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UNDERSTANDING BROWN STOCK WASHING ON ROTARY DRUM VACUUM FILTER

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Brown stock washing is an economically important step in paper making process. Counter current washing on a battery of rotary drum vacuum filters is presently the standard practice for pulp washing. It is hoped that this type of equipment will continue to play its dominant role in Indian pulp and paper industry for quite sometime to come. More and more new varieties of fibrous raw materials are being used for making pulp which have significantly different hydrodynamic and washing characteristics. For optimum design and operation of the washing systems there is a need to study the fundamental characteristics and their effect on the design of washing equipment seprately for different pulps. The present paper critically examines the available models in the literature and identifies the type of data to be generated for development of a suitable design procedure.

1. Introduction

Pulp is washed to remove cooking liquor. The objective is always to use minimum amount of wash solvent and washing pulp to maximum cleanliness. The performance of the washing plant, thus, has a strong influence on the economics of the entire mill. The washing plant, therefore, must be optimally designed and operated.

For most effective washing at minimum dilution of the recovered liquor, counter-current operation is used. Counter-current washing in 3 to 5 stages on rotary drum vacuum filters is the most commonly employed practice. The knowledge of the pulp washing so far, has been mostly empirical. The design and operating procedures for most plant scale washing equipments have evolved from the experience gained over the years. Laboratory and pilot plant experiments have been limited, in general, to softwood pulps. For other pulps, for example, hardwoods and straws similar equipment have been used with little change. Though the use of such equipment is in vogue, for quite sometime, there is no published literature showing the design procedures based on fundamental characteristics. There is a need to look at these systems to evolve sound generalised mathematical procedures coupled with specific washing characteristic of individual pulps Statistical analysis of pulp washing for hardwood and softwood pulp[1] has indicated that the hydrodynamic and mass transfer characteristics of these pulps are significantly different from each other. Consequently the washing equipment designed for one kind of pulp cannot be substituted for another kind of pulp with equal effectiveness.

2. Washing Phenomena

The present paper gives a brief resume of the present state of understanding of the washing phenomena. Various approaches have been suggested in literature. These are broadly.

- Multistage countercurrent washing on a cascade of rotary vacuum filters with intermediate reslushing, and
- countercurrent washing on a single belt filter with no intermediate reslushing.

The total washing process can be broken into two distinct phenomena, namely, filtration and extraction of dissolved solids. Filtration accounts for removal of the liquor from the pulp and delivering the pulp at the greatest consistency. The extraction refers to reduction of concentration of the solute (total dissolved solids; inorganic + organic) 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 in the liquor within the fibers towards an external liquid which is less concentrated. The bound chemical on the fibers (fig. 1) as the washing preogresses and thus aids extraction.

A washing filter (Fig. 2) consists of a skeleton drum covered with a filter cloth partially submerged in a vat. The vat is fed with a low consistency pulp. The drum rotates at slow speed in the vat and a vacuum is applied inside the drum. due to the low pressure within the drum, the pulp from vat moves towards its surface. A part of the liquid is sucked inside the drum. The fibers and the retained liquid deposit on the drum surface in the form of a mat. The thickness of the mat continues to increase until it emerges from the vat. After that it passes through a zone where a washing liquid (water) flows through it extracting the solute (dissolved solids) it contains. The application of the pressure drop is continued for some more time to further expel a part of the liquid present between the fibers and deliver pulp at a greater dryness. It is possible to set several washing zones on the same drum. Each washing liquor in this case can be the filtrate of the former washing zone.

2.1 Filtration

The filtration phenomenon is relatively better understood. Mathematical expressions are available[2] for filtration process on a rotary vacuum filter. The volume of the filtrate collected in the mat formation zone, Qf, is given by

$$Q_t = \frac{\mu}{2Kc'} \psi_1 S t \quad \cdots\cdots\cdots \quad 1$$

the mat thickness t is given by,

$$t = \frac{2K}{\mu} \sqrt{C'(-\Delta P)\psi_1/N} \quad \cdots\cdots\cdots\cdots \quad 2$$

and

$$C' = \frac{\mu \rho C_v}{2K[(1-\varepsilon)\rho_s - \rho\varepsilon C_v} \quad \cdots\cdots\cdots\cdots\cdots \quad 3$$

Here K is the permeability of the mat which is a characteristic of fibers and should be determined experimentally.

