Modeling of brown stock washer

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ABSTRACT

A Computational model based on filtration equations and Cullinan's equations has been developed to enable optimum design and operation of pulp washing systems consisting of a battery of rotary vacuum filters. Results have been presented to show the effect of various operating variables and pulp liquor characteristics on the optimum condition.

INTRODUCTION

The knowledge of the pulp washing has been mostly empirical. The design and operating procedures for most Plant scale washing equipment have evolved from the experience gained over the years. This practice was quite satisfactory when most pulp was produced from woods which were mainly softwoods. But at present due to limited supply of woody raw material the paper industry is inclined to process any fibrous raw material. Notable among non-wood raw materials are bamboo, bagasse, straws and grasses. Since the hydrodynamic and mass transfer characteristics of spent liquors obtained from different raw materials and pulping processes are significantly different, the best washing conditions will be different in each case. Simulation of brown stock washing system on a computer will be useful tool in optimizing the existing systems and in economical design of the new ones.

THEORETICAL BACKGROUND

The total pulp washing consists of simultaneous filtration and mass transfer operations. To build the mathematical model the total washing process has been broken into two distinct phenomena, namely, the filtration and the extraction of dissolved solids. The filtration accounts for the removal of the liquor from the pulp and delivering the pulp at the greatest consistency. The extraction accounts for the reduction of the concentration of the dissolved solids in the liquor which finally accompanies the washed pulp. The extraction is a combination of the displacement of the liquor between the fibers with another liquor by a piston effect and the diffusion of the dissolved solids present in the stagnant liquor within the fibers towards the liquid flowing through the inter-fiber pores. These phenomena are illustrated in Figure-1.

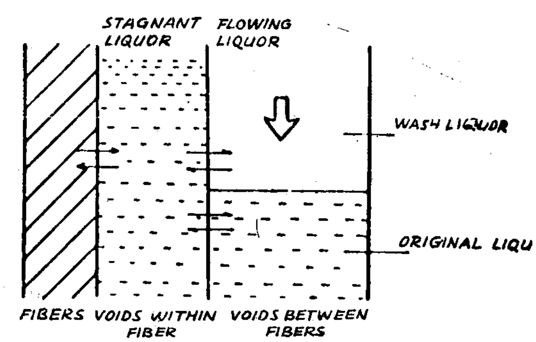

Fig. 1:- Schematic Diagram Showing Different Operations In Washing

MATHEMATICAL EQUATIONS

The filtration phenomenon is relatively better understood and the mathematical equations are usually available in text books on Unit operations However, there are not many expressions to predict the extraction phenomena. The extent of extraction is usually expressed as displacement ratio; the ratio between the actual reduction in the concentration of dissolved solids and the theoretically achievable reduction when all the liqu-

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or in the pulp mat is displaced by wash liquor. For mth stage, the displacement ratio, DR, is given in terms of concentrations as

$$DR = \frac{X_{vat}(m) - x(m)}{X_{vat}(m) - Y(m+1)}$$

Where, X_{vat} (m)— Concentration of liquor in the Vat

x(m) — Concentration of liquar leaving with the pulp.

y (m+1) — Concentration of wash liquor.

In recent approaches (1, 2, 3) pulp washing has been treated analogous to mass transfer operation in equilibrium stages. The performance of washer is expressed in terms of a number of ideal mixing stages (or Nordan stages). This quantity is also referred to as E-factor and is defined by the number of ideal countercurrent mixing stages required to give the same washing efficiency. Cullinan et al (3) have derived expressions to determine washing efficiency for a real stage in terms of system variables and characteristics of pulp and the spent-liquor. The stage efficiency can then be used to determine the displacement ratio. The equations used in the present model have been reviewed by Singh and Rao (4). The steps to determine displaced ratio are reported in Appendix-A.

