OPTIMUM CONSISTENCY FOR PUMPING PULP

Project 3479

Report One
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

January 15, 1981
TO: Members of The Institute of Paper Chemistry

PROJECT 3479 -- PROGRESS REPORT ONE
OPTIMUM CONSISTENCY FOR PUMPING PULP

Enclosed is a copy of Progress Report One which summarizes research on Project 3479. This report shows that there exists an optimum consistency for pumping pulps through long pipelines, at which the frictional resistance and, hence, the electrical power needed for pumping, is at a minimum. The treatment does not include the whole pumping system nor the power required to return the white water, if any. The report provides a practical basis for savings of energy for new and existing installations for the transport of pulp by pumping over a relatively long distance.

The work is reported as progress made in Project 3479, but is, in fact, a spin-off of earlier work in the general area of high consistency processing which has been written up and processed under this project number.

Sincerely,

Douglas Wahren
Vice President-Research

DW/vas
Enclosure

1043 East South River Street
OPTIMUM CONSISTENCY FOR PUMPING PULP

Project 3479

Report One
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

January 15, 1981
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>FRICTION, CONSISTENCY, AND FLOW RATE</td>
<td>3</td>
</tr>
<tr>
<td>Using the TIS Correlation</td>
<td>5</td>
</tr>
<tr>
<td>Examples</td>
<td>7</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>12</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>13</td>
</tr>
</tbody>
</table>
ABSTRACT

For a given production rate and pipe diameter, a consistency exists for pumping pulp that minimizes power requirements.
INTRODUCTION

The purpose of this note is to show that when the production rate (i.e., the mass flow rate of fibers) is specified there exists, for every pipe diameter, a consistency at which the power required to pump the stock is a minimum. Moreover, the consistency at which this minimum occurs can easily be estimated from flow equations given in a TAPPI TIS (Technical Information Sheet) (1). Technical data for approximate optimization of long pulp transport lines are thus readily available.

The fact that an optimum consistency exists must have been realized to some extent by designers, but no analytical treatment has been published. The reason may be that common practice among researchers is to measure and calculate pressure drop or friction factor as a function of velocity or flow rate with other variables, such as consistency, as parameters. In a design situation, however, the objective is to move a certain rate of production from one point to another at minimum total factor cost. Once this question is properly stated energy enters as one important factor. The formulas given below provide sufficient, even if approximate, information on the energy factor. The information is provided in a form which is readily included into any optimization scheme. It might also be used for adaptive control of existing pipelines.

We realize that very often the consistency at which pulp is pumped through pipelines is set by the operating conditions in the mill. Thus for most applications it does not pay to change the consistency in order to minimize pumping costs, particularly if the change implies that the pulp needs to be thickened at a later stage. In mill configurations where there are long pipelines and where a thickening operation is already included in the mill for other reasons it may pay to change the consistency. Even so, a major question remains unanswered: What consistency should be chosen in order to minimize pumping costs?
FRICITION, CONSISTENCY, AND FLOW RATE

The frictional pressure drop when pumping pulps through pipes has been the subject of numerous investigations. A recent review of this subject was published by Norman et al. (2), who also reviewed the functional dependence of the pressure drop per unit of pipe length as a function of flow velocity consistency and pipe diameter. In spite of all the research efforts, the predictions are still only moderately accurate, but sufficiently so to be useful. The Fluid Mechanics Committee of TAPPI has evaluated the various correlations, and has agreed on a reasonably safe, i.e., conservative, set of correlations, which have been published as a TIS (1). The preferred correlation described in the TIS has been used for the numerical examples presented below.

The technique for finding the optimum consistency can readily be transplanted, however, to other correlations, which might be developed to yield improved accuracy, generally or for a particular pulp.

When a pulp of a particular consistency (in excess of approximately 1.5 percent) is pumped through a pipe at various velocities three fairly distinct regions can be observed. At low velocities the pressure drop is fairly high and increases with speed to a maximum or a plateau (3). As the velocity is increased appreciably beyond the maximum, plateau or inflection point, the pressure drop – velocity curve approaches and crosses over that for water. At higher velocities the pressure drop of the pulp suspension approximates but is lower than that for water. The cross-over point is termed "the onset of drag reduction." Qualitative descriptions of the associated flow mechanisms are given in (3) and elsewhere. The high pressure drop at low velocities is caused by the presence of a network of fibers, and it increases rapidly with consistency (approximately as the square of consistency).
The concentration of solids in a suspension can be expressed in many different ways: mass of solids per unit volume, g/L, numerically equal to kg/m³ being the most commonly accepted measure internationally. In the paper industry, however, the most commonly used measure is "percent by weight," i.e., one hundred times the ratio of the mass of solids to the mass of solids plus liquid. This is the measure used below. Since the correlations, and certainly the optimal consistencies to be calculated, are limited to low values, typically 2-5 percent, the density of the suspensions does not deviate significantly from the density of water, i.e., 1,000 kg/m³. This value is implicit in the formulas given.