The mat thickness does not change in washing zone and the flow rate of wash solvent through the mat will be equal to the rate of filtration at the end of the formation zone.

$$V_s = \frac{K(-\Delta P)}{\mu \varepsilon l} \quad \ldots\ldots\ldots \quad 4$$

The volume of filtrate collected in washing zone, Qw, will be same as the wash solvent used through showers.

$$QW = V \quad \ldots\ldots\ldots\ldots \quad 5$$

The volume of filtrate collected in dewatering zone, Qd, is given by Brown[2] as

$$Qd = \frac{\psi_3}{(1-S_r)\frac{\varepsilon\mu+2}{K(-\Delta P)}+\psi_3} \quad \ldots\ldots \quad 6$$

The solution of above expressions demands estimation of permeability, residual saturation along with fractions of the drum surface utilised for different operations. Although, these expressions have been derived under the assumptions of constant pressure filtration, negligible hydrostatic head in the vat, incompressible mat and a negligible resistance of the filter cloth, suitable corrections can be incorporated to accommodate the deviations from this idealized situation for more accurate designs.

2.2 Extraction

In this phase reduction in the solute concentration is achieved by the use of a wash solvent. The result is a combination of fluid displacement and mass transfer. The understanding of these phenomena is still not clear. A number of workers have attempted to analyse this step so that some practical parameters are evolved for plant control. The available models for washing can be broadly classified as macroscopic and microscopic. These are discussed subsequently.

3 Macroscopic Models

In these models washing is explained by using a single parameter to account for both the fluid displacement and the mass transfer. Physically the process is depicted in Fig. 3.

Among the earliest works in this field is that of Perkins et al[3]. In general, the reduction of solute concentration in the underflow (Pulp stream) is a function of the greatest possible reduction and can be expressed as

$$(X_n - x_n) = t(X_n - y_{n+1}) \quad \ldots\ldots\ldots \quad 7$$

Perkins et al expressed it in terms of a proportionality constant DR as under

$$\cdots (x_n - X_n) = DR(X_n - y_{n+1}) \cdots\cdots\cdots 8$$

The constant DR is called "Displacement Ratio". In practice the displacement ratio depends on a number of factors, namely.

-- Dilution factor, D, expressed as (V--L) which represents the increase in the total liquor in overflow going to recovery/disposal.
-- Wash liquor distribution.
-- Mat consistency.
-- Sheet distribution.
-- Shower water temperature.
-- Pulp characteristics.
-- Specific loading which controls sheets thickness and drum speed.
-- Drainage rate which determines the vat consistency.
-- Drum submergence
-- Foam formation, which is dependent on liquor and amount of air entrainment.

The effect of the dilution factor and the wash liquor distribution on the displacement ratio was studied by Perkins et al with the help of a simple model. The total wash liquor sprayed on the mat through m rows of parallel showers was considered equivalent to m perfect mixing and separation operations working one after another as depicted in Fig. 4. A material balance for such a case yielded an idealised displacement ratio, DRi, as

$$\cdots DR_i = 1 \left(\frac{mL_n}{mL_n + V_n}\right)^m \cdots\cdots\cdots\cdots 9$$

Or, writing in terms of dilution factor, D,

$$\cdots\cdots \left(\frac{mL_n}{(m+1)L_n + D}\right)^m \cdots\cdots\cdots\cdots 10$$

Where D is defined as

$$D = V_n - L_n \cdots\cdots\cdots\cdots 11$$

The actual displacement ratio values from plant data were found to follow the general trend shown in equation (10) but the level of actual values was sometimes higher and sometimes lower than the idealised values. It was suggested by Perkins et al that the actual displacement ratio, DR, could be obtained in terms of idealised displacement ratio by multiplying with a constant correction factor K' as shown below.

$$\cdots\cdots DR = K' DR_i \cdots\cdots\cdots\cdots\cdots 12$$

K' is a function of the independent variables of the system such as the characteristics of the pulp. The evaluation requires generation of K' values for a wide variety of pulps. Apparently such data are not available and efforts are needed to compile such information based on plant experiments. Many of the factors influencing displacement ratio can be accounted for, at least partially, if the filtration expressions (1) to (6) involving The geometry of filtration system along with some of the operating parameters are treated simultaneously with extraction expression.

While the Perkins model is simple and easy it suffers from the following major limitations.

1. The effect of many variables such as difference in specific loading, kind of pulp, operating control etc. is not included.

2. It was observed in practical cases consisting of a battery of identical filters that the displacement ratio was found to be different at different stages. The reasons for this deviation are believed to be foaming tendency of liquor and/or air entrainment.

In another similar approach Fitch and Pitkin[4] introduced a new term called filter entrainment, FE, defined as

$$FE = L(1 - DR) \qquad 13$$

Filter entrainment, though uniquely correlated to DR, is superior in explaining the total extraction process. It accounts for the extent of equilibrium reached and the consistency of the mat leaving the filter (dewatering). In the simplest terms FE represents the quantity of vat liquor going with the pulp expressed as kg liquor/kg. pulp. In any washing system the attempt is to reduce entrainment, FE.

The Fig. 5 indicates pictorially the multiple displacement concept of Fitch & Pitkin. They found that the log (FE) is a linear function of, V. the wash liquor used as shown in fig. 6.

