Defibering and specific energy consumption in bale pulpers

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ABSTRACT *The defibering and the specific energy consumption (SEC) for bale pulping of old corrugated containers and supercalendered paper were studied. Experimental variables were pulper dimensions, rotor shape, process temperature, and pulp consistency. The extent of defibering was monitored by measuring Somerville shives, and SEC was determined for a range of pulping conditions. It was found that SEC is reduced by at least 50% when process temperature is increased from 20°C to 60°C and by about 30% when pulp consistency is increased from 3.5% to 7%. The results also showed that defibering is increased by rotors that generate shear forces both radially and tangentially. The more swiftly the mass bale and the flakes are wetted, the lower will be the SEC. The rheology of low-consistency water-fiber suspensions is also discussed, with emphasis on how shear affects defibering during the pulping process.*

KEYWORDS
Consistency
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Energy
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Pulping
Reclaimed fibers

Saving energy is like saving money. Lower operating costs mean larger profit margins, and the energy-intensive pulp and paper industry provides ample opportunity to reduce operating costs through more efficient use of energy.

The pulper consumes between 5% and 15% of the total energy used to manufacture finished paper. This does not apply to integrated pulp and paper mills, where pulpers (especially bale pulpers) are not commonly used, since the pulp slurry is usually fed directly to the paper machine.

The energy consumed by defibering in a bale pulper depends on several factors.

- Pulper type and dimensions
- Rotor geometry
- Clearance between rotor and screen plate
- Screen plate (as a capacity factor)
- Type of processing (batch or continuous)
- Process temperature and pressure
- Pulp consistency
- Dispersing chemicals
- Nature of raw material and fiber species
- Drying history (moisture hysteresis) of raw materials
- Amount of material in pulper.

Pulper economics is a function of how swiftly and with what specific energy consumption (SEC) pulp bales or waste bales of paper are defibered to the desired level. The key to efficiency may be the speed of penetration of free water into the sheets and the flakes. Wetting speed depends on the process temperature and pressure as well as on total shear effects, including the Newtonian rheology of low-concentration fiber suspensions and the hydrodynamic and mechanical effects of the rotor. This report describes the rheology of the defibering process in bale pulpers and presents results from experiments designed to find ways of decreasing SEC in the pulper.

Theory of defibering

Mechanical principles

The influence of rotor geometry on defibering is not well understood. Experimental efforts to optimize rotor geometry have been hampered by the lack of established principles describing the precise nature of the defibering phenomenon.

The main activities of a rotor in defibering are (a) to induce turbulence and acceleration in the pulper and (b) to cut and disperse the flakes. Vokes developed a rotor with high hydraulic shear forces (*1*). The total defibering effect was increased by the pattern of grooves and holes on the screen plate. Vokes's idea was completed by the addition of power-saving wings (*2*). This new construction yielded a better defibering level as a function of SEC. The Vokes model also stimulated new inventions. Couture modified a rotor wing so that it had both a defibering and a pumping effect (*3*). This rotor is said to generate a full and continuous vortex in the pulper.

Danforth introduced a defibering method with two rotors rotating in opposite direction. The aim of this approach was to increase the intensity of the mechanical defibering force directed into the pulp mass (*4*). Jylhävaara developed a rotor whose defibering effect is based on pumping power and on mechanical shredding (*5*).

The intensity of the mechanical force depends on the construction, dimensions, and speed of the rotor. Fibrous material is sucked onto the rotor, where the wings generate strong shocks that loosen the tightly packed sheets, breaking the material down until it forms a fiber suspension.

Rheological model

Holik provides a detailed description of the forces influencing the defibering process (*6*). According to Holik, the clinging and the acceleration effects strongly influence defibering, while viscosity has only a minor effect on the process. The clinging and the acceleration phenomena can be explained by fundamental physics, but the so-called viscosity effect needs a wider examination than it has received.