Given a production rate, \( T \) kg fibers per second, flowing through a pipe having a diameter \( D \), the velocity \( V \) at any consistency, \( C \), is given by the formula:

\[
V = \frac{4Q}{\pi D^2 C} \left[ \frac{Kg}{m^3} \right]
\]

Clearly then, if the consistency is decreased the velocity increases and vice versa. Since at very low consistency the velocity becomes very high, the pressure drop also becomes very high. At very high consistencies, on the other hand, velocities are low, but the pressure drop increases very dramatically as noted above. There should be some intermediate consistency, where the pressure drop is at a minimum. Such a minimum does in fact exist, but of greater interest here is the power consumption. The power (Watt) required to pump the volumetric flow rate \( Q \) of stock through the pipe (excluding everything but pipe friction) is:

\[
E = \Delta P Q
\]

or in conventional units of pressure drop, i.e., loss of liquid head \( \Delta H \) per unit of pipe length \( L \):

\[
E^* = 0.163 \cdot \left( \frac{\Delta H}{L} \right) \cdot Q \text{ kW/100 m}
\]
E** = 2.52 * 10^-4 * \left( \frac{\Delta H}{L} \right) * Q \text{ BHP/100 ft} \quad (2c)

The units of \Delta H/L and Q in (2b) are (m water)/100 m and m^3/min, respectively, whereas in (2c) \Delta H/L is expressed in (ft water)/100 ft and Q in gpm (U.S.).

USING THE TIS CORRELATION

To proceed with the analysis it is necessary to use a measure of the pressure drop. This is provided here by the correlation for the low velocity range given in the TIS (1):

\[ \frac{\Delta H}{L} = F * K * V^a * C^b * D^g \]  

(3)

where \( a, b, g, \) and \( K \) are constants for a given pulp, see (1). \( F \) is a factor that accounts for temperature effects and pipe roughness. Eliminating the mean velocity from Eq. (3) with Eq. (1) yields:

\[ \frac{\Delta H}{L} = F * K * (0.4T/\pi)^a * C^{b-a} * D^{g-2} \]  

(4)

From data given in (1) \( b \) is greater than \( a \); therefore, in this flow regime the frictional pressure drop, \( \Delta H/L \), is a monotonically increasing function of \( C \).

The validity of this correlation is limited to mean velocities below \( V_m \):

\[ V_m = k_1 * C^\sigma \]  

(5)

At the onset of drag reduction, the mean velocity is correlated with consistency by the following formula:

\[ V_w = 1.22 * C_{d}^{1.4} \]  

(6)
For velocities beyond the onset of drag reduction, i.e., \( V > V_w \), the TIS recommends the Blasius formula be used. Although there may be better correlations available, we follow this recommendation. Eliminating the mean velocity, the Blasius formula can be written:

\[
\frac{\Delta H}{L} = 264 \left( \frac{0.4T}{\pi} \right)^{1.75} C^{-1.75} D^{-4.75}
\] (7)

Plainly, for velocities beyond the onset of drag reduction, the frictional pressure drop given by (7) is a monotonically decreasing function of \( C \). Thus we anticipate that the minimum frictional pressure drop occurs in the vicinity of the onset of drag reduction.

In the intermediate zone, \( V_m < V < V_w \), no adequate correlation for pressure drop exists. There are a number of methods available for interpolating the pressure drop in this range (4), but we have used the preferred method described in the TIS for plotting Fig. 3.

Eliminating \( V_w \) in Eq. (6) with the aid of Eq. (1) yields the consistency at which drag reduction occurs for a given production rate. This consistency, \( C_d \), is also to a first approximation the value at which the pressure drop is at a minimum.

\[
C_d (\%) = 0.39 \left( \frac{T}{D^2} \right)^{0.4167}
\]

(8a)

where \( T \) is expressed in kg/s and \( D \) in m. Equivalently:

\[
C_d (\%) = 19.24 \left( \frac{T}{D^2} \right)^{0.4167}
\]

(8b)

when \( T \) is expressed in (metric) t/d and \( D \) in mm. Also:

\[
C_d (\%) = 1.247 \left( \frac{T}{D^2} \right)^{0.4167}
\]