The mat when leaves the vat is saturated with liquid and carries Ls kg of liquor with every kg of fiber. Some amount of liquor is sucked from the mat during dewatering operation and the quantity of liquid finally going with mat as a result of dewatering is L. The difference (Ls - L) represents a reduction in the filter entrainment as a result of liquor displaced by air. This effect can be accounted for by assuming the washing to have been done by an increased quantity of wash liquor as this tends to reduce the concentration of dissolved solids going with the pulp. The authors suggest that the effective quantity of wash liquor is taken as V + Va where Va is the volume of wash liquor obtained from Fig. 6 corresponding to the reduction in filter entrainment from Ls to L.

In this simple model it is presumed that the wash liquor coming from the succeeding stage partially displaces the liquor present with the pulp. The degree of washing can be estimated from Fig. 6. The displacement concept is extended to succeeding stages and diffusional mass transfer is apparently not considered. It is essential to develop curves like those in Fig. 6 which are both system and equipment dependent.

Tomiak[5] developed a washing model for simpler calculations assuming that the recovered washing liquor to consist of certain volume of original filtrate displaced from the filter mat and a portion of wash liquor assuming no diffusion. The displaceable volume was considered proportional to the ratio of volume of original filtrate to volume of wash liquor. The proportionality constant, a , was observed to be a function of V and L. This model may predict the value of displacement ratio greater than unity at high dilution factor which is not physically possible.

4. Microscopic Models

The models discussed so far lay emphasis on simplifying the calculating procedures taking a macroscopic view at the system. More detailed models have been developed which involve separate parameters for fluid displacement and mass transfer. Perhaps Grah[6,7] was the first to make a microscopic analysis considering the pulp mat to consist of the following zones during displacement washing (fig. 1).

1. Zone of flowing liquor.
2. Zone of stagnant liquor.
3. The fibers.

The transfer of solute between the fiber and the liquor is by adsorption/desorption. The desorption isotherm for dissolved solids was considered linear and expressions were derived for axial dispersion. The pulp mat was considered to consist of three different porosities. Perron and Lebeau[8] called these as total porosity, displaceable porosity and non displaceable porosity. The displaceable porosity essentially refers to the flowing liquor zone and the non displaceable porosity refers to the stagnant liquid zone. The flowing liquor was considered to be of plug flow type with no axial dispersion while a first order diffusion is assumed between the flowing and the stagnant portions of the liquid. Though not specifically mentioned the stagnant layer of liquid indicates the liquid film adjacent to the fibers walls and the liquor inside the fiber pores. Perron et al neglected the adsorption on the fiber. The results can be expressed in terms of displacement ratio in the following manner.

$$\ldots\ DR1 - \frac{\varepsilon 1}{\varepsilon} e^{-Kr} \qquad \text{------} \qquad 14$$

Where k is the mass transfer coefficient and T is the average contact time of wash solvent in the mat. T is given as under:

$$T = \frac{t}{V_s}\left(\frac{V - NS t \varepsilon d}{NS t \varepsilon d}\right) \text{ ---------- } 15$$

In order to obtain a high displacement ratio or better washing one can either increase the volume of wash solvent or decrease the velocity of wash solvent in the mat by finely dispersing it. For efficient washing and better removal of dissolved solids desorption from fiber surface is important. Interestingly the adsorption isotherms for organic and inorganic dissolved solids have different non linear behaviour.

In a recent approach Cullinan[9] [10] has treated washing of pulp on a rotary drum analogous to mass transfer operation in equilibrium stages. In the wash zone mass transfer occurs under the influence of spatially varying concentration gradients in the presence of possible fluid dispersion within the porous fibrous mat. The pulp mat moves in a transverse direction with respect to the flow of wash liquor. This method of contact is similar to the flow of the two phases involved on a tray of a distillation column. Although in washing the phases and the physics of the contact are different the analogy is useful and much of the analysis of mass transfer on a distillation tray can be adapted to the wash zone.

In the actual operation the presence of showers and transverse movement of the mat leads to a stage efficiency which will be a cumulative effect of local point contacts. Accordingly stage efficiency is derived by Cullinan as

$$\ldots\; E_s = \frac{(1+R)e^{EW}-1}{R+W} \text{ ------- } 16$$

Where e represents the local efficiency given by,

$$\ldots\; E = \frac{y_n' - y_{n+1}}{x_n - y_{n+1}} \text{ --------------- } 17$$

Where yn' and xn' represent the local concentrations in mat and in filtrate as shown in fig.7

The local efficiencies purely based on mass transfer can go up to 1 whereas stage efficiency being a cumulative effect can be greater than 1. The values of stage efficiency will be higher for increased wash ratio. The relationship between DR and the local efficiency, is given as follows.

