DATE: June 19, 1959

SUBJECT: Theoretical Study of Single-Transfer Line Concatenated Pulse Column Systems

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FROM: H. F. Johnson

ABSTRACT

Calculations indicate that single-transfer line concatenated pulse column systems can be operated with static pressures that are not excessive if a sufficient number of vessels are employed in the system. The required number of vessels can be attained by using a series of short columns or by using holdup pots in conjunction with a limited number of columns.

General equations for calculating pressure drops and power requirements are presented.

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1.0 SUMMARY

General equations for computing pressure drop and power requirements in a single-transfer line concatenated pulse column contacting system are presented. An arbitrary situation is selected for study, and the equations are applied to two basic arrangements: (1) simple multiple columns and (2) three columns with holdup pots. Results for arrangement (1) show that increasing the number of towers from 3 to 20 (while holding the total contacting length and pulse characteristics constant) decreases minimum static pressure required in the system from 475 to 59 psi and decreases theoretical maximum power requirement from 9.0 to 1.0 horsepower. Results for arrangements (2) show that going from 0 to 16 holdup pots decreases minimum static pressure required in the system from 534 to 24 psi and decreases theoretical maximum power requirement from 10 to 0.4 horsepower.

It is concluded that the single-transfer line concatenated column system looks promising and that an experimental investigation of this system would be worthwhile.

2.0 INTRODUCTION

Costs for hot processing plants are governed to a large extent by the volume of the shielded facilities. Shielded volume for extraction equipment can be reduced if one tall column is replaced by two or more shorter columns. The ORNL concatenated column system is a means for operating several pulse columns in series with one pulse generator. Transfer between each successive pair of columns is accomplished by two transfer lines, each equipped with a one-way check valve. Thus organic solution passes in one direction through one transfer line and aqueous solution passes in the other direction through the other line. Much difficulty has been experienced with the ORNL type column. Operation of a three-column concatenated column system in the Thorex Pilot Plant was beset with such extensive difficulties that the unit was shut down. Difficulties were attributed to air binding and/or faulty check valve operation.

Recently Swedish workers\(^3,4\) have reported development of concatenated columns employing single transfer lines between successive columns and no check valves. Each line runs from the top of one column to the bottom of the next. If the holdup volume of each transfer line is less than the displacement volume of one pulse, the organic liquid on the forward stroke will displace all of the aqueous phase in the line and some net organic transfer will be attained. On the back stroke the aqueous solution first displaces the organic solution in the line and then net aqueous phase transfer is accomplished. This type of arrange-
ment is attractive from the standpoint of extreme simplicity. It is claimed that entrained gases are carried through the system without difficulty.

It is the purpose of the present memorandum to investigate in a preliminary way pressure and power characteristics of a single-transfer line concatenated pulse column system.

General equations for computing the pressure and power requirements are first developed. Then an arbitrary situation is selected for investigation where total contacting column length and diameter are assumed and two methods for reducing pressure drop and power requirements are considered. The first method comprises increasing the number of columns but retaining the same over-all contacting length, thereby shortening the necessary transfer line lengths and allowing use of larger transfer line diameters. The second method, suggested by M. E. Whatley, involves the use of small holdup pots between a fixed number of columns. The transfer line from the top of one column connects to the bottom of a holdup pot. A line from the top of this pot is connected to the bottom of another pot or the next column. Several pots can thus be used between two successive columns. For this method to operate, an interface would have to be maintained in each pot. The effect of the pot then is to reduce the length of a single transfer line section, in much the same way as in the use of many columns. Thus larger transfer lines can be used and pressure drop decreased. It is possible that properly designed pots could act somewhat like mixer-settler units and accomplish some mass transfer themselves.

3.0 THEORY

Pressure drop and power requirements in the concatenated pulse column assembly are governed by the same principles that govern the simple pulse column as discussed by Jealous and Johnson. A significant factor in the concatenated system that does not appear in the simple column is pressure drop in transfer lines.