APPLICATION OF THE MODEL

The input variables associated with a pulp washing system can be broadly classified in to two groups; the spent liquor-pulp system characteristics and the operating parameters. The definitions of these variables are given in Tables—1 and 2, The various quantities which can be determined from this model are given in Table—3.

1. The Displacement Ratio

The displacement ratio (DR)is a difficult parameter to determine. Figures–2 to 6 illustrate the steps in the determination of the displacement ratio. Figure-2 show the effect of various variables on the consistency of mat discharging from the filter, C_d. A lower value of dewatering time, i. e. $\phi 3$ results in a lower discharge consistency. A higher vat consistency also results in a reduced discharge consistency. The influence of either vat consistncy or dewatering time on C_d becomes less and less significant

APPENDIX-A

Determination of Displacement ratio, DR, using Cullinan's approach.

The displacement ratio, DR, is given by

$$DR = 1 - \exp(-EW) \quad (A.1)$$

Where the local efficiency E is defined as

$$E = (1 - \exp(-eta)) * (1 + (1 - a)/\eta) \quad (A.2)$$

and the wash ratio is given by

$$w = 1 + DF * c_d/d_l \quad (A.3)$$

The Factor η in equation (A 2) represents number of mass transfer units and is given by

$$\eta = ka * r \quad (A.4)$$

Where r is the contact time of wash solvent in the pulp mat,

$$r = (2*\phi 1/N) * C_{vat}/(C_{mat} - C_{vat}) \quad (A\ 5)$$

and ka is a mass transfer parameter which is a Characteristic of the spent liquor.

The C_d in Equation (A.3) is the consistency of the mat discharging from the washer. C_d is given by

$$C_d = \frac{C_{mat}\,[2\phi 1(1-S_r) + \phi 3\,(C_{mat}/C_{vat}-1)\,]}{C_{vat}\,[2\phi 1(1-S_r) + \phi 3\;S_r(C_{mat}/C_{vat}-1)\,]} \quad (A.6)$$

The other variables have been defined in Tables 1 to 3.

Table—1. Spent-Liquor/Pulp Characteristics

Symbol	Definition
Cmat	Consistency of pulp mat fully saturated, with liquor, kg/m³. The value depends mainly on the pressure difference and the nature of the fibers.
K	Permeability of pulp mat, m²
μ	Viscosity of spent liquor, Ns/m²
ka	Mass transfer parameter to account for the diffusion, 1/s
d_l	Density of liquor, kg/m³
d_s	Density of fibers, kg/m³
S_r	Residual saturation of the pulp mat

Table-2. Washing System Operating Parameters

Symbol	Definition
C_{blow}	Consistency of pulp in blow tank, kg/m^3
TDS	Total dissoloved solids present in the system, kg/kg pulp
$\phi 1$	Fraction of the drum surface used for filtion.
$\phi 2$	Fraction of the drum surface used for washing.
$\phi 3$	Fraction of the drum surface used for dewatering
C_{vat}	Consistency of the pulp in the vat, kg/m^3
N	Rotational speed of the drum, rev./s
M	Number of washers in the system
P	Number of wash presses in the system
$\triangle P$	Vacuum/Pressure drop, N/m^2
DF	Dilution factor, kg/kg pulp. The amount of total wash water added minus that leaving the washing system with the. pulp.
α	Factor to account for the effect of air present in the pulp

Table—3. Values Determined by the Model

Symbol	Definition
DR	Displacement ratio defined in Eq. 1
C_d	Consistency of the mat discharging from the washer.
Eff	Washing efficiency defined as the ratio of dissolved solids recovered in the liquor to the total dissolved solids.
V_{rec}	Volume of liquor going to recovery section, m^3/kg
X (0)	Concentration of liqnor going to recovery, kg/m^3 liquor
Prod	Specific washing rate, kg o.d. pulp/m^2s

