Process Piping Design for Pulp Suspensions

RAO, N.J.*

Pulp and paoer industry is a process industry handling variety of fluids like water, steam, air, pulp suspensions. The flow behaviour of most of the fluids which are single phase, homogenous and newtonian is well understood. Design of such piping is comparatively simple and well formulated. Pulp suspeusions are complex, two phase and non newtonion in character. An attempt has been made to review the present piping design procedures for pulp suspensions.

Piping consists of nearly 25-35% of the cost materials and consumes upto 40% of total engineering man-hours. A well designed piping can result in considerable saving of plant costs. Economic piping systems design is dependent on equipment and plot layouts, proper selection of pipe size and support. The considerations include process sequence, hazards and risks involved, access and safety, future expansion, head room and clearance. Various codes of practice are used in making proper choice

MECHANICAL DESIGN OF PIPING SYSTEM:

A piping system must satisfy the functional, operational and mechanical requirements. The design of a pipe depends primarily on line sizing and mechanical considerations, The considerations for design of pipes for either internal or external pressure primarily include the design pressure and temperature, material construction, allowable design stress. The IS-Code for unfired pressure vessels IS-2825-1969[1] or equivalent German, ASME, ASA or British codes can be used for the purpose. The design for internal pressure is made on the basis of a combination of thin and thick cylinder equations, while the considerations of elastic, plastic buckling and collapse are considered for external pressure.

The pipe wall thickness calculated are corrected to account for tolerences in manufacture, corrosion and erosion in the system and possibilities of threading. Several Indian and other codes indicate available pipe wall thickness.

FLEXIBILITY OF PIPING SYSTEMS :

The subjects of piping expansion and flexibility are important for hot and cold piping. The design must consider the thermal expansion and necessity of preventing excessive thermal stresses and forces. The piping layouts must be flexible enough to take care of thermal variations with regard to excessive end stresses, expansion and distorsions. Though IS-codes do not as yet suggest any procedure to check on thermal flexibility, some procedures are suggested on mandatory checking of piping flexibility by American standards association[2] based on allowable stress range, thermal expansion and modulus of elasticity. Thumb rule procedures are available for easy segregation of lines with adequate flexibility from those without. Many alternatives to achieve these objectives are suggested in literature.

LINE SIZING:

The basic parameters in piping design are dependent on the process conditions as mentioned below:

* Flow rate determines pipe size
* Flow medium determines pipe material
* Operating pressure sets the pipe wall thickness
* Operating temperature range governs the unit expansion and modulus of elasticity
* Major equipment location limits the total expansion between terminals.

From this it will be observed that the most important step is the determination of pipe line size. This is determined either based on the critical considerations or practical considerations. The material should be transferred by the pipe line within the allowable pressure

*Professor in Chemical Engineering & Director
Institute of Paper Technology
(University of Roorkee)
SAHARANPUR.

drop. While too small a line size will lead to excess energy consumption, too large a line will mean extra capital investment. Hence selection of proper line size is of primary importance,

The pressure drop in a line is related to velocity, diameter, length, viscosity and density and is given by the following equation[3,4].

$$\frac{\triangle P}{\varrho} = \frac{4f\, LV^2}{2gD} \quad \ldots\ldots\ldots\ldots \quad (1)$$

The friction factor 'f' is related to Reynold's number and pipe surface smoothness. The values of friction factor in Laminar, transition and turbulent region are available in literature in form of graphs. The approximate expression for friction factor f are given below.

For Laminar zone, Re <2100

$$f = \frac{16}{Re} \quad (2)$$

Turbulent zone, Re >2100

$$f = 0.0014 + \frac{0.125}{Re^{0.32}} \quad (3)$$

for smooth pipes.

Line sizes can be determined for a given pressure drop by trial and error based on the value of friction factor. Alternatively line size can be determined by allowable velocity range. Recommended values of allowable velocity is given in many standard books[5,6,7].

For many common fluids like water, steam, oil, gas and air, literature provides design procedures to determine line size based on emperical equations[8,9].

Line Sizing for Pulp Suspensions :

The pulp suspensions are not simple fluids. They are complicated two phase systems, non-newtonion in character. The accurate design of piping systems for transporting pulp suspensions is important because of high power consumption. Friction loss components for pumping stock at various consistencies may be as high as fifty times that of water. Lack of information of flow behaviour is the reason for improper design of pulp lines. Before establishing any design procedure it is necessary to understand the nature of the friction loss curve for pulp suspensions at various valocities as a function of different parameters and understand the mechanism of such behaviour.

