^{-6}$	1,77	1,22

Table 1 - Determination of constants in the power model of agitation (1) for water-glycerol mixtures.

Table 1 reveals that the constant a can be considered as being independent of the composition of the water-glycerol mixture, which is consistent with the expression (1) :

$$\bar{a} = (1,90 \pm 0,28).10^{-4} \quad (2)$$

This assumption is also in accordance with the physical meaning of the first quadratic term in the decomposition of the power consumed. It seems realistic to admit that the inertial dissipation is independent of the mixture composition. However, this is not the case for the second linear term which expresses the viscous dissipation ; a decrease in the glycerol proportion versus water reduces the b coefficient correspondingly.

On the one hand, if a least mean square (LMS) method is applied for each set of data $\left(n; \frac{P}{\rho} - \bar{a}.n^2\right)$, another coefficient named \bar{b} can be calculated and related to the previous one as follows :

$$\bar{b} = (1,02 \pm 0,12).b \quad (3)$$

On the other hand, a second order function can be obtained between the logarithm of the coefficient \bar{b} and that of

the kinematic viscosity ν of the water-glycerol mixture as :

$$\ln(\bar{b}) = -5,515 - 0,284.\ln(\nu) - 0,027.[\ln(\nu)]^2 \quad (4)$$

If this analysis is relevant to the problem studied, it can include the typical case of the power consumed when only water is present in the laboratory-helical mixer. Following this remark, a better representation for (4) is given when the ratio of viscosities between the mixture and water appears explicitly in the formula. Denoting ν_w for the kinematic viscosity of water, one obtains :

$$\ln(\bar{b}) = -6,744 + 0,462.\ln\left(\frac{\nu}{\nu_w}\right) - 0,027.\left[\ln\left(\frac{\nu}{\nu_w}\right)\right]^2 \quad (5)$$

If expressions (2) and (5) are considered together, then the power dissipation in the laboratory-helical disintegrator studied is given by :

$$\frac{P}{\rho} = 1,90.10^{-4}.n^2 + 1,18.10^{-3}.n.\left(\frac{\nu}{\nu_w}\right)^{0,462}.exp\left\{-0,027.\left(\ln\frac{\nu}{\nu_w}\right)^2\right\} \quad (6)$$

The effective power consumed for the agitation of water only, in the laboratory-helical mixer, is obtained accordingly as a quadratic function of the rotation speed :

$$\frac{P}{\rho} = 1,90.10^{-4}.n^2 + 1,18.10^{-3}.n \quad (7)$$

As it can be seen on figure 1, all the 200 experimental data follow the proposed approach with a relative error of 7,0 %. This approach seems sufficiently interesting to be extended to the case of the agitation of pulp suspensions under the same conditions.

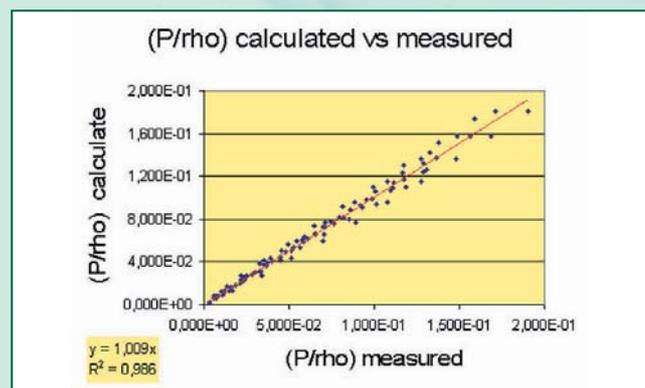


Fig. 1 - Validation of equation (6) using the experimental data for water-glycerol mixtures.

1.3 - Extension to the case of pulp suspensions

In the case of the disintegration of pulp suspensions in the low consistency range (mass solid fraction comprised from 0% to 8%) in a laboratory-helical disintegrator, the power

model used to describe the physical phenomena is given by :

$$\frac{P}{\rho} = 1,90 \cdot 10^{-4} \cdot n^2 + B \cdot n + C \quad (8)$$

The inertial dissipation of power is supposed to be equal to that of water-glycerol mixtures (including water only). Thus, the first quadratic terms are identical in both expressions (6) and (8).

For each set of experimental data $(n; \frac{P}{\rho})$, the coefficients

B and C must be determined for each mass solid fraction denoted x .