In the following treatment, similar to that of Jealous and Johnson, uniform velocity is assumed at any instant in the columns and in the various lines. In order to provide pulsing action, force must be applied to overcome friction effects and inertia effects. A double-acting pulse generator is considered acting on a closed, single-transfer line system, as shown in Fig. 1a. Pressure difference is computed across the pulse generator; and after this is done, it may be determined what minimum static pressure is necessary in the system to prevent cavitation. In the double-acting pulse generator, static pressure has no net effect on the generator, and hence brings about no power requirement effect.
Fig. 1 Various Arrangements of Single Transfer Line Concatenated Pulse Columns
In the single-transfer line system, in order to accomplish net flow of the light or organic phase in one direction and of the heavy or aqueous phase in the other direction, the total volume of each transfer line section must be less than the displacement volume of one pulse stroke. It is seen then that if shorter transfer line sections are used, larger diameter lines may be employed, resulting in drastic reduction in friction loss in the lines since the latter is approximately inversely proportional to the fourth power of diameter.

Figs. 1b and 1c show two schemes by which transfer line sections may be shortened while retaining the same total effective column height; the first method comprises going to more but shorter columns, and the second the insertion of holdup pots. A general theoretical treatment which applies to either method of operation is developed below in terms of the number of transfer line sections employed.

For each case, all columns are assumed the same size. Total effective contacting length is \( L_1 \) and cross-sectional area of each column is \( S_1 \). The length of each of \( T \) transfer line sections is \( L_2 \) and the cross-sectional area is \( S_2 \). A transfer line section is defined as one continuous line with no change in cross-section. For example, in Fig. 1a there are 2 sections, in 1b there are 5 sections, and in 1c there are 6 sections. The length and cross-sectional area for the aqueous side of the pulse generator are \( L_3 \) and \( S_3 \), respectively, and for the organic side \( L_4 \) and \( S_4 \). Subscripts used on diameter \( D \) correspond to those of \( L \) and \( S \). Density of the aqueous and organic phase are \( \rho_{aq} \) and \( \rho_{org} \), respectively. Effective density in regions where two phases are present simultaneously is \( \rho_{av} \); this density is used for liquid in the columns and in the transfer lines. Pressure drop at any instant across the pulse generator is \( \Delta P \). \( y \) represents the vertical distance of a particle of fluid in one of the columns above some arbitrary reference plane. \( n \) denotes the total number of perforated plates or screens in all of the columns and \( \gamma \) is the fractional free cross-sectional area of the screens. \( t \) is time.

Pressure drop due to inertia in the main column is \( \left( \frac{\rho_{aq} L_1}{g_c} \right) \left( \frac{d^2y}{dt^2} \right) \) and in a transfer line section, \( \left( \frac{S_2}{S_1} \right) \left( \frac{\rho_{aq} L_2}{g_c} \right) \left( \frac{d^2y}{dt^2} \right) \). The sum of all the inertia effects is given by:

\[
(\Delta P)_{\text{inertia}} = \frac{1}{g_c} \left( \rho_{av} L_1 + T \rho_{av} L_2 \frac{S_1}{S_2} + \rho_{aq} L_3 \frac{S_1}{S_3} + \rho_{org} L_4 \frac{S_1}{S_4} \frac{d^2y}{dt^2} \right) \tag{1}
\]

Pressure drop due to friction effects occurs across the perforated plates, in various lines, and in contraction and expansion effects. The friction effect from flow through the plates is based on the orifice type of relation as used by Jealous and Johnson,

\[
\frac{n(1 - \gamma^2)}{0.72 g_c \gamma^2} \frac{\rho_{av}}{\left( \frac{dy}{dt} \right)} \left( \frac{\left( \frac{dy}{dt} \right)}{\left( \frac{dy}{dt} \right)} \right).
\]
The absolute value of one derivative is indicated so that the sign of \( \Delta P \) will denote direction. Friction effects from flow in constant cross-section conduits is computed from the Fanning relation, \( P = (fL p v^2)/(2g_c D) \) where \( f \) is "friction factor." Contraction loss for flow from a very large chamber through a sudden contraction into a small cross-section conduit is approximated by \( (p v^2)/4g_c \) and expansion loss for flow from a small cross-section conduit through a sudden enlargement into a very large chamber by \( (p v^2)/2g_c \). The total friction loss, then, for getting a fluid into a small conduit and out of it by means of abrupt transitions in cross-section is \( (3 p v^2)/4g_c \). The enlargement-contraction effects can be reduced by designing all transitions with rounded, smooth contours. It will be assumed here that such design is employed and that friction effect is reduced thereby by a factor of 4. Thus the pressure drop due to friction of entrance and exit of fluid to and from a conduit will be taken as \( (3 p v^2)/16 g_c \). The total pressure drop for all appreciable friction drops is given by

\[
(\Delta P)_{\text{friction}} = \frac{1}{g_c} \left[ \frac{n(1 - \gamma^2)}{0.72} \rho_{av} v^2 + \frac{f_{2L2} \rho_{av} (S_1)}{2 D_2} + \frac{f_{3L3} \rho_{aq} (S_1)}{2 D_3} \right] \left( \frac{dy}{dt} \right) \left| \frac{dy}{dt} \right|
\]