NATURE OF HEAD LOSS CURVE :

The nature of the friction loss curve for pulp suspensions has been studied systematically first by Brecht and Heller in 1950[10]. The effect of velocity, consistency, pipe diameter, pipe roughness, freeness of pulp and temperature on friction loss has been observed. The range of velocities and consistencies include 1.6 to 32.8 ft/sec. and 0–5% respectively.

Effect of Velocity :

The head loss for pulp suspensions increases with increase in velocity (Fig. 1) reaching a maxima, thereafter it decreases upto a minima. On further increase

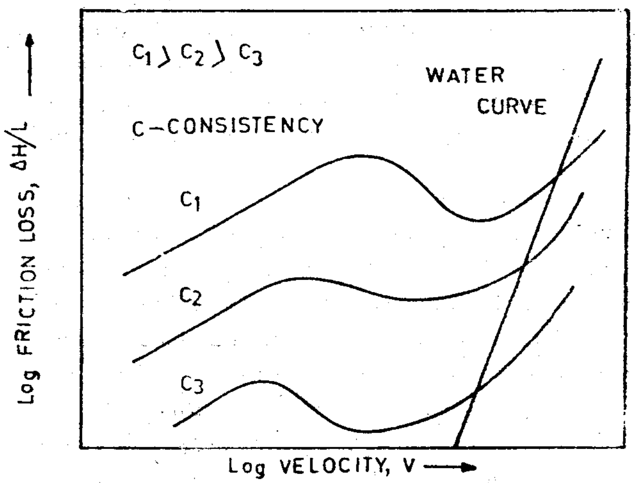

Fig. 1—TYPICAL CURVES FOR FRICTION LOSS VS VELOCITY

in velocity, the head loss increases again. At low velocities, the head loss for pulp suspensions is much higher than that for water. The point where head loss curve for pulp suspensions is lower than that for water is known as the on set of drag reduction. After the onset of drag reduction head loss in pulp lines is lower than these in water lines at same velocity.

Thus there are 3 distinct zones in the head loss eurve[11]. At low flow rates the suspension flows as a plug of fibres surrounded by water in the thin annulus adjacent to the pipe wall. At high flow rates, water fibre aggregates are in complex turbulent motion. At the intermediate flow rates there is a transition regime between plug flow and turbulent flow where a central intact plug is surrounded by a turbulent fibre–water annulus. This is termed the transition flow regime and it starts at the onset of drag reduction and extends through the region of drag reduction to the maximum level and beyond that to the point of fully developed turbulent flow. Thus it is important to identify the point of maxima, the point of minima and the point of intersection between water and pulp suspension head loss curves.

Effect of Consistency :

The head loss for pulp suspensions, at a given velocity first decreases with increase in consistency reaching a minimum and there–after it increases again (fig. 2).[12] In most of the actual applications, the consistency is in the range of 0–5% and the optimum consistency for minimum pumping energy falls in this region. Thus from the point of minimum energy for transport, there exists an optimum consistency for any pulp depending on the pipe diameter.

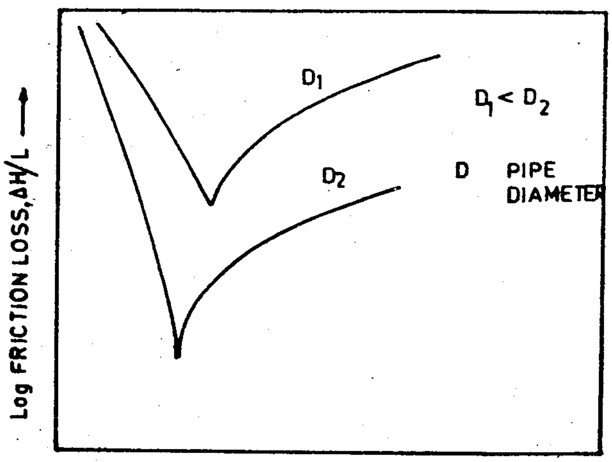

Fig. 2 TYPICAL CURVES FOR FRICTION LOSS VS CONSISTENCY

The velocity at maxima increases with increase in consistency (fig. 1).

Effect of Pipe Diameter :

The friction loss is higher for smaller pipe diameter under similar conditions of pulp flow (fig. 2).