Mechanical shocks as well as clinging and acceleration effects cause sheets to defiber. At this point, the consistency of the "free flakes" and fibers is lower than that of the limit consistency, C_s, defined in Eq. 1 (*7*). (At low consistency, the free flakes behave like separated fibers.)

$$C_s = 108\pi\,(r/l)^2 \qquad (1)$$

where the fiber suspension behaves like a real suspension, i.e., with viscosity increasing with consistency, and where

r = average fiber radius

l = average fiber length

The rheology of this type of suspension has a Newtonian behavior. The viscosity of water as a function of temperature has a dominating role, and viscosity increases with increasing consistency.

$$\tau = \eta\,(\dot\gamma)\,\dot\gamma \qquad (2)$$

$$\eta(\dot\gamma) = \eta_0 = \text{constant} \qquad (3)$$

$$\eta_0 = f(T,\,p,\bar\rho) \qquad (4)$$

where

τ = shear stress

η = viscosity

η_0 = Newtonian constant viscosity

$(\dot\gamma)$ = shear speed

T = process temperature

p = process pressure

$\bar\rho$ = mean consistency

Equations 2-4 indicate that at constant η_0 and increasing consistency, shear stress increases with increasing shear speed. In a water-fiber suspension, local shear stress fields occur because of the local variations in viscosity created by nonuniform fiber distribution in the pulper. In an uneven suspension such as this, movement occurs in gradients. Every flow circle has its own velocity and, thus, an individual velocity gradient or shear speed.

Increased temperature decreases the viscosity of water. Increased consistency, on the other hand, increases the total viscosity of the flake-fiber-water suspension. Both of these opposing viscosity phenomena have a diminishing effect on SEC. The decrease in viscosity at higher temperatures reduces the friction coefficient of water, while the higher consistency increases the shearing of solid particles and shortens the required defibering time. Operating at higher temperatures also helps to shorten the defibering time by speeding up water penetration into the pulp.

The previous discussion relates to the free turbulence that occurs in the interior of the pulping vessel, away from the walls. Shear at the walls can be described using the rheological principles for pulp flow in pipes. Assuming the speed in the turbulence on the wall to be so high that the flow resistance of the flake-fiber suspension approaches that of water, the shear stress on the wall is equalized by the function

$$\tau_w/\tau_u = f\,[\bar u\,(\bar\rho/\tau_u)^{1/2}] \qquad (5)$$

where

τ_w = shear stress on the wall

τ_u = shear strength of the fiber network

$\bar u$ = average velocity

Equation 5 describes the pressure difference as a function of velocity in dimensionless form. Assuming the velocity of the suspension on the wall to be much lower than that in turbulence, there is a sliding on the wall, providing no more than a minor shear stress.

Thus, there are two rheological phenomena occurring within the pulper: the shear stress fields generated by free turbulence and the minor shear stress generated at the vessel wall. The magnitude of the stress is dependent on the viscosity and the temperature as well as on velocity gradients in the flake-fiber-water suspension.

Experimental

Organization of experiments

The batch bale pulper was powered by a 90-kW motor. Motor current was monitored by a computer that provided the average time values of the current for defibering and average values for the whole pulping time. A printer was used to plot the current-vs.-time curve.

Materials

Experiments with unbleached and 90% bleached pulp showed a very rapid defibering. These materials were abandoned in favor of materials providing greater resistance to defibering: old corrugated containers (OCC) and

I. Somerville shives for OCC as a function of consistency, process temperature, and pulping time (Pulper A1, Rotor 1)

		Somerville shives, %				
		Pulping time, min				
Consistency, %	*Temperature, °C*	*5*	*10*	*15*	*20*	*30*
3.5	20	...	32.93	19.91	14.28	8.18
	40	...	5.12	2.98	1.98	1.34
	60	...	1.82	1.27	0.83	0.74
	80	5.08	1.88	1.08	0.84	0.72
7.0	20	39.20	21.28	14.60	10.82	6.28
	40	...	7.49	4.08	2.54	1.45
	60	...	2.63	1.62	1.04	0.72
	80	6.97	2.50	1.29	0.75	0.54
8.5	20	...	40.95	25.70	17.12	9.65
	40	...	9.52	4.84	2.84	1.48
	60	14.38	4.31	1.80	1.05	0.64
	80	8.50	3.75	2.27	1.30	0.81

II. Relative defibering efficiency for Rotors 1 and 2 on OCC

		Relative defibering efficiency*		
		Consistency, %		
Pulper type	*Temperature, °C*	*3.5*	*7.0*	*8.5*
A1	20	0.8	0.8	1.0
	40	0.8	0.4	0.4
	60	0.2	0.3	0.2
A2	20	0.8	1.3	...
	40	0.2	0.7	...
	60	0.5	0.9	...
A3	20	0.7	...	...
	40	0.6	0.5	...
	60	0.6	0.3	...

*Numerical values depict efficiency of Rotor 2 in relation to Rotor 1 (Rotor 1 = 1).