as the value of residual saturation, S_r, increases. Usually the value of S_r for pulps is greater than 0 5 in such cases the value of C_d/C_{mat} is almost entirely dependent on S_r. Figure-3 shows the dependece of the pulp-wash liquor contanct time on the drum submergence $\phi 1$, the drum speed, N, and the vat consistency, C_{vat}. Figure-4 shows how the number of transfer units varies with the contact time r, and mass transfer coefficient ka. Plots of local efficiency, E, versus the number of transfer unit, for various amounts of residual air in the pulp are shown in Figure-5. The values of E approach unity for very large values of η. However, for low value of α the curve passes through a maxima and the value of local efficiency E exceeds unity in the practical range of η between 1 and 2. The increase in efficiency above unity illustrates the important role played by the displacement phenomena in washing. The importance of deaeration of pulp between the wahers is clearly shown in these curves. Generally, the pulp picks up air during the dewatering on the filter which does not fully disengage in the reslushing operation thus lowering the efficiency of second and subsequent washers. The foaming characteristics of the liquor also affect the amount of residual air. Usually the foaming tendency decreases as the liquor concentration decreases on subsequent washers. Finally the Figure-6 shows how the displacement ratio, DR, can be determined from the local efficiency, E, and the dilution factor. The displacement ratio can be increased by increasing both E and DF.

2. The Washing Efficiency

The overall efficiency of washing operation is defiend as :

$$\text{Eff} = 1 - \frac{\text{Loss of dissolved solids}}{\text{total dissolved solids present in the system}}$$

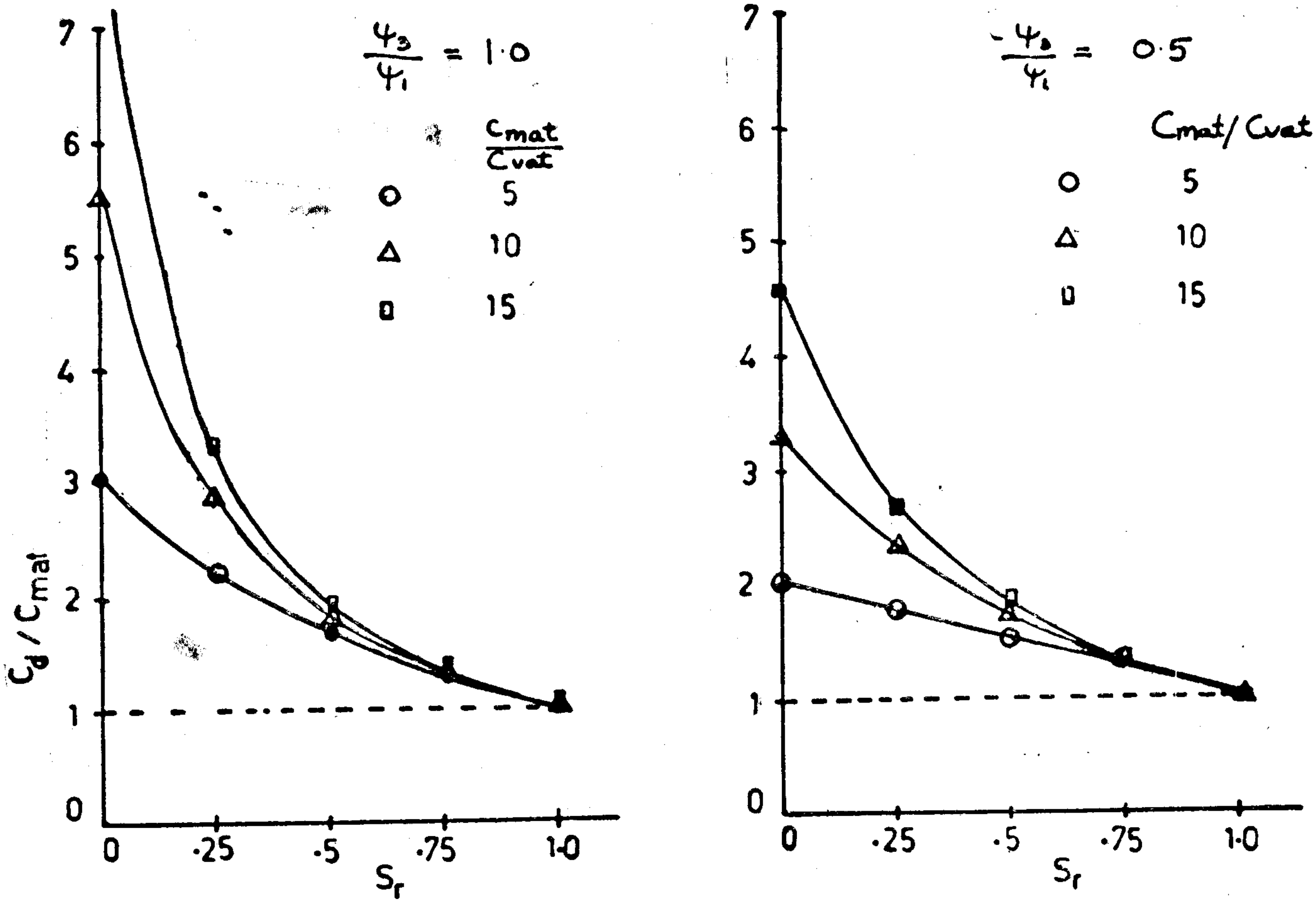
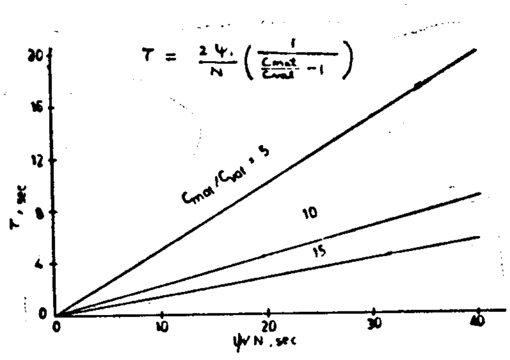