Effect of Pipe Wall Roughness :

The effect of pipe wall roughness is shown in Fig. 3. At lower velocities the rough pipes cause marginally higher pressure drop than the smooth pipes. However the maxmiumin friction loss curve occured at much lower velocities for rough pipes. At velocities greater than that at the maximum friction losses in rough pipe fell below than in smooth pipe and remained lower upto significant higher velocities. This leads to two important conclusions.

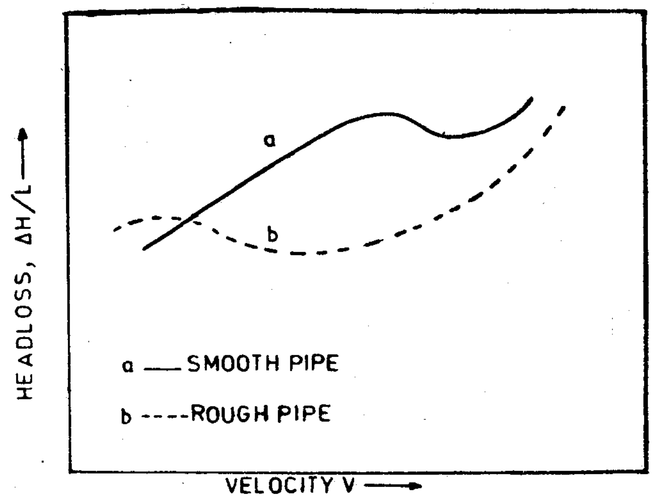

Fig 3—TYPICAL CURVES SHOWING THE EFFECT OF PIPE ROUGHNESS FOR FLOW OF SAME PULP SUSPENSION.

(i) The marked shift in the maximum to lower velocities with rough pipes can limit the use of existing design correlations in this region.

(ii) over the range of flow rates normally used in mill practice (1-10 ft/sec), it may be more economical to pump stocks in rough pipe lines.

Effect of fibre length :

In the range of investigations where data is available, pulps with a higher average fibre length show a higher friction loss. Addition of short fibred pulp to long fibred pulp reduces the velocities at maxima.

Effect of beating :

The increase in slowness of stock increases the pressure drop in the lines.

Effect of Temperature :

Temperature has an effect on the head loss due to friction for pulp suspensions. Rise in temperature results in linear decrease in friction loss. The correlations of the following type show the vatiation in head loss with temperature :

$$\triangle H' = \triangle H\,[1-E_t\,(t'-t)] \qquad (4)$$

Where E_t is the temperature Coefficient and the value ranges between 0.004 to 0.016.

Effect of Refining, bleaching, drying and reslushing :

The qua'ity of pulps have an impact on the head loss. In general unrefined pulps have a higher maxima value than refined and bleached pulps (Fig. 4). The

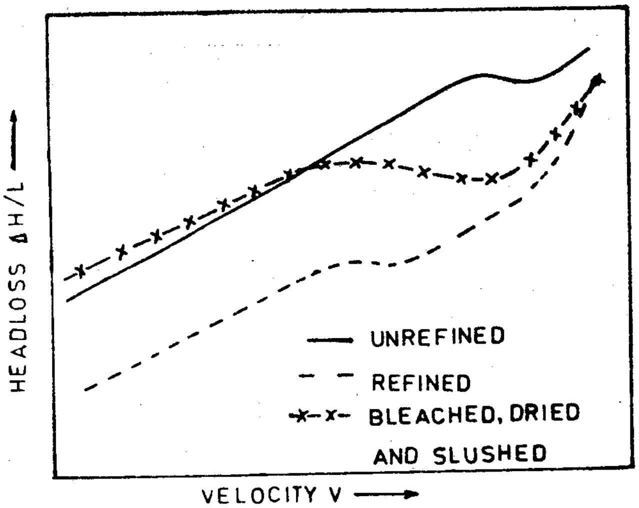

Fig. 4—TYPICAL HEADLOSS CURVES SHOWING THE EFFECT OF QUALITY OF PULP

same pulp when bleached, dried and reslushed showed lower friction drop than unrefined and refined pulps in the lower velocity regions. Even the maxima volocity is lower.

The information clearly indicates that the individual velocity limits for each pulp must be applied to the general correlations. This can be done by regular experimental data either at mill site or in laboratories.

