

## THE EFFECT OF SHEAR RATE ON APPARENT VISCOSITY FOR DIFFERENT PULP SUSPENSIONS

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### SYNOPSIS

The goal of this work was to study the relationship between chemical pulps suspensions rheology and the operating variables of beating for three different paper fibres, namely *Pinus sylvestris*, *Eucalyptus globulus* and *Betula verrucosa*. It was intended to establish the best conditions for the refining of chemical pulps for paper production. In order to obtain that, the hydromechanics of the beating was analysed for the three pulps. So, the normal and tangential forces were evaluated, the distance between rotor and stator was measured and the pulp apparent viscosity evolution during refining was calculated. The refining essays took place in a laboratory Valley refiner, and the studied variables were the *charge on the roll*, the *rotor speed of rotation* and the *specific applied energy*. The following adaptations to the Valley were made: a rotor speed of rotation variation controller, a sensor to measure the distance between rotor and stator and an electrical power consumption meter. A global relationship between the apparent viscosity and the shear rate was finally obtained.

### MATERIALS AND METHODS

The disintegration of the pulp was made in a Lamor pulper working at 1200 rpm for 20 minutes at room temperature, at a consistency of 3,6%. The beatings were made in a laboratory Lorentzen & Wettre Valley beater, at a consistency of 1,56% and an initial temperature of 20°C. These equipment are shown in Figure 1.



Figure 1 Valley beater and pulper.

The required characteristics for the Valley laboratory beater are normalised in TAPPI T200 sp-96. Figure 2 gives a schema of the details of this equipment. It can be seen that the equipment has a oval basin with a volume of 25 litres, where the pulp flows due to the rotor movement. The pulp passes through the space between the rotor bars and stator bars, where

the fibres are subject to normal and tangential forces. It can be seen that a vertical force is exerted in this space, as the action of a weigh is transmitted through a lever.

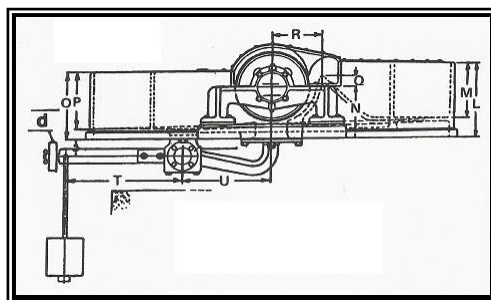


Figure 2 Valley beater schema (Source: Tappi T200 sp-96, 1996)

One Altivar speed variation device was adapted to the beater, so the standard 500-rpm rotor speed of rotation could be changed. Another adaptation was that of the online device MDGE (Espírito Santo, 2001) which measures the effective power with a relative error smaller than 2%. The signals were acquired every 375μseconds and the software integrated the values for the interval of 0,06 seconds. For the treatment of results sixty seconds averages were made. The average gap between the rotor bars and stator bars were evaluated adapting a Sensorex LVDT (linear variable differential transformer) transducer with a connection to a Kosmos RS232C and a signal acquisition software developed for this purpose. The measurement uncertainty was 1 μm and its linearity was ±0,23%.

## THEORETICAL PRINCIPLES

Ebeling (1980) defines refining as “the process of creating desired structural changes in the cell walls of the fibres at the expenditure of mechanical energy”. These modifications permit the attainment of the structural characteristics of a paper grade with specific desired properties and behaviour. The principle of the refiner lies on the treatment of the fibres between opposing stationary and moving bars in the presence of water (Lumiainen, 2000). Rance e Steenberg published in 1951 results, where the refining was analysed as a lubrication process of a journal bearing (Ebeling, 1980). The goal of lubrication is the reduction of friction, wearing and heating of the machine elements which are moving. The refiners can be considered one journal bearing, where the film of fibre suspension acts as a lubricant between the rotor and stator.

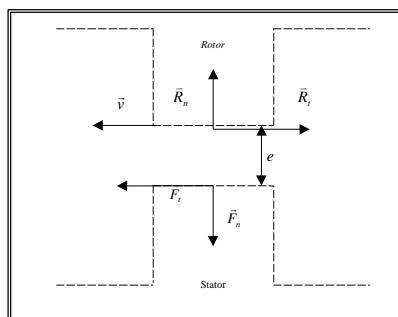


Fig. 3 Hydromechanical model of refining.