$$DR = 1 - e^{-EW} \text{ --------------- } 18$$

One can consider the total washing to be a sum of mass transfer and displacement. While mass transfer will be governed by the concentration difference at different points in the mat the extraction due to displacement will be a function of effective velocity of wash liquor in wash zone, ve, effective mass transfer area per unit volume and thickness of the mat. In fact one can talk of number of transfer units due to mass transfer and due to displacement. The local efficiency for such situations is estimated as

$$\text{....}\quad E=(1-e^{-n})\left(1+\frac{1}{n}\right) \quad \text{———} \quad 19$$

where

$$\text{....}\quad n=\frac{k\,a\,t}{Ve} \quad \text{———} \quad 20$$

Depending on the value of a the local efficiency values will change.

In multistage washing operation the pulp from the previous stage is reslushed and mixed with filtrate from the succedding stage. The mat will always have some amount of residual air which will render the mat ineffective for washing. The local efficiency is related to, f, the fraction of the wash water rendered ineffective due to air in the mat as follows–

$$\text{....}\quad E=(1-e^{-n})\left(1+\frac{1-t}{n}\right) \quad 21$$

Higher is the residual air lesser will be the the local efficiency as the displacement component will be reduced. Cullinan believes that the a values normally range between 1 and 3 giving local efficiency between 1 and 1.3.

5 Estimation of Number of Stages

The operation of the cascade of filters can be represented in terms of operating and equilibrium lines. Many of the earlier calculations are based on the concepts of perfect stages. In the recent approaches the equilibrium line is defined as xn = yn (also known as Norder line). This represents a perfect mixing stage where underflow and overflow strems have equal solute concentrations. This does not represent, the theoretically attainable washing as indicated by Perkins et al. The Norden line concept, however, gives a simple graphical construction procedure for estimating the number of Norden stages for a given wash loss.

The operation of a cascade of filters is given in fig. 8. A material balance between the last (mth) and any other (nth) filter gives the operating line as under

.... $$y_n = \left(\frac{1}{w}\right)(x_{n-1}) + y_{m+1} - \left(\frac{1}{w}\right) x_m \quad \text{--------} \quad 22$$

The equilibrium line and the operating line are used to predict the number of stages by graphical construction as shown in fig. 9. The performance being non equilibrium in character it is useful to define stage efficiency, Es, which indicates the deviation from equilibrium values in each stage as

.... $$E_s = \frac{y_n - y_{n+1}}{x_n - y_{n+1}} \quad \text{----------------} \quad 23$$

Using these values for each stage it is possible to get the actual number of stages by graphical construction using the Norden line and operating line.

As in other stage wise mass transfer operations, here also it is possible to define minimum wash ratio which indicates the slope of the operating line which would touch the equilibrium curve for the specified wash loss. Alternatively, it represents an approach to minimum wash liquor demand for infinite stages of operation and is given by

.... $$W_m = \frac{1 - x_m/x_o}{1 - y_{m+1}/x_o} \quad \text{----------------} \quad 24$$

This approach appears quite sound for design of multistage washing systems provided reliable data are generated for estimation of mass transfer coefficients effective surface area of the mat, effective velocity of the wash liquor in the mat and residual air for different type of furnishes.

6 Conclusions

The above description clearly indicates the washing phenomena to be a complex operation involving combined mass transfer and displacement. Modelling such systems require clear understanding of the principles governing the operation. Empiricism will lead to erroneous expressions. A dependable approach would be to treat the operation as completely mass transfer dominated where equilibrium curves can be drawn taking into account the recycle ratio, wash ratio, the dimensionless mass transfer coefficient and, the fraction of the wash water rendered ineffective in washing zone due to presence of air in the mat. This pseudo equilibrium curve will have to be estalished for each system and conventional graphical procedure can be followed without resorting to efficiency factor estimation.

Washing should be carried out to give maximum recovery at highest concentration. The above analysis indicates that this will depend on the knowledge of the following major factors.

- mass transfer coefficient permeability or specific mat resistance to evaluate t, a, and ve
- amount of entrained air present in mat after reslushing to determine a.

- These parameters can be obtained in laboratory simulated experiments and can be compared with actual plant data. Once such information is available with reliability optimal design of washing system can be done.