REVIEW OF THE DESIGN CORRELATIONS :

The pulp suspension is non-newtonian in character. The flowproperties are related to modified Reynold's number (Re') defined as follows :

$$Re' = \frac{D^n V^{2-n}}{\gamma} \qquad (5)$$

The generalised viscosity Coefficient is defined as under :

$$\gamma = g_k 8^{n-1} \qquad (6)$$

Where k' is an experimentally determined constant and n is the experimentally determined degree of non-newtonian behaviour for pulp. For a 4% pulp suspension n = O.575 and γ=6.13 lbs/ft.sec. Raise[5] suggests using some friction factor as for water in low Reynolds number zone upto 2100. and it be taken as

$$f = 16/Re' \qquad (7)$$

But for Re' in the zone of 2100 to 10^5, a friction factor f is estimated as-under

$$4f = \frac{a_n}{b_n\ Re'} \qquad (8)$$

a_n and b_n are constant whose values range from 0.0643-0.078 and 0.35-0.25 for n ranging from 0.2 to 1.0.

These equations are easy to use provided n and γ are estimated correctly and a_n and b_n are known.

Duffy[13] has tabulated the available correlations and graphical data in Tappi technical information sheet No. TIS-408-2 (1978). Some of these correlations are summarised in table-1. The expressions are of the following generalised form

TABLE-1

SUMMARY OF PUBLISHED CORRELATIONS FOR FINDING FRICTION LOSS FOR PULP SUSPENSIONS

Author	K	alpha α	Beta β	Gama γ	Remarks
Riegel Eqn (14,15)	12.68	9.364	1.89	−1.33	Modified Univ of Marine Eqn (22) V=1-10 ft/sec. consistency 2-6%
Pump Industri AB (16)	5.53 $(0.61)^x$	0,15+x	2.26	−1.00	$x\ \eta / \left[\frac{D}{19.69+D}\right]$. Values vary high for large diameter pipes. No. Temperature compensation.
Bodan heimer (17)	5–4	0.15	2.80	−1.00	Multiplying factors for different types of pulps. No velocity limits. Consistency 2–18%
Itaya etal (19)	K^1	−0.36	2.90	−1.00	K^1 depends on specific volume and specific surface of pulp fibre. Equation for ground wood pulp.
Univ of Auckland (20, 21)	16.8	0.33	1.33	−1.12	Beta is on (O-0.65), Small pipes, Chemical–Mechanical pulps.
Univ of Auckland (20, 22)	11.75	0.31	1.81	−1.34	Large pipes, Kraft pulp.

Note : Equation $\frac{H}{L} = K\ V^{\alpha}\ C^{\beta}\ D^{\gamma}$

$$\frac{H}{L} = K V^{\alpha} C^{\beta} D^{\gamma} \qquad \text{........ ....(9)}$$

The values of the diameter exponent and velocity exponent vary from −1.0 to −1.34 and 0.2-0.36 respectively. The exponent on consistency varied from 1.33 to 2.90. The value of K varied from 1.52 to 16.8 and was even a function of diameter. The largest differences between the variation correlations were the values of consistency exponent γ and constant K. such data is not available for many Indian pulps

The use of these correlations must be made with care realising the range of their applicability with regards to velocity, consistency and type of pulp. The upper limits are not properly defined in many equations. Misuse of these correlations at low rates beyond the limits of original data can result in excessive over design as all these data are limited to linear portion of the curve upto maxima. Multiplication factors for different types of pulps, temperature variations or freeness variations may or may not be available.

Similarly validity of design correlations derived based on small smooth pipe lines for large conmercial pipes is questionable. The scale up has to be done carefully. Duffy and Moller[20,21] derived the following correlations for bleached kraft pulp in small and large diameter test loops.

For small diameter (50-100 mm)

$$\frac{\Delta H}{L} = 6.46\, V^{0.26} C^{1.80} D^{-1.14} \qquad (10)$$

For large Diameter (100-200 mm)

$$\frac{\Delta H}{L} = 11.75\, V^{0.31} C^{1.81} D^{-1.34} \qquad \text{..... (11)}$$

As can be observed the essential difference is the increase in magnitude of the diameter exponent for larger pipes.