For the cellulose fibres, the apparent kinematic viscosity of pulp suspensions is supposed to have an exponential evolution versus the consistency (or versus the mass solid fraction) :

$$\frac{\nu}{\nu_w} = \exp(k \cdot x) \quad (9)$$

A general expression for the C coefficient is also given by this formula where c_0, c, c' are three numerical constants :

$$C = c_0 \cdot x \cdot \{ \exp(c \cdot x) - c' \} \quad (10)$$

If the expression (6) is applied for the typical case of cellulose fibres, taking into account the previous equations (9) and (10), the power model may be written as follows :

$$\frac{P}{\rho} = 1,90 \cdot 10^{-4} \cdot n^2 + 1,18 \cdot 10^{-3} \cdot n \cdot \exp\{0,462 \cdot (k \cdot x - 0,027 \cdot (k \cdot x)^2) + c_0 \cdot x \cdot \{ \exp(c \cdot x) - c' \} \} \quad (11)$$

In this model, four numerical parameters must be determined. For example, the coefficient k is used to evaluate the apparent kinematic viscosity of a pulp suspension under analysis. The other coefficients describe the solid-solid friction phenomena. Table 2 gives identified values of the four parameters for the case of a bleached softwood Kraft pulp (BSK), unrefined and highly refined, and an unrefined bleached hardwood Kraft pulp (BHK).

Pulp type	Identified parameters			
	k	$c_0 (m^5 \cdot s^{-3})$	c	c'
unrefined-BSK	92	0,24	11	0
90°SR-BSK	142	0,09	33	0
unrefined-BHK	152	0,05	39	0,6

Table 2 - Determination of the constants in the power model of agitation (11) for different types of pulp suspension.

Figure 2 confirms the validation of the proposed model for describing the net power dissipation in the agitation of an unrefined BSK pulp in the pilot disintegrator.

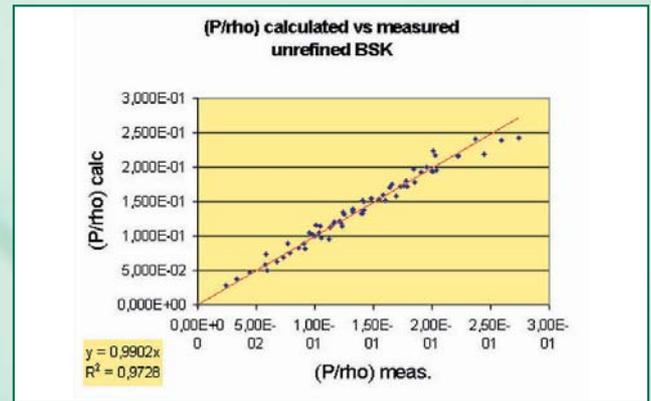


Fig. 2 - Validation of equation (11) from the experimental data in the case of unrefined BSK.

Remark for the case of highly concentrated suspensions (above 8,5 %)

If the suspension consistency exceeds a mass solid fraction of 8,5 %, a quadratic power model can no longer be used. When pulp suspensions are highly concentrated, the motion arises only in the vicinity of the rotor, but not in the bulk volume. This explains why both the inertial and the solid-solid friction terms vanish. Consequently, the consumption of power is only due to the viscous dissipation in the bulk. For example, the power dissipation obtained in the agitation of unrefined bleached softwood Kraft pulps (BSK) seems constant from 8,5 % to 10 % :

$$\frac{P}{\rho} = 46 \cdot 10^{-3} \cdot n \quad (12)$$

2. Modelling of the power consumed for the agitation of a pulp suspension in the low consistency range [0%;8%]

The power consumed for the agitation of water in a laboratory-helical disintegrator (considered as a mixer) is easy to determine and measure. However, this is not always true for pulp suspensions. Our aim is to predict the power dissipation to rotate the same volume of pulp suspension, given the :

- nature of the pulp
- rotation speed
- pulp consistency.

In another study already published [4], at constant rotation speed, the ratio of the volumetric power consumed for the agitation of a pulp suspension, compared to that of water, was characterized as a linear function of the mass solid fraction, or consistency, denoted x as follows :

$$\frac{\Phi_w}{\Phi} = 1 - K.x \quad (13)$$

This expression is interesting in practice since the parameter K measures the propensity of a pulp to absorb energy during the disintegration process. However, on the one hand, the characterization is obtained under constant rotation speed conditions, which limits its range of application. On the other hand, it is likely that the parameter K must be a function of both the rotation speed and the consistency. Our objective is to determine this function.