III. Somerville shives for SC paper as a function of consistency, process temperature, and pulping time (Pulper A1, Rotor 1)

		Somerville shives, %			
		Pulping time, min			
Consistency, %	*Temperature, °C*	*2*	*3*	*5*	*7*
3.5	20	16.23	7.42	2.30	0.71
	40	14.23	4.45	0.79	0.18
	60	2.62	0.34	0.076	0.056
	80	0.12	0.076	0.068	0.068
7.0	20	19.27	10.13	4.45	0.48
	40	10.08	3.25	0.70	0.38
	60	5.28	0.34	0.064	0.048
	80	0.32	0.060	0.052	0.044
10.0	20	18.95	11.62	3.25	0.94
	40	12.52	4.80	0.51	0.09
	60	8.23	2.10	0.15	0.072
	80	1.73	0.73	0.048	0.044

supercalendered (SC) paper.

Temperature and consistency

The defibering experiments were carried out at temperatures of 20°C, 40°C, 60°C, and 80°C. The consistency was 3.5%, 7%, and 8.5% for the OCC and 3.5%, 7%, and 10% for the SC paper.

Bale pulper and rotors

Defibering experiments were carried out in Tampella bale pulpers of three different widths. Pulper A1 was 2100 mm wide; Pulper A2 was 1840 mm wide; and Pulper A3 was 1580 mm wide. Clearance between the rotor and the screen plate was 2.0 mm. Two rotor shapes, R1 and R2, were tested.

Analysis

The following parameters were measured or controlled:

- Current, A
- Power, kW
- SEC, kW•h/metric ton
- Somerville shives, %
- Freeness, mL CSF
- Consistency, %
- Handsheets

Power was calculated using Eq. 6.

$$P = 3^{1/2}\, VI \cos\phi\, n \qquad (6)$$

where

P = power

V = voltage

I = current

ϕ = angle of lag and lead

n = power transfer ratio

SEC was calculated using Eq. 7.

$$P = (3)^{1/2}\, VI \cos\phi\, n\, (t/m) \qquad (7)$$

where

t = process time.

m = mass, tons

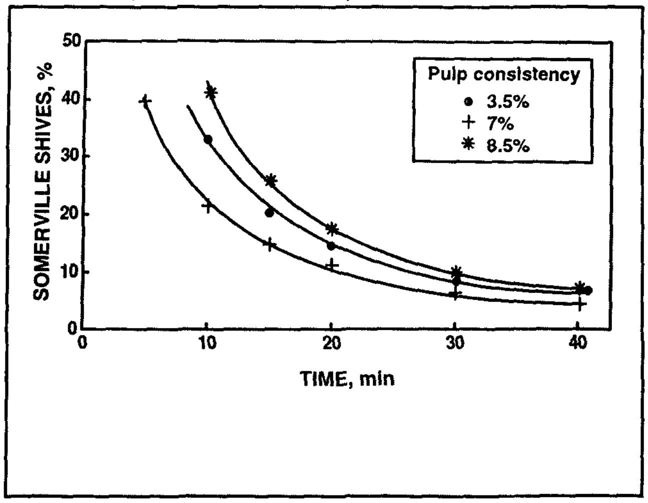
Somerville shives, freeness, consistency, and handsheets were determined using accepted test methods.