The total pressure drop across the pulse generator at any instant is the sum of equations (1) and (2). Theoretical power requirement at the pulser is obtained by multiplying pressure drop by volumetric rate of flow, or

\[
\text{Power} = (\Delta P) S_1 \frac{dy}{dt}
\]

The sign here indicates the direction of energy flow. Positive power means the pulser is putting energy into the system and vice versa.

In the single-transfer line concatenated system each transfer line must have a holdup volume less than the displacement volume of one pulse in order to accomplish net transfer of the two phases. The maximum transfer line cross-section that can be used, then, is

\[
S_2 = \frac{2h S_1}{L_2}
\]

where \( h \) is amplitude in the columns, or one-half of the total displacement distance. In practice \( S_2 \) will have to be smaller than the value from equation (4) in order to attain net flow. In typical pulse column operation the volumetric flow rate of one stream does not exceed 10-15% of the volumetric displacement rate of the pulse. \( S_2 \) thus would not have to be less than the value from equation (4) by more than 15%.

The relations developed thus far apply for any type of pulse action. Most mechanical pulse generators produce pulses which approximate a sine-wave form. For this type of pulse

\[
y = h \sin \theta
\]
where \( \theta \) is displacement angle and is taken as having a value of zero at the midpoint of the upstroke of a pulse. \( \theta \) is related to frequency by

\[
\theta = 2\pi \omega t.
\]

From the above two equations it is seen that

\[
\frac{dv}{dt} = h(2\pi \omega) \cos \theta
\]

and

\[
\frac{d^2v}{dt^2} = -h(2\pi \omega)^2 \sin \theta
\]

Use of equations (5) and (6) with (1) and (2) gives

\[
(\Delta P)_{\text{Total}} = A(-\sin \theta) + B(\cos \theta)(\cos \theta)
\]

where

\[
A = \frac{1}{g_c} \left( \rho_a L + T \rho_a L^2 \frac{S_1}{S_2} + \rho_a L_3 \frac{S_1}{S_3} + \rho_{\text{org}} L_4 \frac{S_1}{S_4} \right) h(2\pi \omega)^2
\]

and

\[
B = \frac{1}{g_c} \left[ \frac{n(1-\gamma^2) \rho_a}{0.72 \gamma^2} + T \frac{f_2 L_2}{2 D_2} \rho_a \left( \frac{S_1}{S_2} \right)^2 + \frac{f_3 L_3}{2 D_3} \rho_a \left( \frac{S_1}{S_3} \right)^2 + \frac{f_4 L_4}{2 D_4} \rho_{\text{org}} \left( \frac{S_1}{S_4} \right)^2 \right] h^2(2\pi \omega)^2
\]

The above development applies to a double-acting pulse generator connected to the two extreme terminals of the multicolumn system as shown in Fig. la. If a single-acting pulse generator is used, it would be connected in the same manner as the left-hand pulse line of Fig. la. The column system would then be pressurized at the top of the last column. In order to prevent cavitation a static pressure equal to or greater than the maximum \( \Delta P \) across the pulser would have to be maintained. Thus the single-acting pulse scheme would require approximately twice the static pressure of the double-acting scheme. This static pressure would act on the single-acting pulse generator and thus an additional power consideration would be associated with such a pulser. Over a complete cycle, no additional net power would be required because that which is used on the forward stroke would be recovered on the back stroke. However, since pulse generators normally do not employ energy reservoirs (such as fly-wheels) the generator would have to be capable of supplying the peak power requirement of the cycle. Addition of this requirement due to static pressure to that for inertia and friction effects would roughly double the peak power requirement of the single-acting pulser over the double-acting one.
4.0 CALCULATIONS FOR MULTIPLE COLUMN SYSTEM