2.1 - First determination of the K value

The parameter K can be calculated from the derivative of the ratio (13) versus x for the special case where $x = 0$. Keeping the density of pulp constant and close to that of water, the ratio of the power is then equal to the ratio of the volumetric powers. With the help of both equations (7) and (11), the previous ratio can be written as follows :

$$\begin{cases} \frac{\Phi_w}{\Phi} = \frac{a.n^2 + b.n}{a.n^2 + b.n.exp(\alpha.x - \beta.x^2) + c_0.x.(exp(c.x) - c')} \\ \Phi_w \cdot \frac{V}{\rho} = a.n^2 + b.n \end{cases} \quad (14)$$

Denoting :

$$a = 1,90.10^4 ; b = 1,18.10^3 ; \alpha = 0,462.k ; \beta = 0,027.k^2 ; V = 4,5.10^3 m^3 ; \rho = 10^3 kg.m^3$$

the value of the constant K_0 is given by the formula :

$$K_0 = - \left(\frac{d\left(\frac{\Phi_w}{\Phi}\right)}{dx} \right)_{x=0} = \frac{b.\alpha.n + c_0.(1-c')}{a.n^2 + b.n} \quad (15)$$

$$\text{or } K_0 = \alpha + \frac{\rho}{V} \cdot \frac{(c_0.(1-c') - a.\alpha.n^2)}{\Phi_w}$$

If the rotation speed is varied from 5 to $60s^{-1}$, the corresponding values of K_0 were calculated and are given in table 3 for different types of pulp suspension.

$n(s^{-1})$	$\Phi_w(kW.m^{-3})$	K_0	K_0	K_0
		unrefined-BSK	90°SR-BSK	unrefined-BHK
5	2,38	46,1	45,0	41,1
10	6,84	24,2	28,1	27,7
15	13,4	16,5	20,8	21,0
25	32,9	10,2	13,8	14,3
40	78	6,53	9,38	9,71
60	168	4,53	6,62	6,98

Table 3 - Numerical values of the constant K_0 for different rotation speeds and pulp types.

From these results and for a given pulp type, the parameter K_0 is dependent on the rotation speed (the scale of variation ranges from 1 to 10). At low speed of rotation, the relative difference among all K_0 values (for different pulp types) seems small. However, when there is an increase in the rotation speed, the different types of pulp lead to different values for this parameter. Whatever the pulp type, an increase in the rotation speed leads to a decrease in K_0 . In the limiting case, if the rotation speed is high, the pulp suspension may behave nearly as water, with a small numerical value of the parameter.

It can be useful to try to correlate the parameter K_0 with the volumetric power Φ_w consumed by water under the same conditions. This can be done for all pulps studied and the parameter is obtained as a unique function of the constant k appearing in the kinematic viscosity law and the volumetric power consumed by water at a defined exponent. Using table 5 for the numerical values of the constants (k, γ), a general expression is found :

$$K_0 = (1,00 \pm 0,03) \cdot (1 + 5,2.10^{-2} \cdot k) \cdot \left(\frac{9,78.10^4}{\Phi_w} \right)^\gamma \quad (16)$$

Pulp type	K_0	K_0	K_0
	unrefined-BSK	90°SR-BSK	unrefined-BHK
k	92	142	152
γ	0,554	0,452	0,420

Table 5 - Constants used to calculate the parameter in equation (16).

2.2 - Variations of the volumetric power ratio versus pulp type, consistency and rotation speed

If equation (16) is applied to different pulp types (different set of constant k, c_0, c, c' according to table 2), the evolution of the volumetric power ratio versus the mass solid fraction x and the rotation speed n is characterized by the following general expression :

$$\frac{\Phi_w}{\Phi} = \frac{1,90.10^{-4}.n^2 + 1,18.10^{-3}.n}{1,90.10^{-4}.n^2 + 1,18.10^{-3}.n.exp(0,462k.x - 0,027.k^2.x^2) + c_0.x.(exp(c.x) - c')} \quad (17)$$

Table 6, 7 and 8, give, respectively, the numerical values of the preceding ratio for the case of a bleached softwood Kraft pulp (unrefined-BSK), a bleached softwood Kraft pulp (BSK refined at 90°SR) and an unrefined bleached hardwood Kraft pulp (BHK). Figures 3, 4 and 5 illustrate the evolution of the previous ratio versus the pulp consistency for different volumetric powers consumed by water Φ_w , expressed in $kW.m^{-3}$.