Results and discussion

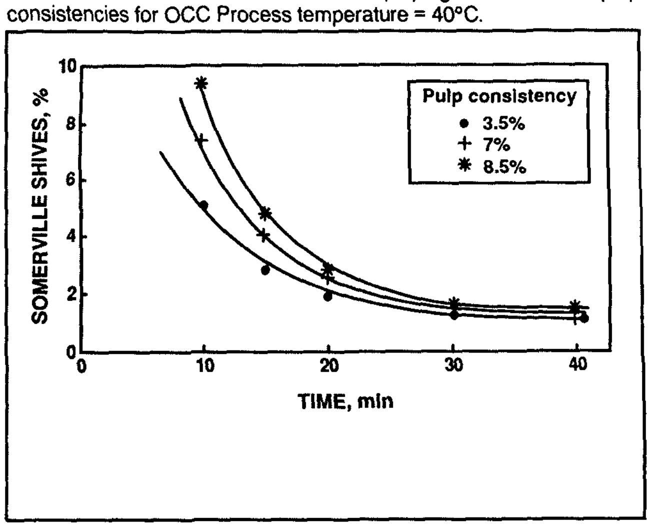
Defibering

Defibering speed was dependent on process temperature, consistency,

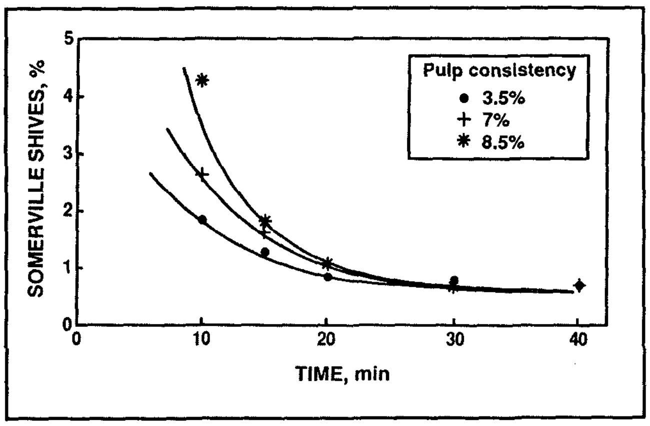
1. Somerville shives as a function of pulping time at three pulp consistencies for OCC. Process temperature = 20°C.



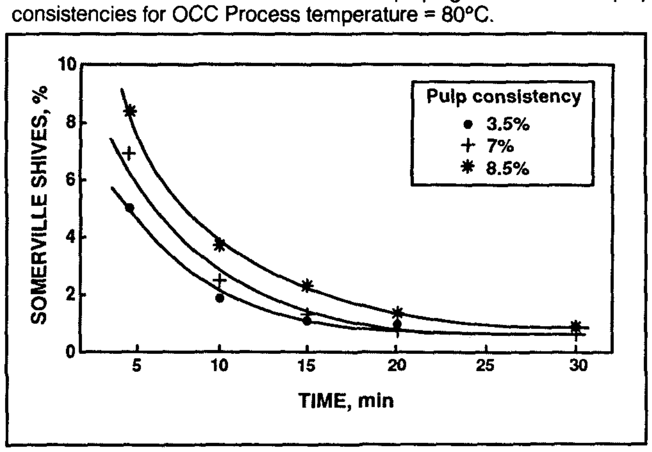
2. Somerville shives as a function of pulping time at three pulp consistencies for OCC Process temperature = 40°C.



3. Somerville shives as a function of pulping time at three pulp consistencies for OCC Process temperature = 60°C.



4. Somerville shives as a function of pulping time at three pulp consistencies for OCC Process temperature = 80°C.



rotor shape, and the ratio of pulper diameter to rotor diameter.

Old corrugated containers. Temperature had the greatest influence on the speed of defibering. **Table I** shows that the defibering gradient for the OCC was greatest when process temperature was increased from 20°C to 40°C. The increase in defibering between 20°C and 40°C is remarkable for all three of the tested pulp consistencies. Increasing the temperature from 40°C to 60°C or 80°C had only a minor influence on defibering time. The pulping time to reach Somerville shives <5% at 40°C was 10-12 min, depending on the consistency.

Table II shows that Rotor 1 provided better defibering than Rotor 2. The hydrodynamic forces generated by Rotor 1 are more effective than those generated by Rotor 2. In Rotor 1, the mass accelerates both tangentially and radially, while Rotor 2 has more of a pumping effect, with the mass accelerating radially. The information in Figs. 1-4 and 6-15 were obtained using Pulper A1 and Rotor 1.

IV. Relative Somerville shives for SC paper in Pulpers A1, A2, and A3 (all pulpers equipped with Rotor 1)*

Temperature, °C	*Pulper A1*		*Pulper A2*		*Pulper A3*	
	Consistency, %		*Consistency, %*		*Consistency, %*	
	3.5	*7.0*	*3.5*	*7.0*	*3.5*	*7.0*
20	1	1	1.3	1.1	1.9	1.5
40	1	1	2.3	1.3	8.0	12.5
60	1	1	3.5	1.1	6.6	3.1