FIG. 2: EFFECT OF RESIDUAL SATURATION ON DISCHARGE CONSISTENCY. (PROMINANT AT LOW VALUES OF SR AND CVAT)



IG. 3 CONTACT TIME OF WASH SOLVENT IN THE WASHING ZONE

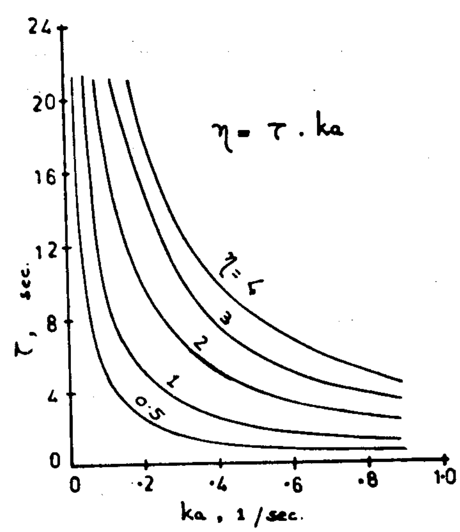


FIG. 4: DETERMINATION OF NUMBER OF MASS TRANSFER UNITS

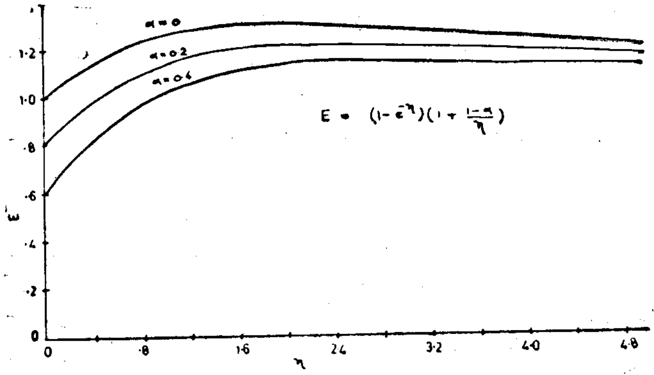


FIG. 5 DETERMINATION OF LOCAL EFFICIENCY. EFFECT OF PRESENCE OF AIR IN THE PULP

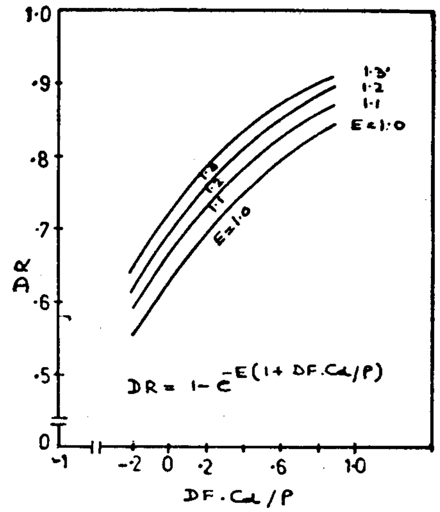


FIG 6 EFFECT OF DILUTION FACTOR AND LOCAL EFFICIENCY ON ON DISPLACEMENT RATIO

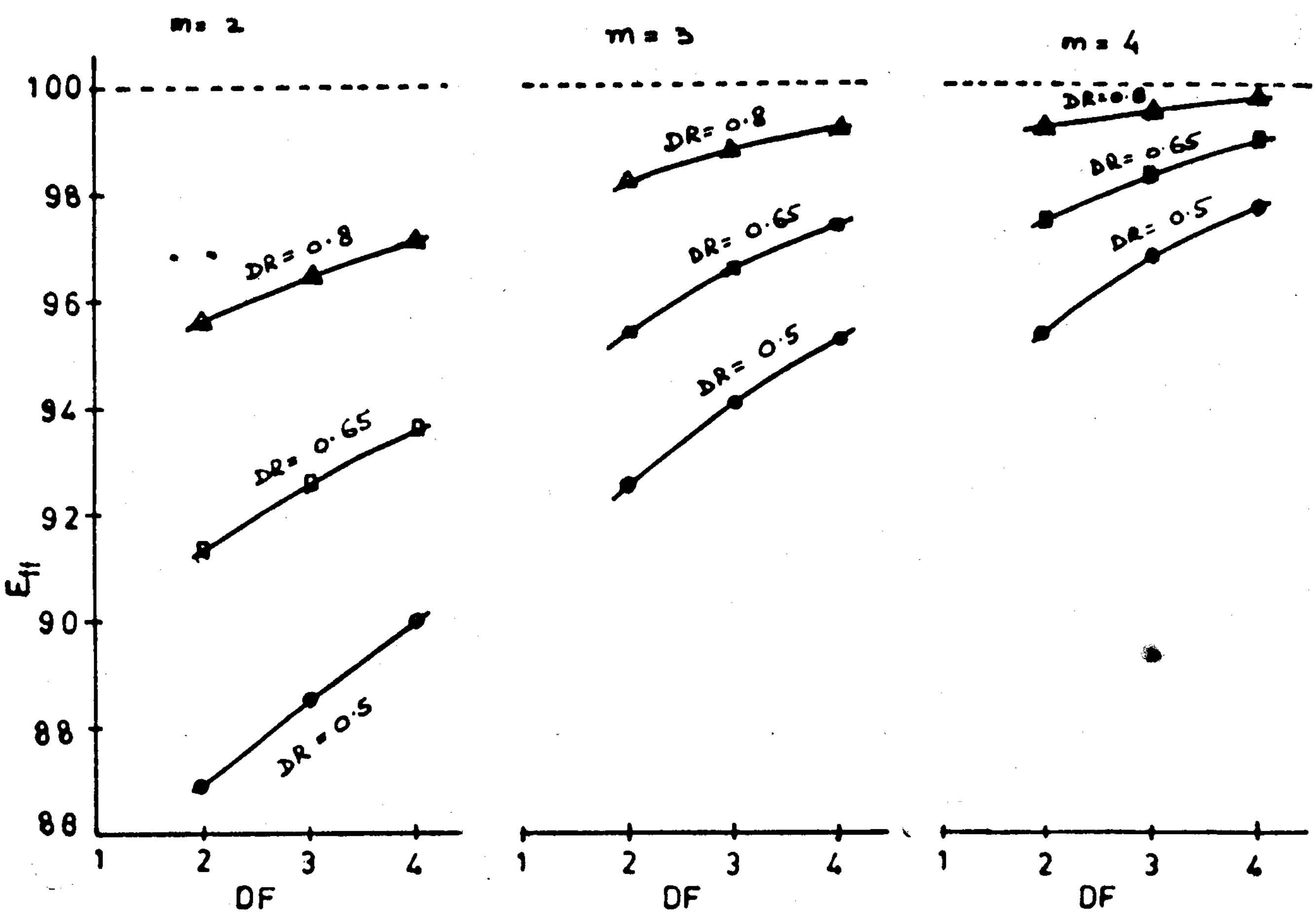


FIG. 7: EFFECT OF DILUTION FACTOR, DISPLACEMENT RATIO, AND NUMBER OF STAGES ON WASHING EFFICIENCY.

Figure-7 shows the plots of washing efficiency as function of the displacement ratio, DR, the dilution factor, DF and the number of washing stages in the system, M. The washing efficiency can be increased by increasing DR, DF and M. while every effort should be made to achieve the highest possible valus of DR, the improvement in the efficiency due to increased dilution of liquor and number of stages should outweigh the additional cost of evaporation of diluted liquor and of the washing equipment.

Table-4 presents results for various washing systems at a typical set of pulp-liquor characteristics and operating parameters. The results have been presented for cascades of filters with and without the provision of an additional wash press at the end of the cascade. The discharge consistency of pulp mat for wash press has been assumed to be 400 kg pulp/m³ liquor.

The Specific Washing Rate