$n(s^{-1})$	$x(\%)$							
	0,50	1	2	3	4	5	6	7
5	0,802	0,655	0,456	0,333	0,253	0,199	0,162	0,135
10	0,886	0,783	0,614	0,486	0,391	0,322	0,272	0,235
15	0,919	0,841	0,699	0,580	0,484	0,411	0,355	0,314
25	0,949	0,896	0,790	0,691	0,604	0,531	0,474	0,431
40	0,967	0,931	0,855	0,778	0,705	0,641	0,588	0,547
60	0,977	0,952	0,897	0,838	0,780	0,726	0,680	0,643

Table 6 - Φ_w / Φ ratio for the case of a bleached softwood Kraft pulp (unrefined-BSK).

$n(s^{-1})$	$x(\%)$							
	0,50	1	2	3	4	5	6	7
5	0,797	0,635	0,412	0,281	0,204	0,156	0,123	0,098
10	0,863	0,737	0,533	0,395	0,306	0,250	0,215	0,188
15	0,895	0,792	0,610	0,474	0,382	0,324	0,288	0,265
25	0,929	0,853	0,705	0,581	0,490	0,432	0,400	0,386
40	0,951	0,897	0,783	0,678	0,595	0,541	0,513	0,508
60	0,966	0,927	0,840	0,753	0,682	0,634	0,611	0,612

Table 7 - Φ_w / Φ ratio for the case of a bleached softwood Kraft pulp (BSK refined at 90°SR).

$n(s^{-1})$	$x(\%)$							
	0,50	1	2	3	4	5	6	7
5	0,810	0,650	0,425	0,293	0,217	0,162	0,140	0,113
10	0,864	0,737	0,531	0,394	0,310	0,261	0,232	0,210
15	0,893	0,788	0,602	0,466	0,380	0,330	0,304	0,302
25	0,926	0,847	0,701	0,568	0,483	0,433	0,413	0,413
40	0,949	0,892	0,771	0,664	0,584	0,538	0,523	0,533
60	0,964	0,922	0,829	0,740	0,671	0,630	0,619	0,634

Table 8 - Φ_w / Φ ratio for the case of a bleached hardwood Kraft pulp (unrefined-BHK).

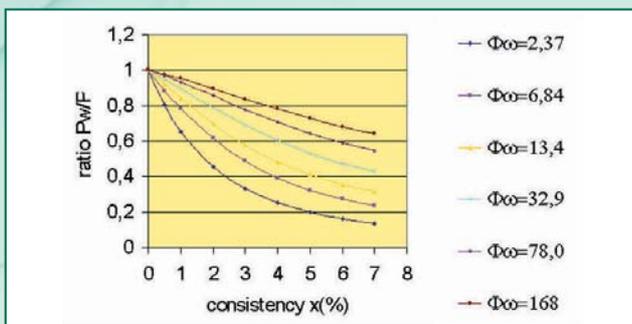


Fig. 3 - Evolution of the power ratio versus the consistency for an unrefined BSK (Φ_w is expressed in $kW.m^{-3}$).

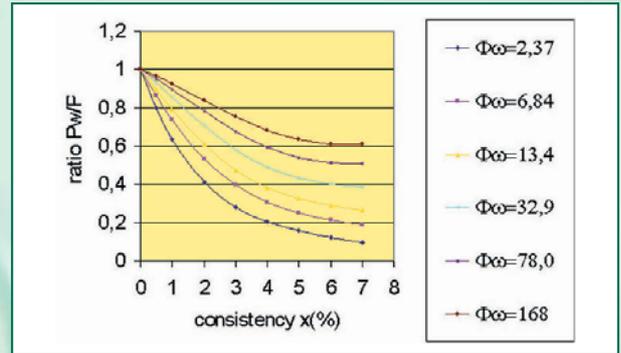


Fig. 4 - Evolution of the power ratio versus the consistency for BSK refined at 90°SR (Φ_w is expressed in $kW.m^{-3}$).