Hemstrom and Co-workers[23] studied the boundary layer separation for pulp suspensions and developed mechanims of flow. The onset of plug disruption occured at a point when the shear yield strength of the fibre net work was equal to wall shear stress. An approximate relationship correlated the concentration (C%) and velocity V(m/sec) at the onset of plug disruption

$$V = 1.8\, C^{1.4} \qquad \text{..................(12)}$$

This infact corresponds to the maxima. Moller and Duffy[11] developed expression for transion regime (from plug flow to turbulent flow). This starts at onset of drag reduction and extends to fully developed turbulent flow. These expressions are of the same form as equation[21] with different constants and exponents.

Similarly expression are available for predicting optimum pulp consistency for minimum energy consumption.[12] The optimum consistency $C_d(\%)$ is related to total quantity transported T(Tonnes/day) and pipe diameter D(mm) as under,

$$C_d(\%) = 19.24(T/D^2)^{0.4167} \qquad \text{...........(13)}$$

Flow in turbulent region :

Flow resistence can be correlated in terms of friction factor defined as under (24)

$$\phi = \frac{1}{Re_t} = \frac{\lambda_\omega}{V^2} = \frac{\Delta P}{L} \cdot \frac{D}{4 V \varrho^2} \qquad \text{..............(14)}$$

Where λ_ω is the wall shear stress and Re_t is the annulus Reynold's number. The dimensionless friction factor ϕ is 1/8 of the fanning friction factor. Typical curves for friction factor versus velocity for wood pulp suspensions are shown in Fig. 5. At bulk velocities lower than A, the fibre suspension flows as coherent

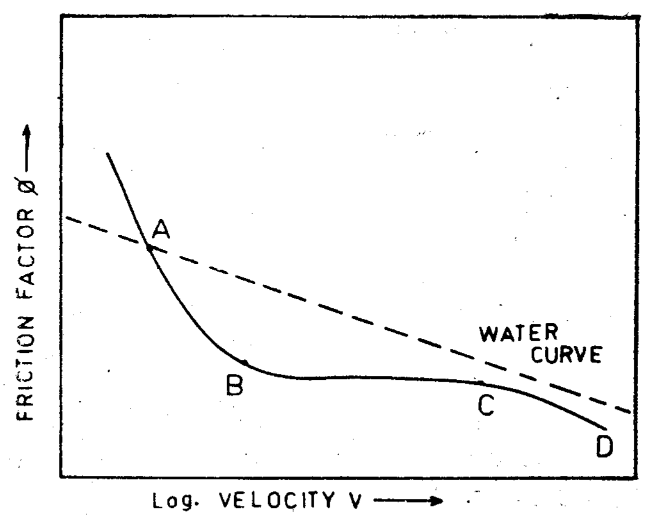

Fig. 5—TYPICAL CURVES OF FRICTION FACTOR VS VELOCITY

plug of fibres with all the shear confined to the narrow region between the plug and the pipe wall. In the regime AB, drag reduction develops to a maximum at B. At bulk velocities higher than B, drag reducing ability of the fibres decreases as bulk velocity increases. In the regime BC the values of friction factor are almost independent of bulk velocity and suspension friction curve approach the water curve. In the regime CD the friction factor decreases as bulk velocity is increased. The flow resistance is lower than that of water and the differences between the water and pulp curves increases with an increase in fibre concentration at point B, point of maximum drag reduction, the ratio of pug diameter to pipe diameter is approximately O.2.

Based on local reduced velocities and distance (dimension-less form) it is possible to get velocity profiles, in the pipe as a function of distance. The slope of such curves n, (called Von Karman Constant) can be correlated to bulk velocity, particularly in turbulent region. One such expression correlating friction factor ϕ and equivalent Reydold's number Re is as under :

$$\frac{1}{\sqrt{\phi}} = \frac{1}{m} \ln \left[R_e \sqrt{\phi} \right] + \left[14 - \frac{5.6}{m} \right] \quad \ldots\ldots (15)$$

R_e= Equivalent Reynolds number for water= $\frac{DVP}{\mu}$

Graphs are available correlating such data for predicting friction factor in turbulent region.

DESIGN PROCEDURE FOR OBTAINING PIPE FRICTION LOSS FOR SUSPENSIONS :

The most accurate source of pipe friction data are those obtained in the mill. But these are rarely available because of the experimental difficulties. Therefore for design purpose, these data are usually obtained from graphs, correlation equations and friction calculations.

But the development of design correlation is quite complicated. Most of the published design correlations have been based on data obtained in the regime of flow before maxima. Therefore at higher velocities, the predicted results are higher resulting in over design of pumping system.