Notation

a = effective mass transfer area per unit volume
C' = a parameter defined by eg. (3)
Cv = consistency in the vat, kg fiber/kg liquid.
D = dilution factor
DR = displacement ratio
DRi = idealized displacement ratio as derived by Perkins et al
E = local efficiency
Eo = overall efficiency
Es = stage efficiency
f = fraction of the wash water rendered ineffctive due to presence of air in the mat
FE = filter entrainment defined in Eq. (13).
k = global mass transfer coefficient
K = permeability of the cake.
K' = correction factor to obtain actual displacement ratio from the idealized displacement ratio calculated using Perkins' model, defined in eq (12).
L = amount of liquor leaving with the cake.
Ls = kg of liquor/kg of fiber held by the mat as it leaves the vat
m = total number stage in the cascade
n = general stage index
N = rotation speed of the drum
Q = total filtrate collected
Qd = volume of filtrate collected in dewatering zone.
Qf = Volume of filtrate collected in mat formation zone.
Qw = volume of filtrate collected in washing zone
R = the recycle ratio, (Q–V)/L
S = total surface of the drum, m^2
Sr = residual saturation of cake i.e. volume of non extractable liquor/volume of pores in the cake.
t = mat thickness, m.
T = average contact time of wash solvent in the mat
ve = effective liquor velocity through the cake in the wash zone.
vs = superficial velocity of solvent throuth the mat in the washing zone
V = amount of wash solvent used in the showers.

W = wash ratio, L/V
Wm = minimum wash ratio

x = concentration of the dissolved solids in the liquor going with the pulp
X = concentration of dissolved solids in vat
y = concentration of the dissolved solids in the filtrate.

-Δp = pressure drop across the cake.
-E = porosity of the cake.
-Ed = displaceable porosity
-Ef = non displaceable porosity
-fl = liquor viscosity.
-P = density of liquor, kg/m
-Ps = density of fibers, kg/m

ψ1 = fraction of the drum surface submerged in the vat
ψ2 = fraction of the drum surface used for washing
ψ3 = fraction of the drum surface used for dewatering

References

1. Norden, H.V., Pohjola V.J., and Seppanen, R., Pulp Paper Mag. Can. 74(10), T329(1973).
2. Brown, G.G., Unit Operations, John Wiley and Sons
3. Perkins, J.K., Welsh, H.S. and Mappus, J.H., Tappi, 37(3) 83 (1954).
4. Fitch, B., Pitkin, W.H. Tappi 47(10), 170 A(1964).
5. Tomiak, A., Pulp Paper Mag. Can. 75(9), T331 (1974).
6. Grahs, L.E., Svensk Papperstid., 78 446(1975).
7. Grahs, L.E., Svensk Papperstid.,79 84(1976).
8. Perron, M., Lebeau, B., Pulp Paper Mag. Can. Transactions TRI (March 1977).
9. Cullinann, H.T. Jr., Tappi 69(8), 90(1986).
10. Cullinann, H.T. Jr., Harper F.D. and Parker P.E., Pulp Washing Conference (1987) Helsinki.,