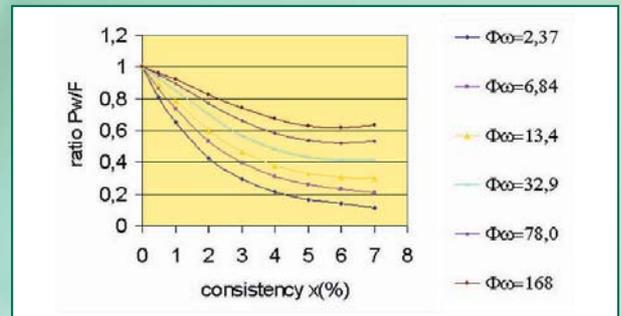


Fig. 5 - Evolution of the power ratio versus the consistency for an unrefined BHK (Φ_w is expressed in $kW.m^{-3}$).

For the small values of the volumetric power Φ_w , all the curves displayed on figures 3, 4 and 5 look like decreasing exponential. However, for high values of the same parameter, the shape of the curve evolution is close to a sigmoid.

It is possible to characterize the power ratio by a linear evolution versus the consistency by taking the average slopes of the corresponding curves in the low consistency range [0%; 5%]. This description leads to average values of the constant \bar{K} denoted \bar{K} :

$$\frac{\Phi_w}{\Phi} = 1 - \bar{K} \cdot x \quad \text{where } x \leq 5\% \quad (18)$$

Some indicative numerical values of the constant \bar{K} are given in table 9 for different pulp types and different volumetric powers consumed by water Φ_w .

Pulp nature	$\Phi_w (kW.m^{-3})$				
	13,4	32,9	78,0	164	∞
unrefined-BSK	15,0	10,0	7,31	5,30	5,29
90°SR-BSK	19,5	14,1	10,4	7,65	8,17
unrefined-BHK	19,9	14,5	11,4	8,46	8,74

Table 9 - Numerical values of the constant \bar{K} for different pulp types and volumetric powers consumed by water.

The experimental values verify the following correlation which considers two main variables : the coefficient k in the kinematic viscosity law and the volumetric power consumed by water Φ_w .

$$\bar{K} = 5,75.10^{-2}.k + 15.exp\left(-\frac{\Phi_w}{3,6.10^4}\right) \quad (19)$$

From this expression and for a given pulp type, an increase in the volumetric power leads to an exponential decrease in \bar{K} .

2.3 - Determination of a critical volumetric power

If equation (19) is extrapolated to the limiting case for which $\Phi_w \rightarrow 0$, then the average constant \bar{K} exhibits the highest numerical value given by :

$$\bar{K} [\Phi_w \rightarrow 0] = 5,75.10^{-2}.k + 15 \quad (20)$$

This value has a physical meaning of the level of separation from the water behaviour. It is also equal to the constant K_0 calculated by equation (16). From both equations (16) and (20), a critical value for the volumetric power can thus be evaluated :

$$(\Phi_w)_{critical} = 9,78.10^4 \cdot \left(\frac{1+5,2.10^{-2}.k}{15+5,75.10^{-2}.k}\right)^{1/\gamma} \quad (21)$$

The interesting result obtained indicates that, whatever the pulp type, the critical volumetric power is the same and has a value of :

$$(\Phi_w)_{critical} = (1,00 \pm 0,05).10kW.m^{-3} \quad (22)$$

Another relevant consequence can be shown, if the critical volumetric power is related to a critical rotation speed according to equation (14). In this case, for the laboratory-helical disintegrator analysed, the critical rotation speed, which is the minimum rotation speed needed to obtain a sufficient motion of the pulp in the tank, is $12,6 s^{-1}$. This concept is in accordance with the minimum power required to get an appreciable motion of the pulp suspension in a mixer.

Conclusion

The purpose of this communication was to give new insights into the operation of agitation which occurs in the paper industry, in the disintegration process of a pulp suspension in the low consistency range, from 0% to 8% of mass solid fraction. A physical description of the phenomena is proposed which accounts for the inertial, viscous and solid-solid friction power consumption, summarized by equation (1) :

$$\frac{P}{\rho} = a.n^2 + b.n + c \quad (1)$$

All these terms are gathered in a quadratic function of the effective power versus the rotation speed of the rotor.