The specific production rate on a rotary drum filter is proportional to the square root of the consistency in the vet, the rotational speed of the drum, the drum submergence and the pressure drop across the mat. Generally not much variation in the values of these parameters is possible in a given washing svstem. For example an increased loading of the system by increasing consistency in the vat results tn a thick and non-uniform mat formation leading to channeling of wash liquor, poor dewatering of the mat and overall poor efficiency of the operation.

Under a given set of operating conditions, the production rate is proportional to the square root of the permeability of the pulp and inversely proportional to the square root of the viscosity of the spent liquor. The most significant difference between washing of wood pulp and agri-residue pulps is that the latter have poor permeability and high viscosity of their spent liquors resulting in a much reduced specific production rate.

Xie (5) has found empirically that the permeability of pulps can be expressed in terms of Schopper Reigler drainage (°SR) or canadian standard freeness (CSF) values of pulp. Xie found that under normal conditions the permeability could be expressed by the equation (2)

$$K\ 2.08\ 10^{-13}\ \frac{(100 - {}^{\circ}SR)}{({}^{\circ}SR - 4)} \qquad (2)$$

Where K = Permeability, m²

°SR = Degree Schopper Reigler

Table—4 Washing Efficiency and Dissolved Solids Loss as a function of number of washers and the dilution factor. Characteristics assumed in the example

Cmat = 90	ka = 0.2	d_s = 1500	a = 0.4
d_l = 1000	S_r = 0.6	°SP = 14	C_{vat} = 10
ϕ1 = 0.50	ϕ3 = 0.25	N = 0.025	TDS = 1.5
	C_{blow} = 120	P = 20000	

A—Washing Efficiency, % (Without Wash Press)