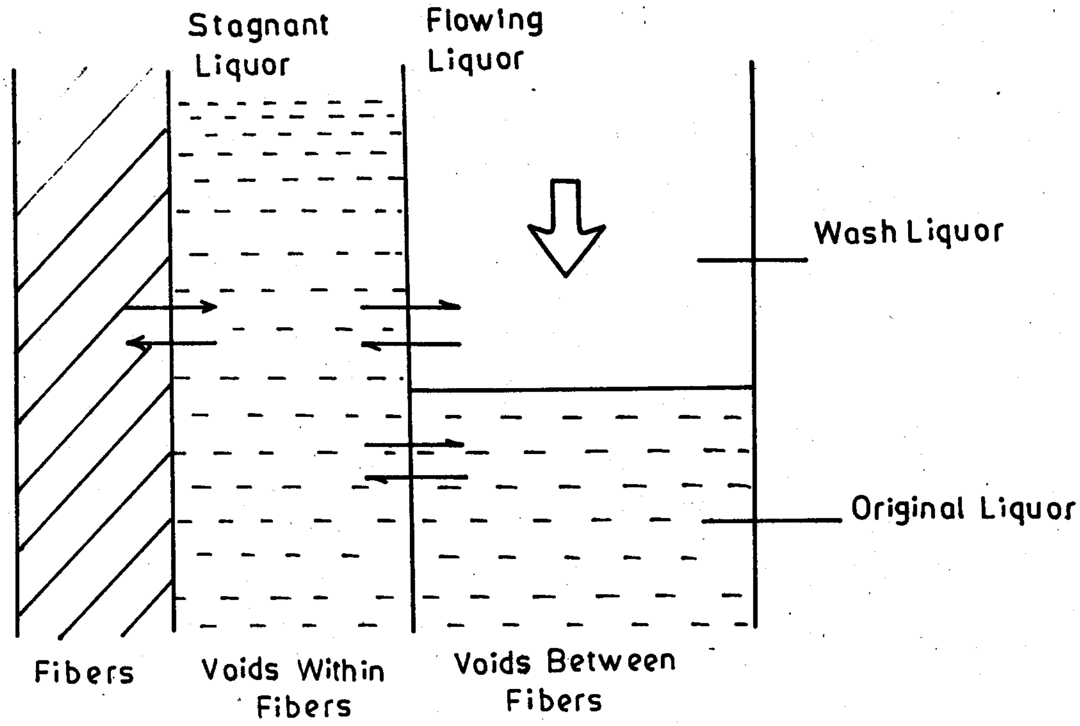

Fig. 1 Schematic Diagram Showing Different Operations in Washing

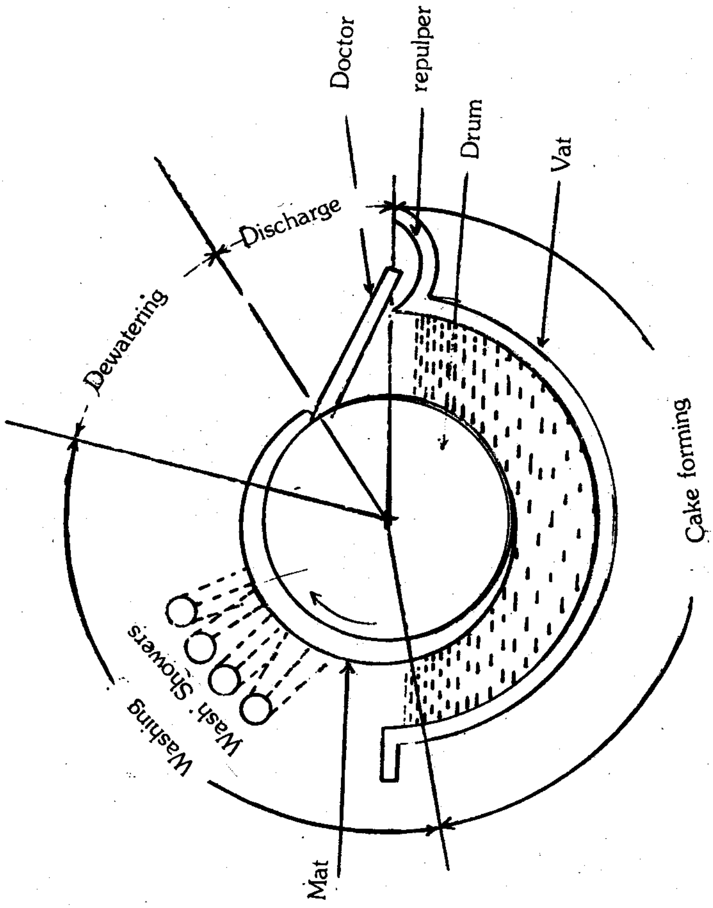

Fig 2 Different Zones in a Rotary Drum Vacum Filter