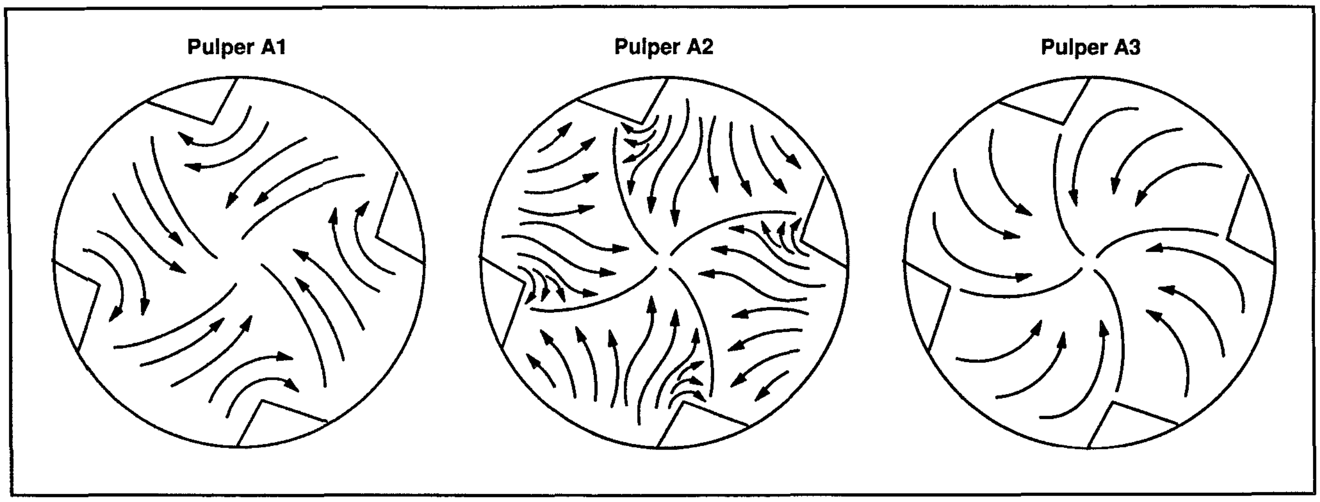
*Numerical values depict efficiency of Pulpers A2 and A3 in relation to Pulper A1 (Pulper A1 = 1).

Figures 1-4 show the decrease in Somerville shives over time at 20°C, 40°C, 60°C, and 80°C, respectively, for OCC at consistencies of 3.5%, 7%, and 8.5%. [Note: The scales for Somerville shives (y-axis) and time (x-axis) are different in each figure.]

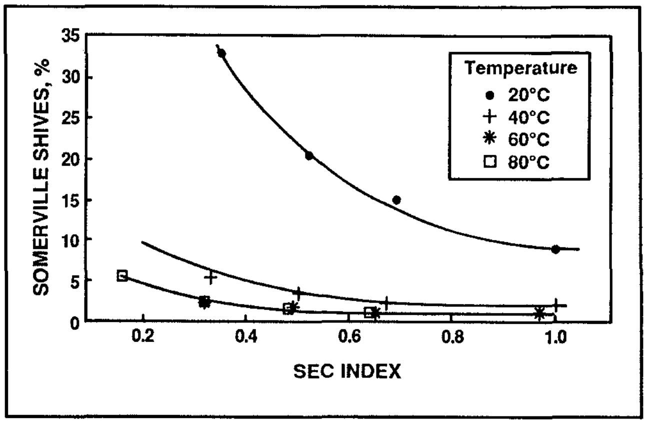
For a given pulping time, OCC flakes defiber more thoroughly as the temperature increases. The shortest defibering times were obtained at low consistency and high temperature.

Supercalendered paper. The results in **Table III** show that defibering for the SC paper increased dra-

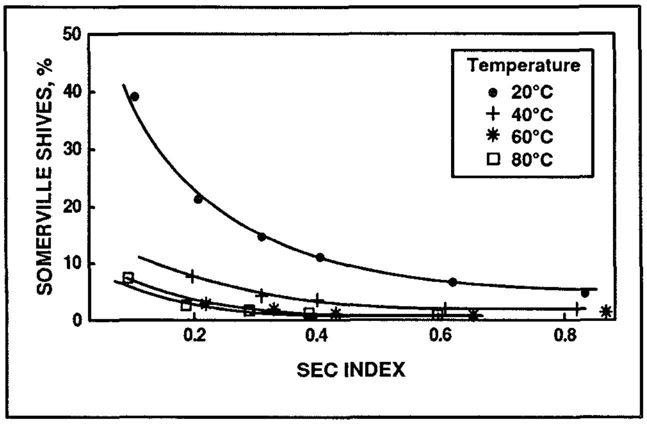
5. Flow vortices in Pulpers A1, A2, and A3. The ratio of pulper diameter to rotor diameter is largest for Pulper A1 and smallest for Pulper A3.