DF	V_{rec}	DR1*	DR2*	Number of stages 2	3	4	5
—4	4.3	.3	.23	51.05	51.83	51.97	51.99
—3	5.3	.4	.32	61.72	63.39	63.83	63.95
—2	6.3	.49	.39	71.19	74.10	75.20	75.65
—1	7.3	.57	.46	79.11	83.18	85.13	86.21
0	8.3	.63	.52	85.32	90.00	92.41	93.88
1	9.3	.69	.57	89.94	94.46	96.64	97.86
2	10.3	.73	.62	93.21	97.09	98.65	99.36
3	11.3	.77	.66	95.47	98.51	99.48	99.82
4	12.3	.8	.7	96.99	99.24	99.80	99.95

*DR1 is displacement ratio in first stage. DR2 is displacement ratio in subsequent stages calculated considering presence of residual air in the pulp.

B - Dissolved Solids Loss, kg/tonne pulp (without Wash Press)

DF	V_{rec}	DR1	* DR2	Number of stages 2	3	4	5
— 4	4 3	.3	.23	734	723	720	720
— 3	5.3	.4	.32	574	549	543	541
— 2	6.3	.49	.39	432	389	372.	365
— 1	7.3	.57	.46	313	252	223	207
0	8.3	.63	.52	220	150	114	92
1	9.3	.69	.57	151	83	50	32
2	10.3	.73	.62	102	44	20	10
3	11 3	.77	.66	68	22	8	3
4	12.3	.8	.7	45	11	3	1

C - Washing Efficiency, % (With Wash Press)

DF	V_{rec}	DR1	* DR2	Number of stages 2	3	4	5
— 4	4.3	.3	.23	52.55	52.10	52.02	52.00
— 3	5.3	.4	.32	64.42	64.12	64.03	64.01
— 2	6.3	.49	.39	75.17	75.64	75.84	75.93
— 1	7 3	.57	.46	83.88	85.51	86.43	86.99
0	8.3	.63	.52	90.14	92.49	93.94	94.92
1	9.3	.69	.57	94.20	96.50	97.78	98.55
2	10.3	.73	.62	96.65	98.46	99.27	99 65
3	11.3	.77	.66	98.07	99.34	99.77	99.92
4	12.3	.8	.7	98.89	99.71	99.92	99.98

D—Dissolved Solids Loss, kg/tonne of pulp (With Wash Press)

DF	V_{rec}	DR1	* DR2	Number of stages 2	3	4	5
—4	4.3	.3	.23	712	718	720	720
—3	5.3	.4	.32	534	538	539	540
—2	6 3	.49	.39	372	365	362	361
—1	7.3	.57	.46	242	217	204	195
0	8.3	.63	.52	148	113	91	76
1	9.3	.69	.57	87	52	33	22
2	10.3	.73	.62	50	23	11	5
3	11.3	.77	.66	29	10	3	1
4	12.3	.8	.7	17	4	1	0