The effect of varying the number of towers in a single-transfer line concatenated pulse column battery is calculated below. A system employing the same column capacity as the three-tower system that was used in the pilot plant is studied. As the number of towers is changed, the total length is held constant. The length of each transfer line is taken as the height of one column plus two feet. Transfer line size is taken as the maximum limiting case equation (4). The number of columns \( C = T + 1 \). The following conditions are used in the calculations:

\[
\begin{align*}
\text{L}_1 &= 52 \text{ ft} \\
\text{L}_2 &= (\frac{\text{L}_1}{C} + 2) \text{ ft} \\
\text{L}_3 &= 4 \text{ ft} \\
\text{L}_4 &= \text{L}_2 \\
h &= 0.0416 \text{ ft}(1/2 \text{ in.}) \\
\rho_{aq} &= 62.4 \text{ lb/cu ft} \\
\text{Re}_2 &= \frac{398}{D_2^2} \\
f_2 &= f(\text{Re}_2) \\
f_3 &= 0.027 \\
f_4 &= 0.030 \\
S_1 &= 0.1389 \text{ sq ft} \\
S_2 &= \frac{2(0.0416)(0.1389)}{\text{L}_2} = 0.01157 \text{ sq ft} \\
S_3 &= 0.0218 \text{ sq ft} \\
S_4 &= 0.0218 \text{ sq ft} \\
\omega &= 1 \text{ cycle/sec} \\
\rho_{org} &= 50 \text{ lb/cu ft} \\
D_1 &= 0.420 \text{ ft} (5.047 \text{ in.}) \\
D_2 &= \frac{4}{\pi} S_2 \\
D_3 &= 0.1667 \text{ ft} (2 \text{ in.}) \\
D_4 &= 0.1667 \text{ ft} (2 \text{ in.}) \\
\gamma &= 0.230 \\
n &= 315 \\
\rho_{av} &= 58 \text{ lb/cu ft} \\
\end{align*}
\]

Transfer line Reynolds number \( \text{Re}_2 \) is based on maximum velocity in the cycle and an assumed viscosity of 10 centipoises. Friction factor plot of Brown is used to obtain \( f_2 \).

Use of equations (7b) and (7c) leads to the values for \( A \) and \( B \) tabulated in Table 1 for 3, 6, 10, 15, 20, and 30-column systems.

Figure 2 depicts \( \Delta p \) as a function of displacement angle for 3, 10, and 20-column systems. \( (\Delta p)_{\text{Inertia}}, (\Delta p)_{\text{Friction}}, \) and \( (\Delta p)_{\text{Total}} \) are shown. It can be seen that for the 3-column system, friction effect dominates but as the number of columns increases, this effect drops rapidly and becomes of the same magnitude as the inertia effect. Figure 3 shows the total \( \Delta p \) curves for all the cases of Table 1. Maximum \( \Delta p \)'s as determined from \( (\Delta p)_{\text{Total}} \) plots of Figure 3, are tabulated in Table 1. Since operation of the system with negative absolute pressures is impossible, the whole system must be pressurized. The optimum point for pressurization would
be one located midway with respect to $\Delta P$ in the system. Thus the minimum static pressure that could be used with the double-acting pulser would be one-half the maximum total $\Delta P$. Actually minimum pressure in the system must be greater than the vapor pressure of the fluid being handled in order to prevent cavitation. Such vapor pressure would usually be small relative to the total pressure of the present calculations; hence zero is taken as the permissible lower limit on absolute pressure in the system. In Table 1 and in Fig. 6 minimum allowable static pressure vs number of columns is shown. It is seen that not much further reduction in minimum static pressure is obtained by going to more than 20 columns. For the present example, the effective height of one such column would be $52/20 = 2.6$ feet.

5.0  CALCULATIONS FOR SYSTEM WITH HOLDUP POTS

The effect of using a varying number of holdup pots with the basic 3-column system of the previous calculation is considered below. Again transfer line size is taken as maximum according to equation (4). Let $P$ be the number of total pots. Then for the three-column system, $T = P + 2$. Values for the parameters here are:

- $L_1 = 52$ ft
- $L_2 = \frac{40 + P}{T} = \frac{40 + P}{P + 2} \text{ ft}$
- $L_3 = 4 \text{ ft}$
- $L_4 = 18 \text{ ft}$
- $h = 0.0416 \text{ ft (1/2 in.)}$
- $\rho_{eq} = 62.4 \text{ lb/cu ft}$
- $Re_2 = \frac{398}{D_2}$
- $S_1 = 0.1389 \text{ sq ft}$