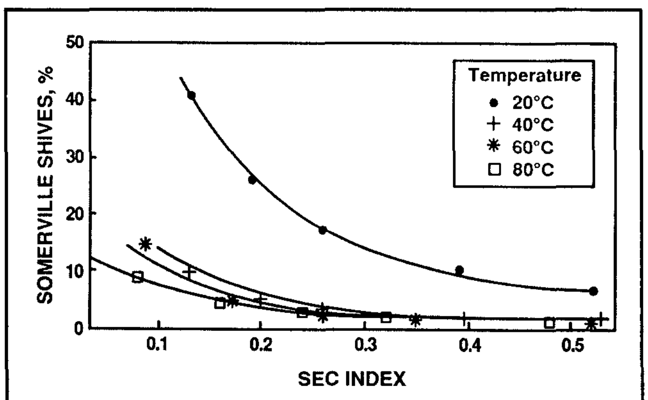
6. Somerville shives as a function of SEC at four temperatures for OCC. Consistency = 3.5%.



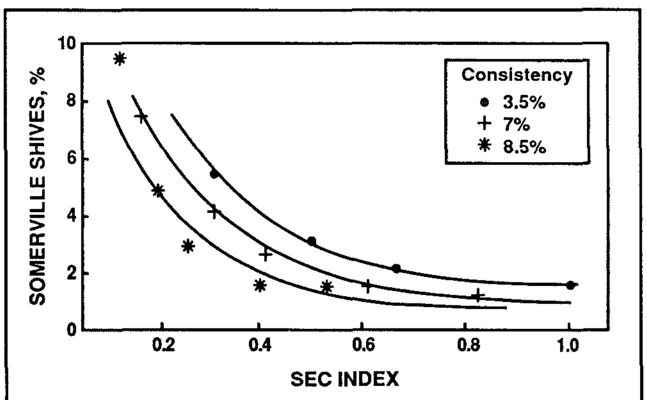
7. Somerville shives as a function of SEC at four temperatures for OCC. Consistency = 7%.



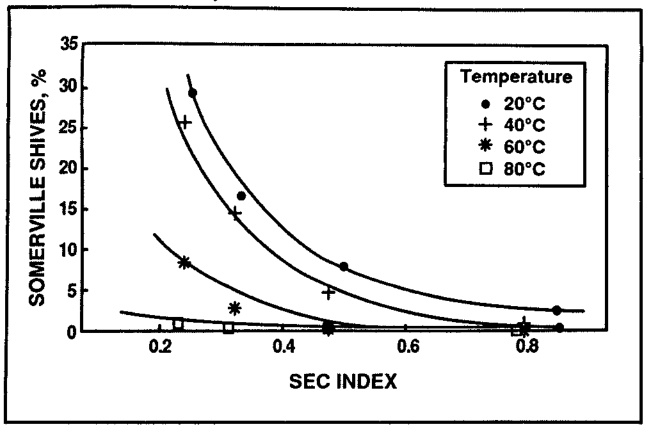
8. Somerville shives as a function of SEC at four temperatures for OCC. Consistency = 8.5%.



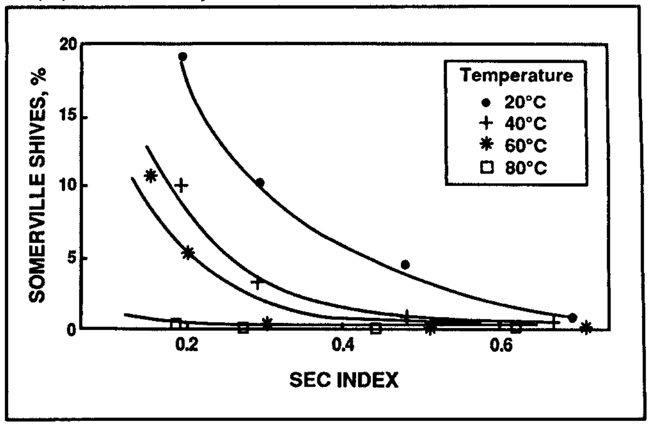
9. Somerville shives as a function of SEC at three pulp consistencies for OCC. Temperature = 40°C.