Based on this model, it is possible to make a hydromechanical analysis of the process (represented in figure 3), evaluating the tangential and normal forces developed in the gap

between the rotor and the stator, and afterwards calculating the apparent viscosity (Vaz, 2005).

The average normal force in the gap is calculated using the principle of equilibrium of forces on a lever, which eventually gives:

$$F_n = m * g * \left( \frac{T}{U} \right) \quad (\text{Equation 1})$$

in which  $F_n$  (N) is the average normal force in the gap,  $m$  (N) is the mass applied on the lever,  $g$  ( $ms^{-2}$ ) is the gravity acceleration constant and  $T/U$  is the ratio between the arms of the Valley lever (Figure 2).

The average normal stress  $\tau_n$  ( $N/m^2$ ) in the gap is given by the formula:

$$\tau_n = \frac{F_n}{A_c} \quad (\text{Equation 2})$$

in which  $A_c$  ( $m^2$ ) is the contact area between the rotor and the stator in  $m^2$ .

The calculation of the average tangential force resorts to the formula of the work of a tangential force on a rotating cylinder:

$$dw = F_t * ds = F_t * r * d\alpha \quad (\text{Equation 3})$$

in which  $dw$  (W) is the work developed by the tangential force  $F_t$  (N) as it goes through the distance  $ds$  (m) on the cylinder surface, equivalent to the product of the radius  $r$  (m) of the cylinder by the angle  $d\alpha$  (rad) which was traversed.

For the calculus of the tangential force  $F_t$  (N) the following formula was obtained:

$$F_t = \frac{P_L}{2 * \pi * r * \dot{N}} \quad (\text{Equation 4})$$

in which  $\dot{N}$  ( $s^{-1}$ ) is the speed of rotation and  $r$  (m) is the rotor radius.

The average tangential stress  $\tau_t$  ( $N/m^2$ ) in the gap is calculated with the formula:

$$\tau_t = \frac{F_t}{A_c} \quad (\text{Equation 5})$$

The calculus of viscosity  $\mu$  for a fluid in laminar flow is given by the formula:

$$\tau_t = \mu * \frac{dv}{dz} \quad (\text{Equation 6})$$

in which  $\frac{dv}{dz}$  ( $s^{-1}$ ) is the speed gradient in the fluid, also represented as  $G$ .

Using these formulas for the case of a non-newtonian fluid (the pulp suspension), one can relate the average tangential stress  $\tau_t$  ( $N/m^2$ ) and the apparent viscosity  $\mu_{ap}$  (Pa.s) in the gap  $e$  (m) of the Valley by the formula:

$$\tau_t = \mu_{ap} * \frac{\Delta v_e}{e} \quad (\text{Equation 7})$$

in which  $\Delta v_e (ms^{-1})$  is the speed differential between rotor bar surface and the stator bar surface.

Finally, one may calculate the pulp suspension apparent viscosity as beating evolves through the formula:

$$\mu_{ap} = \frac{\tau_t}{\left(\frac{\Delta v_e}{e}\right)} = \frac{\tau_t}{\left(\frac{2\pi \cdot \dot{N} \cdot r}{e}\right)} = \frac{\tau_t}{G} \quad (\text{Equation 8})$$

To test the underlying hypotheses of a laminar flow, the Reynolds was evaluated as being lower than 14, which confirms its validity.

## RESULTS

In figure 4 it is represented the relationship between apparent viscosity and the shear rate in the gap clearance for all the refining essays carried out at a consistency of 1.56%, with all different fibres. It can be seen that the apparent viscosity  $\mu_{ap}$  decreases with the increase of the shear rate. So, the pulp suspension can be considered as a pseudoplastic non-newtonian fluid. Many different mathematical models were proposed by different researchers to describe the rheological behaviour of pseudoplastic fluids. Amongst them we can refer those of Prandtl-Eyring, Ellis, Reiner-Philippoff, Sisko, Cross, Meter e Herschel-Bulkley (Kao, 1983). Anyhow, the equation which best describes most of the pseudoplastic fluids is the power law of Ostwald – de Waale:

$$\mu_{ap} = K \cdot G^{n-1} \quad (\text{Equation 9})$$

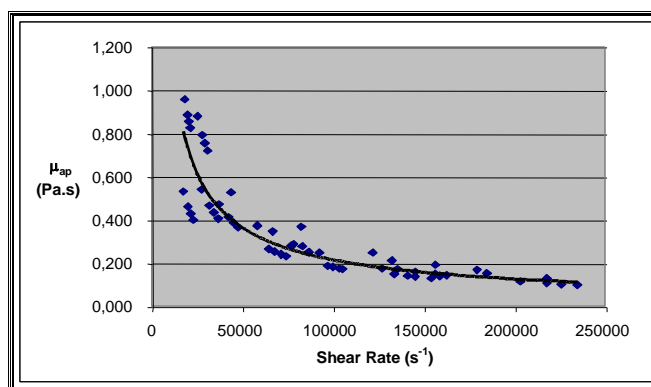


Fig. 4 Pulp apparent viscosity (Pa.s) versus shear rate ( $s^{-1}$ ) in the gap clearance.

Kao (1983) refers essays with a 4% pulp suspension presenting a value of  $n = 0.58$ . Radoslavova (1996) obtained values for  $n$  between 0.51 and 0.66. Norman et al (1978) present a value of  $n = 0.333$ , which is close to the results obtained in this work.

The influence of fibre morphological characteristics on the apparent viscosity obeys the Batchelor law:

$$\ln\left(\frac{\mu_{ap}}{\mu_{Water}}\right) = n_1 + n_2 \cdot \ln\left(\frac{L}{D}\right) \quad (\text{Equation 10})$$

As the different pulps used in the present experimental work exhibit similar aspect ratio L/D (L is the fibre average length and D is the fibre average diameter), the main effect on the apparent viscosity is the shear rate.

The results also show that different pulps reveal different rheological behaviour, namely apparent viscosity, for the same operating conditions of the Valley laboratory beater (speed of rotation and charge on the rotor), which highlights the different response of the various pulp suspensions to the beater variables.

## CONCLUSIONS

The pulp suspensions present rheofluidificant behaviour. For a given pulp suspension the apparent viscosity diminishes with the beating time, as a result of the reduction in the gap clearance due to the increased fibre flexibility and shortening. The different rheological behaviour under the same operating conditions for different pulps leads to the inference that from the hydrodynamical point of view one should treat pulps with different morphological characteristics separately.

## REFERENCES

- EBELING, K. - **A Critical Review of Current Theories for the Refining of Chemical Pulps**. International Symposium on Fundamental Concepts of Refining, Appleton: 1980, p. 1-36.
- ESPÍRITO SANTO, A. – **Instrumentação Digital para Medida e Processamento de Grandezas Eléctricas**. Tese de Mestrado, Universidade de Coimbra, 2001.
- KAO, D.T.Y. – Rheology of Suspensions. Chapter 33. In CHERMISINOFF, N.P.; GUPTA, R: - **Handbook of Fluids in Motion**. Ann Arbor Science, p. 863-893. 1983. ISBN 0-250-40458-3.
- LUMIAINEN, J. – Refining of Chemical Pulps. IN PAULAPURO, H. (EDITOR) – **Papermaking Part 1, Stock Preparation and Wet End (Chapter 4)**. Papermaking Science and Technology (Book 8), Fapet Oy, Helsinki, 2000, p. 87-122. ISBN 952-5216-00-4.
- NORMAN, B.; MOLLER, G. K.; EK, R.; DUFFY, G. G. - **Hydrodynamics Of Papermaking Fibres In Water Suspension**. Symposium on Fibre –Water Interactions in Papermaking, Oxford. Vol. I. ISBN 0-900219-04-1.1978, p. 195-249.
- RADOSLAVOVA, D. – **Modélisation Hydrodynamique du processus de Raffinage des Pâtes a Papier**. Doctoral Thesis. Institut National Polytechnique de Grenoble. 1996, p. 67-93.
- Vaz, A. – **The Refinability of Paper Chemical Pulps: a contribution for its evaluation using the Valley beater**. Doctoral Thesis. Universidade da Beira Interior. 2005, p. 75-97.