First Design Procedure proposed by Duffy and Titchener[25] :

To overcome this problem, Duffy proposed a reliable procedure to cover the velocity range both before and after the head loss maxima. The head loss curve is divided into segments as shown in Fig. for a specific consistency. The design is based on the assumption that the curve ABB'C D (B'C being horizontal line) provides a satisfactory representation. It ignores the trough in the real curve, takes B' as sufficiently precise estimate of the maximum. Thereafter it takes the water curve in the region CD to be a conservative estimate.

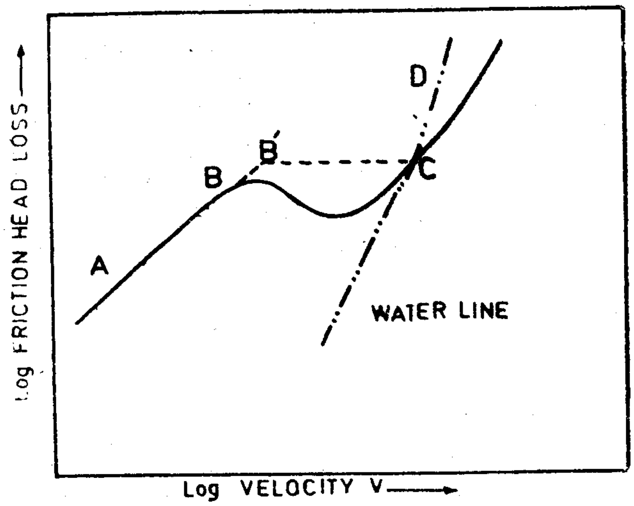

Fig. 6—FIRST DESIGN PROCEDURE BY DUFFY TITCHENER (25)

Duffy[25] showed that at different consistency the curves before maximum are alomost parallel and gave the following expression for unbleached pine kraft pulp :

$$\frac{\Delta H}{L} = 16.8 V^{0.33} (C\text{-}0.65)^{1.33} (D)^{-1.12} \quad \ldots\ldots\ldots (16)$$

$$\phi = \frac{1}{Re_t} = \frac{\lambda_w}{v^2} = \frac{\Delta P}{L} = \frac{D}{4 \varrho v^2} \quad \ldots\ldots\ldots (14)$$

STEP–I

A small test loop (20-25 feet) of say 2″ diameter pipe is required. The pipe material should be same as to be used in mill. Only two runs are required, one at the maximum consistency and one at lower consistency (say 2%.) The values of the head loss are plotted against the corresponding velocities on logarithimic co-ordinates. From this, the velocity at maxima and minima is determined. The linear portion of the curve enables the determination of the constant term K in equation (16) for the desired pulp (Assuming that the values of β & γ used in equation (16) hold good for each chemical pulp).

Now the head loss at the upper velocity limit 'B' taken as

$$\left\{\frac{\triangle H}{L}\right\}_B = A\phi_B \frac{V^2_B}{D} \quad \text{.................... (17)}$$

Therefore from the head loss at maxima, the value of $A\phi_B$ (Constant for a given pulp) is determined.

STEP–II

In this method, it is assumed that the curve ABB'CD (Fig. 6) provides a satisfactory representation of the pipe friction loss for design purpose. It ignores the trough in real curve and takes the water curve CD to be an accurate description of head loss at velocities greater than at C.

The head loss for the linear portion of the curve (AB) can be determined from the expression

$$\frac{\triangle H}{L} = KV^{0.33} (C\text{-}0.65)^{1.33} D^{-1.12} \quad \text{........(18)}$$

The values of K and α found in **Step-I** are used in this equation. The head loss at the upper velocity limit 'B' is taken as

$$\left\{\frac{\triangle H}{L}\right\}_B = (A\phi_B). \frac{V^2_B}{D} \quad \text{.................... (19)}$$

To calculate the velocity at maxima in head loss curve, one can use

$$V_B = \left[\frac{0.133K\ (C\text{-}0.65)^{1.33}}{(A\phi)_B\ D^{0.12}}\right]^{1/1.67} \quad \text{.............. (20)}$$

For velocity range B'C, assume the head loss at point B^1 as 15% higher than that at point B. Therefore,

$$\left(\frac{\triangle H}{L}\right)_{B'C} = 1.15 \text{ x Head loss Maxima in the real curve.} \quad \text{...........(21)}$$

The corresponding velocity at B^1 the pseudo maximum is equal to $1.52\ V_B$ determined earlier.