In order to prove this postulate, the model was evaluated with a water-glycerol mixture, well known for its Newtonian behaviour. For each composition, the effective power was measured when the rotation speed was varied from 5 to 60 s^{-1} in a laboratory-helical disintegrator, considered, for the circumstance, as a mixer. From this experimental campaign, the model of the power dissipation was validated and the linear term was correlated to the kinematic viscosity of the mixture as given by equation (6) :

$$\frac{P}{\rho} = 1,90.10^{-4}.n^2 + 1,18.10^{-3}.n \cdot \left(\frac{V}{V_w}\right)^{0,462} \cdot exp\{-0,027 \cdot \left(\ln \frac{V}{V_w}\right)^2\} \quad (6)$$

Then the proposed model was applied for the agitation of pulp suspensions of different origin (unrefined and refined at 90°SR) bleached softwood Kraft pulp (BSK) not refined, unrefined bleached hardwood Kraft pulp (BHK). An apparent kinematic viscosity can be attributed to a pulp suspension in the conditions of experience during the agitation process and the solid/solid friction can also be described by an exponential term of the consistency as expressed by equation (11) :

$$\frac{P}{\rho} = 1,90.10^{-4}.n^2 + 1,18.10^{-3}.n \cdot exp\{0,462 \cdot (k.x) - 0,027 \cdot (k.x)^2\} + c_0.x \cdot \{exp(c.x) - c'\} \quad (11)$$

The last part of the communication is devoted to the analysis of the ratio of the volumetric power consumed for the agitation of a pulp suspension compared to that of water, at the same rotation speed and the same agitated volume on the same apparatus. This ratio was studied as a function of the consistency and the rotation speed, as expressed by equation (17) :

$$\frac{\Phi_w}{\Phi} = \frac{1,90.10^{-4}.n^2 + 1,18.10^{-3}.n}{1,90.10^{-4}.n^2 + 1,18.10^{-3}.n \cdot exp(0,462k.x - 0,027.k^2.x^2) + c_0.x \cdot (exp(c.x) - c')} \quad (17)$$

For a given rotation speed, the ratio was found to be a sigmoid function of the consistency with a decreasing exponential shape in the low consistency range. It revealed that, at low rotation speed, a pulp suspension, whatever its nature, behaves differently from water. However, when the rotation speed increases, the differences between the fibrous types appear clearly and the behaviour tends toward that of water. Another result was obtained, when the level of separation from the water behaviour was the highest (at low speed) then the existence was demonstrated of a critical and minimum volumetric power necessary to obtain a sufficient motion of the pulp suspension in the volume concerned. This critical volumetric power was independent of the pulp type and was evaluated at

10kW.m⁻³ for the laboratory-helical disintegrator studied. Even if this kind of disintegrator runs at [16%; 20%] of mass solid fraction, this research constitutes the basis for new insights in the agitation of pulp suspensions in mixers of complex geometry, which can be found in the paper industry.

Acknowledgements

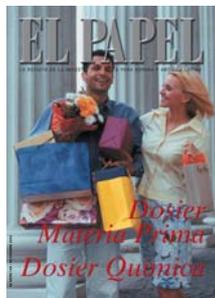
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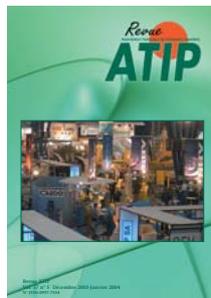
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France, Afrique du Nord, Belgique - 5200 exemplaires -



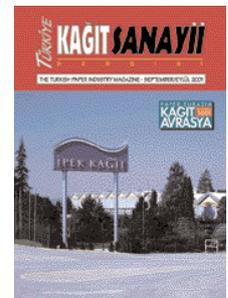
Espagne et Amérique Latine - 12100 exemplaires -



France - 2000 exemplaires -



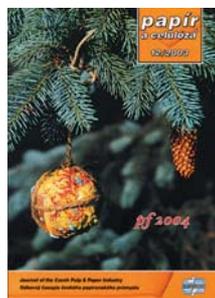
Portugal et Brésil - 5000 exemplaires -



Turquie - 2800 copies -



Brésil - 5000 exemplaires -



République Tchèque - 1500 exemplaires -



Pologne - 2000 exemplaires -



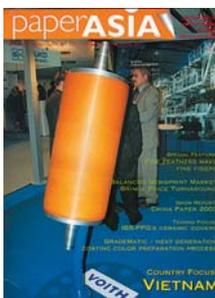
Chine - 10000 exemplaires -



Italie - 5000 exemplaires -



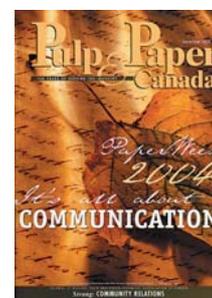
Grande-Bretagne - 2500 exemplaires -



Asie - 5000 exemplaires -



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