(8c)

when \( T \) is expressed in sht/d and \( D \) in inches.
The power required to pump stock of a given production rate is at a minimum at the consistency $C_d$, if one follows the recommended procedure of the TIS and assumes that the pressure drop in the region $\dot{V}_m < V < \dot{V}_w$ is given by the maximum pressure drop expressed by Eq. (4) with $V = \dot{V}_m$. Combining Eq. (1), (2b), (4) and (5) the power consumption at the minimum is found:

$$E^* = 11.35 \times 10^{-3} F K_1 \alpha C (\alpha+\beta-1) (D/25.4)^{\gamma} T \{kW/100 \text{ m}\}$$

(9a)

when $T$ is given in (metric) t/d, $D$ in mm and $C$ in percent.

Equivalently:

$$E^{**} = 4.21 \times 10^{-3} F K_1 \alpha C (\alpha+\beta-1) (D/25.4)^{\gamma} T \{\text{BHP/100 ft}\}$$

(9b)

when units are given as sht/d, inches and percent, respectively. Values for the parameters are given in the TIS (1). At points other than the minimum the TIS or other correlations can be used to find the friction loss at any given consistency and production. The power requirements are then calculated according to Eq. (2). The TIS is easily programmed for computer or calculator use, but the expressions become even more awkward than the ones above if expressed analytically.

EXAMPLES

Figure 1 is a plot of Eq. (8), showing the optimum consistency (according to parameters from the TIS) for pumping various production rates through pipes of various diameters. The "optimum" is optimum only with respect to the energy requirements for overcoming frictional resistance.
Figure 1. The optimum consistency defined by Eq. (8) plotted against the production rate for various pipe diameters.
Figure 2 is a plot of the corresponding pumping power, i.e., the minimum necessary power 100% effectively used. In real installations power is also required for overcoming resistances in valves, bends, etc., and for overcoming gravity and for accelerating and pressurizing the pulp. Moreover, in real installations pumps do not have 100% efficiency. These factors are readily taken into account by the experienced designer, and will not be covered here.

Figure 3, finally, shows two examples of the effective pumping power necessary for moving 500 (metric) t/d at various consistencies. The curves were computed from the equations given above and using the preferred method of the TIS, and data from the TIS pertaining to a long-fibered kraft pulp with a freeness of 725 mL.

It is seen that the minimum of the pumping power – consistency relationship is very sharp indeed. Studying the curves in detail, one finds, in fact, that there is a slight discontinuity at the minimum. As the minimum is passed, from left to right in the diagram, the power consumption increases in a discontinuous fashion from the minimum to a value slightly above the minimum. This is due, of course, to the approximations involved in the TIS procedure when shifting from one flow regime to another. The effect is rather small, and probably well within the general uncertainties of the method.

In any case, there exists a sharp minimum of power consumption, indicating that substantial energy savings might be realized by operating long pulp transport lines at optimum consistency.
Figure 2. The minimum effective pumping power required to overcome friction in pipes of various diameters. See Eq. (9).
Figure 3. Effective pumping power requirement to overcome friction for transporting 500 (metric) tons of pulp per day through pipes having diameters of 200 mm and 300 mm (the measurements given in inches are approximate). Pulp data from Ref. 1 as given for long-fibered, never dried kraft at 725 CSF. The parameters used were: $K = 1301; \alpha = 0.31; \beta = 1.81; \gamma = -1.34; k_1 = 0.27; \sigma = 1.5; F = 1.$
DISCUSSION

It has been shown quite rigorously that there exists a consistency at which the energy expended to move a given rate of production of pulp through a pipeline is at a minimum. The accuracy of the prediction of this minimum is no better than the empirical data available for connecting pressure drop, flow rate and consistency for various pulps in pipes of various diameters. Since the TAPPI TIS (1) is considered to be the best accepted, although conservative, estimate of such data, it has been used in the development of formulas and examples.

The existence of an "optimum consistency" from an energy requirement point of view, and the fact that this consistency can be expressed by relatively simple formulas, should be useful input for designers of long pipelines for pulp. The need for accurate control of consistency in the operation of long pipelines appears obvious. With or without the use of the formulas developed above, merely the fact that the minimum exists should make it feasible to apply adaptive control technology to the operation of long pipelines in order to minimize the energy consumption.
LITERATURE CITED


THE INSTITUTE OF PAPER CHEMISTRY

B. G. Higgins
Research Fellow
Papermaking Group
Engineering Division

Douglas Wahren
Vice President - Research