At velocities beyond C, the head loss curve may be taken as that of water and can be expressed as

$$\frac{\triangle H}{L} = 0.94 \frac{V^{1.75}}{D^{1.25}} \quad \text{.............. (22)}$$

This procedure gives a fairly conservative estimate of pressure drop, particularly in the drag reduction zone.

Second Design Procedure of Duffy and Titchener[25] :

The head loss curve EFF^1GHI is shown in Fig 7. It requires an acceptable design correlation for calculating head loss in the region before the maximum in the curve EF as in the first method detailed in section 7.1. Reliable estimates of the upper limit of the correlation F and the pseudo maximum F' on EF extended are also required. The procedure uses the correlations for the positions of the minimum in the curve C, the point at which the friction loss curve for pulp cuts across the water curve at H and the point I where the mixmum reduction in friction below the water curve occurs. Thus approximate synthesis of the portion of the curve beyond the maximum is therefore possible if small amount of additional data relating to C, H and I are available.

The minimum in the head loss curve (G) can be expressed in terms of the friction factor ϕ. The wall shear stress at G is proportional to $C^{2.9}$ and $V^{1.65}$. The following equation is available for unbleached unbeaten kraft pulp to predict the velocity at the minimum (V_{min}) is at the point G.

$$V_{min} = 1.36\, C^{1.75} \quad \text{........................ (23)}$$

The minima point is effected by pulp properties and pipe roughness.

The wall shear stress where the head loss curve crosses the water curve (i. e. at onset of drag reduction point H in the Fig. 7) has a characteristic value. The

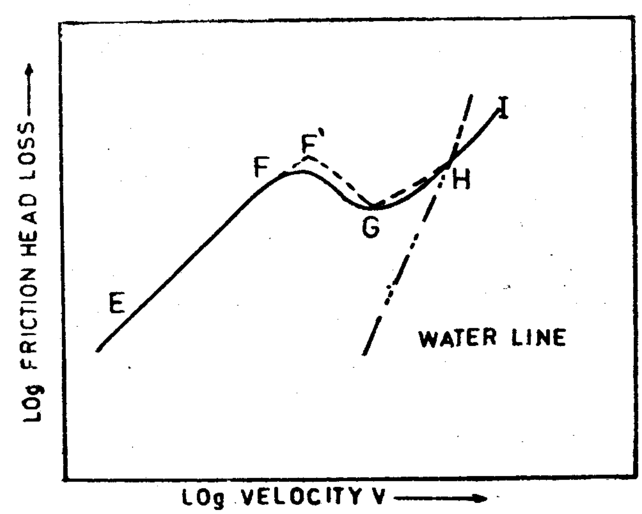

Fig. 7—SECOND DESIGN PROCEDURE BY DUFFY TITCHENER (25)

wall stress at the onset of drag reduction can be estimated as.

$$(\lambda w)_H = 7.1\times 10^{-2} C^{2.64} \quad \text{.......... (24)}$$

$$(\lambda w)_H = 5.2\times 10^{-3}\ V^{1.88} \quad \text{.......... (25)}$$

(λw in lb/ft^2, V in Fps and C is in %)

This gives a method to evaluate wall shear stress at H. The point I, where maximum drag reduction occurs, corresponds to the onset of fully developed turbulence. This represent the region of constant friction factor ϕ. This value of friction faction ϕ can be taken as 0.0011 and the c orrosponding wall shear at I is given by

$$(\lambda w)_I = 2.14\times 10^{-3}\ V^2 \quad \text{.......... (26)}$$

(λw) in lb$_f$/ft^2, V in fps)

The velocity at I, representing fully developed flow is given by

$$V = 16.7\ C-5 \quad \text{.......... (27)}$$

The maximum drag reduction is about 30% below water curve. Thus approximate position of I can be obtained by deducting an appropriate amount of friction head loss from water curve at the velocity of maximum drag reductian as given by Eq. (27).

Thus the points FGHI on curve can be located and the friction loss curve is synthesized, The accuracy will depend on predicting the region of, points G, H and I.