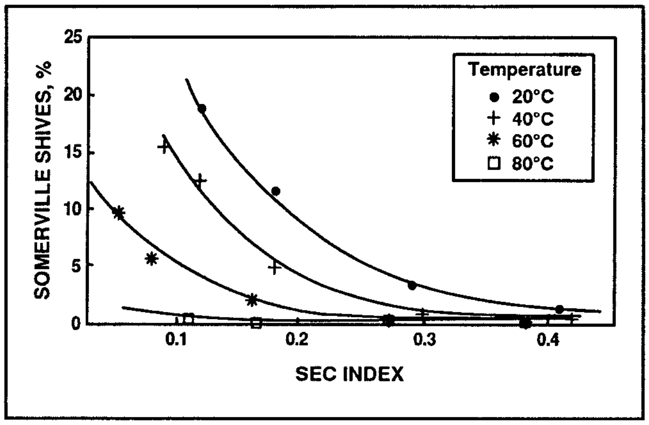
10. Somerville shives as a function of SEC at four temperatures for SC paper. Consistency = 3.5%.



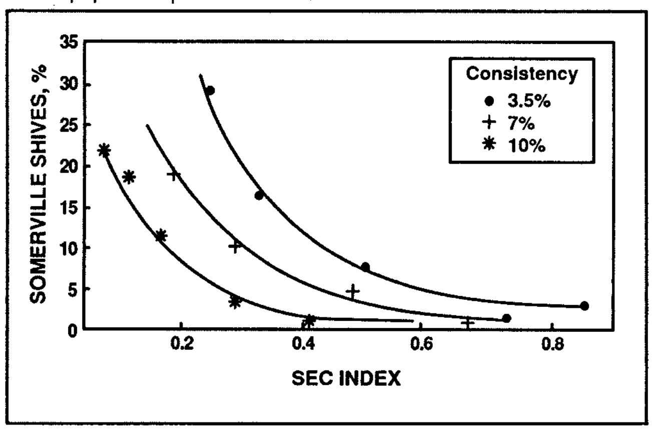
11. Somerville shives as a function of SEC at four temperatures for SC paper. Consistency = 7%.



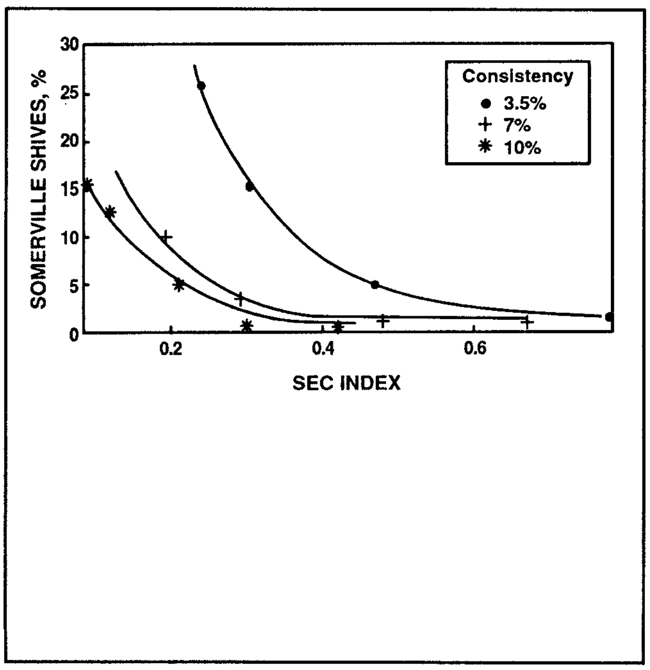
12. Somerville shives as a function of SEC at four temperatures for SC paper. Consistency = 10%.



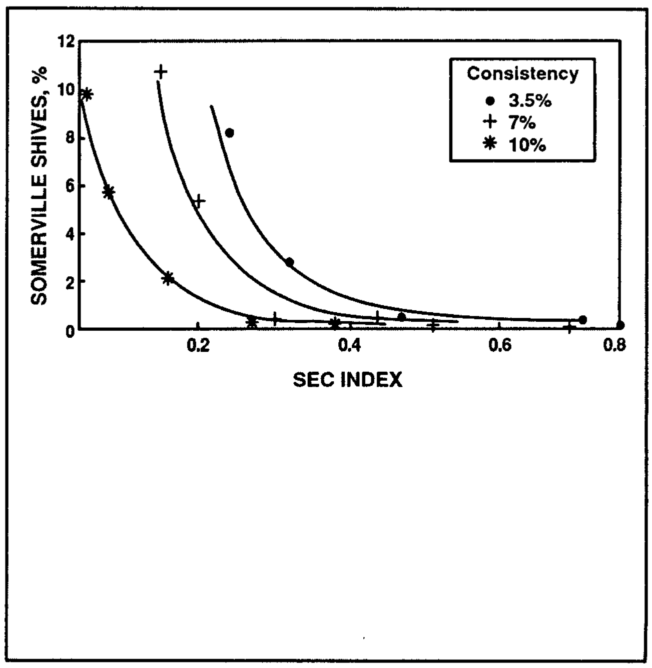
13. Somerville shives as a function of SEC at three pulp consistencies for SC paper. Temperature = 20°C.