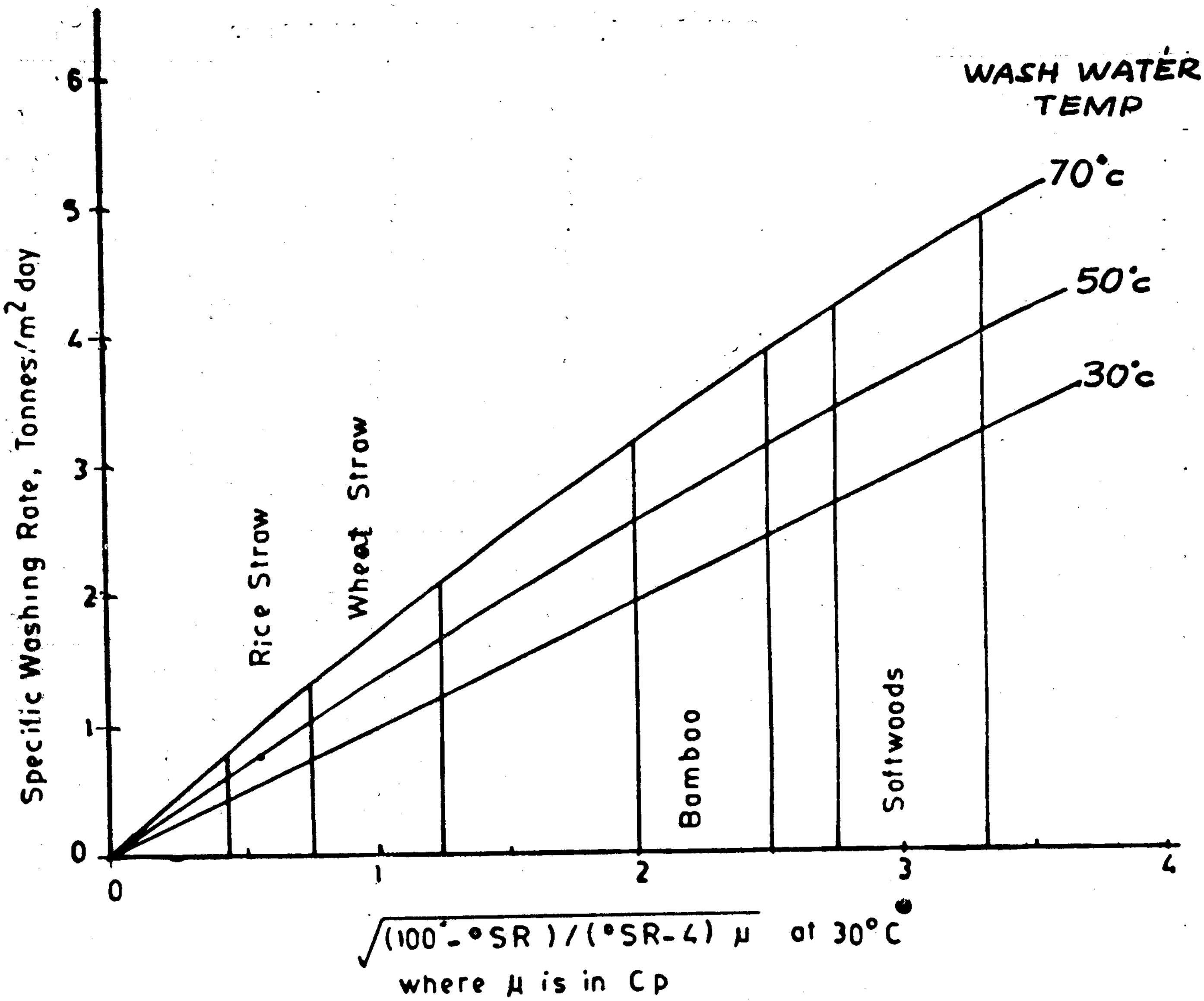


FIG. 8 SPECIFIC FILTRATION RATE AS FUNCTION OF PERMEABILITY OF PULP AND VISCOSITY OF LIQUOR

Figure-8 shows the specific productivity of filter as a function of $\sqrt{[(100 - °SR)/(°SR-4).\ \mu]}$. The productivity of washer is reduced as much as by a factor of 4 or 5 in case of straw pulps as compared to softwood pulps under the similar conditions of operation.

THE LEAST COST WASHING SYSTEM

The primary objective of the pulp washing operation is to wash the pulp clean and to recover the inorganic and organic chemicals dissolved in the black liquor economically. The optimum situation would be one in which the sum total of the cost of washing equipment, cost of evaporating the liquor and the cost of dissolved solids going along with the pulp is minimum. The model presented here can be easily applied to determine the optimum conditions in a given economical environment. Due to dynamic nature of economic parameters it is necessary that the optimum conditions be evaluated time to time and the required changes be incorporated in the system. For example, the increasing energy costs may favour an additional washer in the system with reduced dilution of the liquor. On the other hand growing concern about the cleaner environment may necessitate an increased washing efficiency even if it means additional washers in the system and extra dilution of the liquor.

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