Design Method Proposed By Moller[26] :

This method is anologous to the well known friction factor-Reynold's Number diagram for Newtonian fluid. In this method a term $\frac{(\Delta P / L).D}{4\ \lambda_w}$ involving wall' shear stress is plotted against a term involving the mean flow velocity $\left[\frac{V^5\ \varrho^2\ \mu}{\lambda^3_w\ D}\right]^{1/6}$.

The typical curves are shown in Fig. 8.

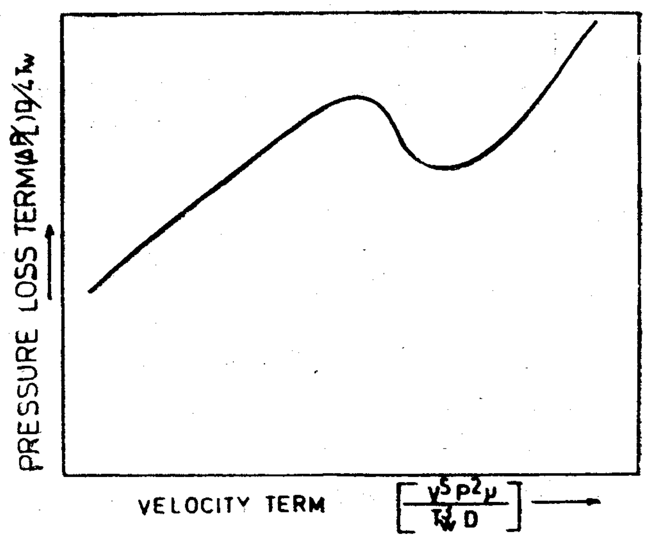

Fig. 8—DESIGN PROCEDURE BY MOLLER (1976)

The value of λ_w is as given by equation

$$\lambda_w = (\frac{P}{L})\ D \cdot\ D/4 \quad \text{.......... (28)}$$

Step I.

Determine pipe flow data in a laborato:y scale flow circuit for water and pulp desired at a consistency of 2%. The pipe should have same E/D ratio as in the mill circuit. For most practical cases the range is

$$.2 < \left[\frac{V^5 \varrho^2 \mu}{\lambda^2_w\ L}\right]^{1/6} < 1.5$$

Step II.

Using equation (28), calculate the value of w from the flow data at 2% consistency. Moller[26] has shown that the slope of straight line curve of λ w versus C on a log-log graph paper is 2 6 after a consistency of 2% for chemical pulps and 3.4 for ground wood pulps. Therefore, from the value of λ w at 2% consistency, draw a line of slope 2.6 on a log-log graph paper and curve the line slightly at lower concentrations.

Step III.

With the help of above, draw a curve between $\left[\frac{(\Delta P/L).\ D}{4\lambda_w}\right]$ and $\left[\frac{V^5\ \varrho^2\ \mu}{\lambda^3_w.\ D}\right]^{1/6}$ on the logarithimic co-ordinates (fig. 8),

Then use the curve of Fig. 8 to calculate the pipe friction loss for any concentration, temperature or velocity of the given pulp in any size of pipe.

Information is available on head losses in pipe bends and fitting. Head losses are normally proportional to the square of velocity, and increases by about 20% for every 1% increase in consistency. The pulp flow behaviour in entry flow to constriction has been reported in literature[27].

In order to get reliable designs it is necessary to generate systematically information on friction loss for Chemical TMP CTMP pulps under various combinations of fibre lengths, temperatures, consistencies.

NOMENCLATURE

a_n, b_n — Constants is Eqn. (8)
c — Pulp Consistency, %
C_d — Optimum Pulp Consistency, % for minimum energy usage
D — Pipe diameter
F — Foaming friction factor.
G — Acceleration due to gravity.
$\triangle H$ — Head loss
$\triangle H^t$ — Head loss at temprature t^1
L — Length of pipe
m — Uon Karman Constant
n — Degree of non-newtonian behaviour in Eqn. (5)
P — Pressure drop
Re — Reynold's number, $\frac{DV\varrho}{\mu}$
Re^1 — Modified Reynold's number
Re_t — Reynold's number based on annulus
T — Tonnes of pulp transported per day
t, t^1 — Temperature
V — Linear velocity
α, β, γ — Exponent in equation (9)
μ — Viscosity
γ — Generalised viscosity constant Eqn. (6)
ϱ — Density
E — Temperature coefficient of head loss in eqn. (4)
ϕ — Friction Factor (1/8 Fanning friction factor)
λ_w — Wall shear stress
ϵ — Pipe roughness.

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