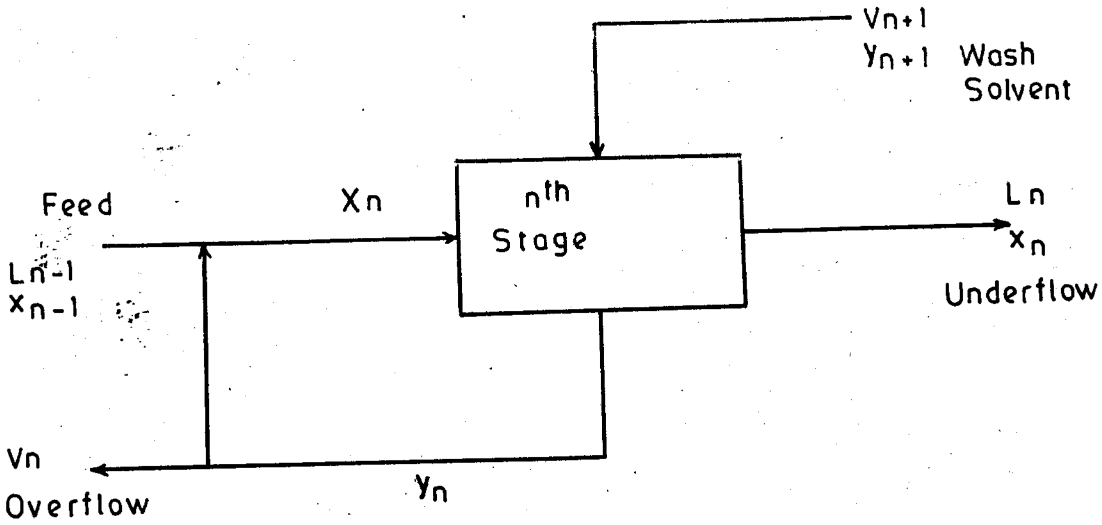

Fig. 3 A Stage in A Washing Cascade

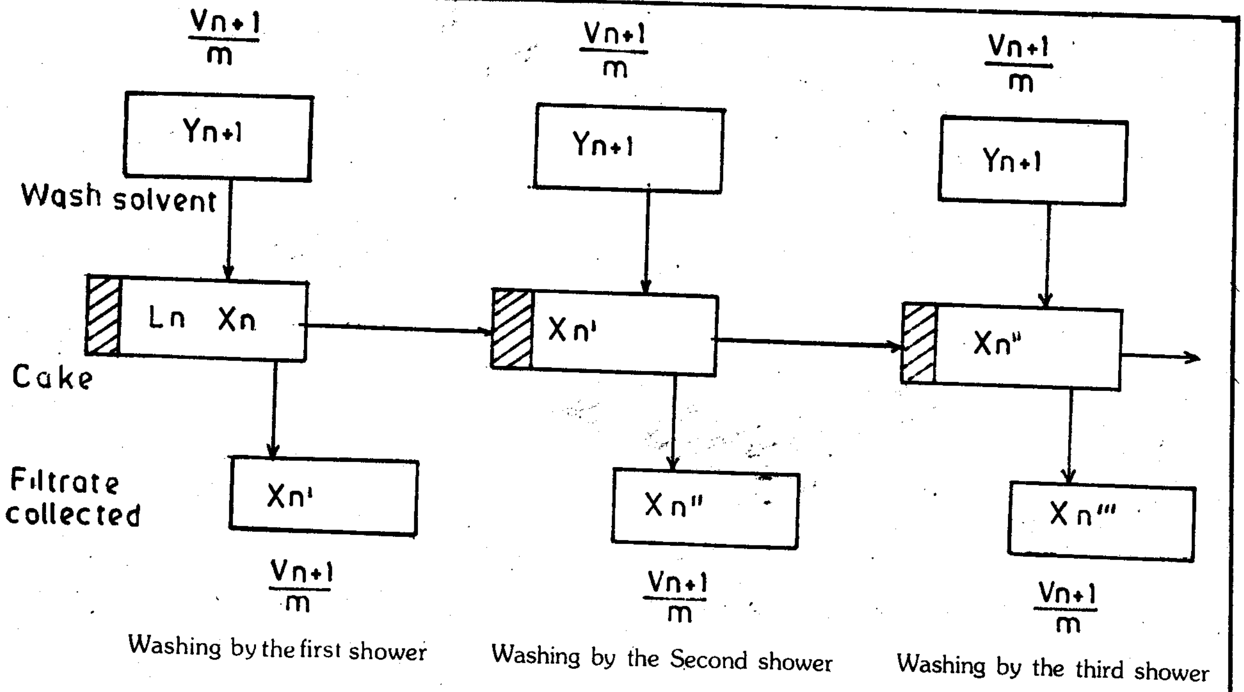

Fig. 4 Mixing And Separation Stages of Perkin et al.