14. Somerville shives as a function of SEC at three pulp consistencies for SC paper. Temperature = 40°C.



15. Somerville shives as a function of SEC at three pulp consistencies for SC paper. Temperature = 60°C.



matically when temperature was increased from 40°C to 60°C. The defibering time to Somerville shives <1% at 60°C was only 3 min for the pulp at consistencies of 3.5% and 7%. Consistency did not play as dominant a role in defibering of SC paper as it did for OCC. The flow vortices in Pulpers A1, A2, and A3 are illustrated in **Fig. 5**. The different flow figures are a function of the changing ratio of pulper diameter to rotor diameter. (Rotors 1 and 2 had the same diameter.) **Table IV** depicts the relative defibering efficiency on SC paper for the three pulpers equipped with Rotor 1. The reduction in defibering time with the decrease in pulper size is obvious. In Pulpers A2 and A3, the mass moves partly against the flow guidance and sinks on the wall of the pulper and then back onto the rotor. When the mass comes down along the center vortex onto the rotor, the defibering effect is much stronger. Increasing the power-to-volume ratio in the pulper decreases the defibering time.

Specific energy consumption

The maximum SEC was defined to correspond with 90% defibering for the OCC bales and 95% defibering for the bales of SC paper. The heating energy of water was not taken into account in the computation of SEC.

Old corrugated containers. Figures 6-8 show Somerville shives as a function of SEC at consistencies of 3.5%, 7%, and 8.5%, respectively, for OCC at temperatures of 20°C, 40°C, 60°C, and 80°C. [Note: The scales for Somerville shives (y-axis) and SEC index of relative energy consumption (x-axis) are different in each figure.] For each consistency, there is a dramatic drop in SEC when process temperature is increased from 20°C to 40°C. Furthermore, **Fig. 9** shows that SEC was reduced by about 50% when pulp consistency was increased from 3.5% to 8.5% at 40°C (during the slope of the curves). An SEC of 20 kW·h/ton was required to obtain OCC in a pumpable state.

Supercalendered paper. Figures 10-12 show Somerville shives as a function of SEC at consistencies of 3.5%, 7%, and 10%, respectively, for SC paper at temperatures of 20°C, 40° 60° and 80°C. [Note: The scales for Somerville shives (y-axis) and SEC index (x-axis) are different in each figure.] All three pulpers consumed about 15-30% less energy when process temperature was increased from 20°C to 40°C. Increasing process temperature from 20°C to 60°C, however, reduced SEC by about two-thirds. (Indexed SEC values corresponding to Somerville shives of 5% in Figs. 10-12 are equivalent to 8-10 kW·h/ton, on average.)

For SC papers, process economics favors high-consistency pulping. **Figures 13-15** show that increasing the consistency from 3.5% to 7% reduced SEC by 30-40%, while SEC was reduced by 50-65% when consistency was increased from 3.5% to 10%.

Freeness

There are many unit operations between the bale pulper and the paper machine. The pulp coming into the headbox must have the appropriate drainability. For the OCC, the maximum freeness was 650-680 mL CSF at Somerville shives of 20-40%. At Somerville shives of about 1%, a drainability of 450 mL CSF was obtained. The SC paper showed a freeness of 350 mL CSF at Somerville shives of 20-30%. Drainability was affected by the same factors affecting the defibering operation in the pulper.

Conclusion

Specific energy consumption (SEC) for bale pulping of old corrugated containers (OCC) and supercalendered (SC) paper can be reduced by

- Increasing the process temperature from 20°C to 40°C in the case of OCC or 60°C for SC paper. This will reduce SEC by at least 50%.
- Pulping at higher consistency. Increasing consistency from 3.5% to 7% reduced SEC by about 30%.
- Increasing the pulper's power-to-volume ratio. This will reduce the time required to defiber the pulp to a given level.□

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