<table>
<thead>
<tr>
<th>Number of Columns</th>
<th>Maximum $\Delta P$ (Psi)</th>
<th>Minimum Required Static Pressure (Psi)</th>
<th>Maximum Theoretical Power (HP)</th>
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<tbody>
<tr>
<td>C</td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
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<td>118</td>
</tr>
<tr>
<td>30</td>
<td>102</td>
<td>95.5</td>
<td>108</td>
</tr>
</tbody>
</table>
Fig 2 Pressure Drop Across Pulse Generator in Multiple-Column Single-Transfer Line Concatenated Column System
Fig. 3 Total Pressure Drop Across Pulse Generator in Multiple-Column Single-Transfer Line Concatenated Column System
\[ S_2 = \frac{0.01157}{L_2} \text{ sq ft} \]
\[ S_3 = 0.0218 \text{ sq ft} \]
\[ S_4 = 0.0218 \text{ sq ft} \]
\[ \omega = 1 \text{ cycle/sec} \]
\[ \rho_{\text{org}} = 50 \text{ lb/cu ft} \]
\[ f_2 = F(\text{Re}_2) \]
\[ D_1 = 0.420 \text{ ft} \ (5.047 \text{ in.}) \]

\[ D_2 = \sqrt{\frac{h}{\pi}} \]
\[ D_3 = 0.1667 \text{ ft} \ (2 \text{ in.}) \]
\[ D_4 = 0.1667 \text{ ft} \ (2 \text{ in.}) \]
\[ \gamma = 0.230 \]  
\[ n = 315 \]
\[ \rho_{\text{ev}} = 58 \text{ lb/cu ft} \]
\[ f_3 = 0.027 \]
\[ f_4 = 0.030 \]

\( L_2 \) is based on 20 feet for no holdup pots plus one foot for each pot; the no holdup pot case here is not quite in agreement with the limiting case of \( L_2 \) for the previous calculation because when \( C = 3 \), \( L_2 = 19.33 \text{ feet} \). Thus there will be a slight discrepancy in \( \Delta P \)'s for the two base cases. Use of equations (7b) and (7c) leads to the values of \( A \) and \( B \) tabulated in Table 2 for 0, 2, 4, 8, 16, 24, and 36 pots.

<table>
<thead>
<tr>
<th>Number of Holdup Pots</th>
<th>Maximum ( \Delta P )</th>
<th>Minimum Required Static Pressure</th>
<th>Maximum Theoretical Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P )</td>
<td>( A )</td>
<td>( B )</td>
<td>( \text{Psi} )</td>
</tr>
<tr>
<td>0</td>
<td>202</td>
<td>1067</td>
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</table>

Figure 4 shows \( \Delta P \) as a function of displacement angle for 0, 2, and 16 holdup pots. \( (\Delta P)_{\text{Inertia}} \), \( (\Delta P)_{\text{Friction}} \), and \( (\Delta P)_{\text{Total}} \) are shown. It can be seen that again for the basic three-column system (no holdup pots) friction effect dominates; but as the number of holdup pots increases, this effect drops rapidly and becomes of the same magnitude as the inertia effect. Figure 5 shows the total \( \Delta P \) curves for all of the cases of Table 2. Maximum \( \Delta P \)'s as determined from the \( (\Delta P)_{\text{Total}} \) plots of Fig. 5 are tabulated.
Fig. 4 Pressure Drop Across Pulse Generator in Three-Column Single Transfer Line Concatenated Column System With Holdup Pots
FIG. 5 TOTAL PRESSURE DROP ACROSS PULSE GENERATOR IN THREE COLUMN SINGLE-TRANSFER LINE CONCATENATED COLUMN SYSTEM WITH HOLDUP POTS
Fig. 6. Effect of number of towers and holdup pots on minimum static pressure required.
in Table 2. The minimum required static pressures (one-half the maximum ΔP's) are also tabulated in Table 2 and plotted in Figure 6.

It is seen that not much further reduction in minimum static pressure requirement is obtained by increasing the number of holdup pots beyond 20.

On comparing the effect of multiple towers on static pressure with that of holdup pots by means of Fig. 6, use of holdup pots appears to have some advantage in that a lower static pressure can be used for the limiting case (i.e., a large number of holdup pots compared to a large number of towers). This difference is due to geometry rather than to any inherent characteristics of the systems. For a given number of vessels, shorter transfer lines can probably be used for holdup pot systems than for multiple column system. Such an assumption was made for the calculations.