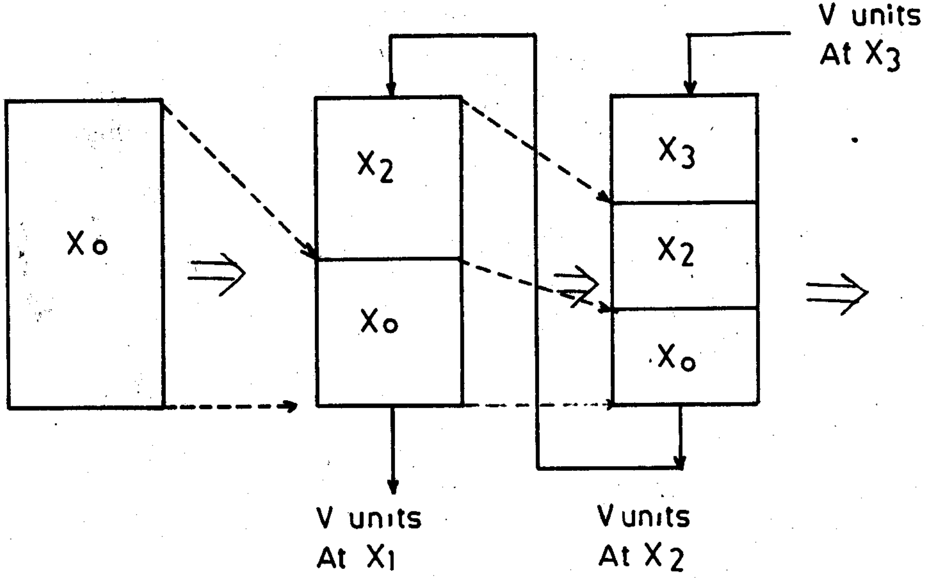

Fig. 5 Multiple Displacement Model of Fitch And Pitkin

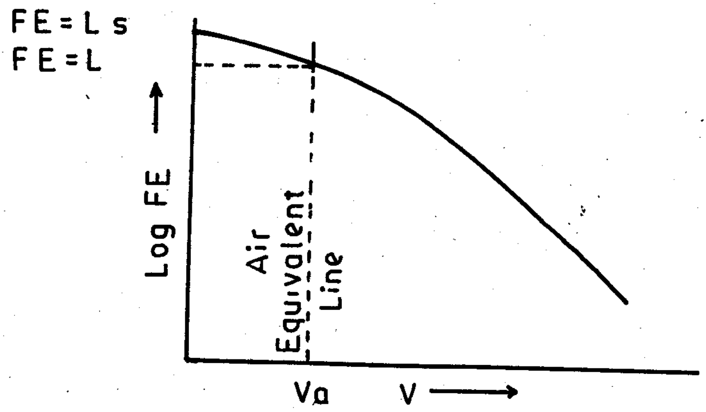

Fig. 6 Effect Of Wash Liquor Quantity On Filter Entrainment

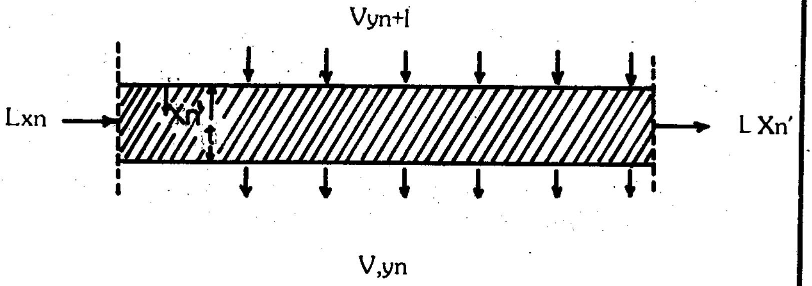

Fig. 7 Schematic of Wash Zone Showing The Concept Of Local And Stage Efficiency

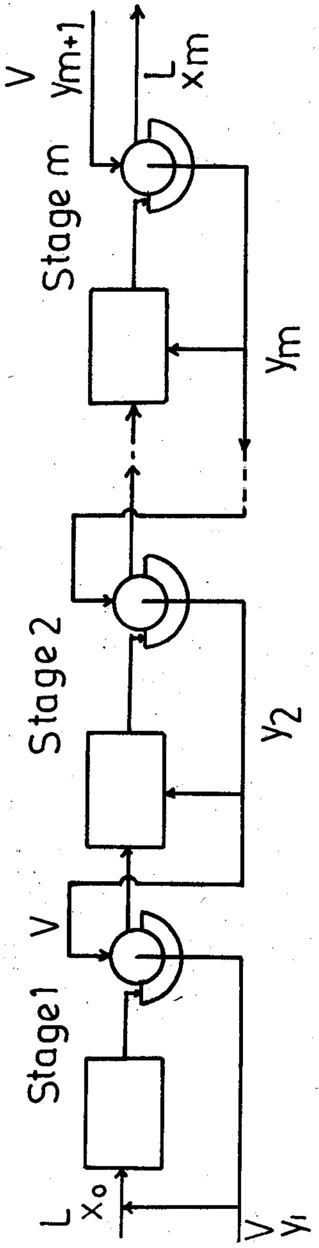

Fig. 8 Countercurrent Cascade Of Filters.

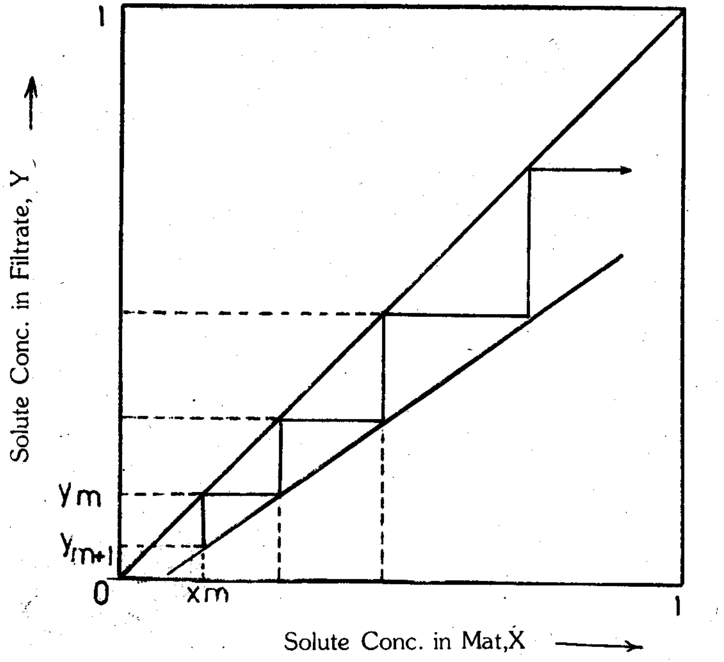

Fig. 9 Graphical Procedure For Estimating Number Of Theortical Stage