6.0 POWER CALCULATIONS

Data for (ΔP)Total depicted in Figs. 3 and 5 have also been used with equation (3) to compute theoretical power requirements, and the results are shown in Figs. 7 and 8. It will be seen that theoretical power fluctuates widely over one cycle. The pulse generator must be designed to supply power for the maximum requirement in the cycle. In some cases, negative power is indicated. This means that for such portions of a cycle, the inertia effect actually is more than sufficient to overcome friction and can supply energy to the pulser. In other words, flow of energy is out of the system rather than into it as is the case when the pulser is driving. The theoretical maximum power requirements as taken from Figs. 7 and 8 are plotted in Fig. 9 and tabulated in Tables 1 and 2. It is seen that power requirement drops off rapidly with increase in number of towers or with increase in number of holdup pots much in the way that maximum ΔP behaves.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Application of the single-transfer line concatenated column system appears feasible if a sufficient number of vessels are employed to allow use of adequate size transfer lines such that pressure drops will not be prohibitive. Limiting pressure drop in this manner reduces the maximum pressure for which the system must be designed and reduces the theoretical power requirement for the pulse generator.

The number of vessels required can be attained by using short columns in series, or by using a limited number of columns combined with smaller holdup vessels. For the case where 52 feet of 5-inch diameter contacting column is desired, the use of 20 columns would require design for a theoretical maximum pressure of about 120 psi and a theoretical pulse power requirement of 1 horsepower. The use of three columns together with 20 holdup pots would require design for 44 psi maximum pressure and about 0.4 theoretical pulse horsepower. The static pressure that would have
Fig 7. Theoretical Power Requirements for Pulse Generator in Multiple Column Single-Transfer Line Concatenated Column System
FIG. 8 THEORETICAL POWER REQUIREMENTS FOR PULSE GENERATOR IN THREE COLUMN SINGLE-TRANSFER CONCATENATED COLUMN SYSTEM WITH HOLDUP POTS.
Fig. 9 Effect of number of towers and number of holdup pots on maximum theoretical power requirements.
to be provided the systems in the two cases above would be about 60 and 22 psi, respectively.

Calculated results of this study will be on the optimistic side since only limiting conditions were investigated. No allowance was made in sizing transfer lines for net transfer of liquids. In practice, these cross-sections would have to be some 10% lower than those used herein. Resulting pressures and power requirements would then run correspondingly higher.

It is recommended that experimental studies of single-transfer line concatenated column systems be undertaken. The major items of question are:

1. Design of holdup pots. Entrance and exit transitions must be smooth. Sufficient holdup must be provided such that some phase separation is obtained or an interface is maintained. The upper line must connect vertically to the uppermost point of the pot such that entrained gas will be carried out.

2. Transport of entrained gases through system. This would appear to be primarily a question of linear velocity through the transfer lines. The lowest linear velocities (maximum velocity in a cycle) for the cases studied here are about 6 ft/sec. These range up to 80 ft/sec for systems with few vessels.

3. Pressurization System. Static pressure on the system can be maintained by tying in a tank partly filled with continuous phase to the system by means of a line sufficiently long and small in diameter to dampen out column pressure fluctuation. Air pressure would be maintained in the tank at the desired pressure level. The pressurization system should be tied into the mid-point (with respect to pressure drop) of the column system in order to allow use of minimum static pressure.

4. Pressure drop in transitions between transfer lines and vessels. Design should minimize these losses by utilizing smooth transitions. Calculations have assumed pressure drop of one-fourth those for abrupt transitions; this assumption should be experimentally verified or modified.

5. Double-acting pulse generator. This type of pulser offers advantages in operation with lower permissible static pressure and lower pulse power requirement, and its development appears worthwhile.
8.0 NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units in Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Number of columns in system</td>
<td>--</td>
</tr>
<tr>
<td>D</td>
<td>Inside diameter</td>
<td>ft</td>
</tr>
<tr>
<td>f</td>
<td>Friction factor</td>
<td>--</td>
</tr>
<tr>
<td>$g_c$</td>
<td>Conversion factor</td>
<td>lb mass-ft/lb force-sq sec</td>
</tr>
<tr>
<td>h</td>
<td>Pulse amplitude in column, one-half total displacement distance</td>
<td>ft</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>ft</td>
</tr>
<tr>
<td>P</td>
<td>Number of holdup pots in system</td>
<td>--</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Pressure difference across pulser</td>
<td>lb force/sq ft</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pressure difference across pulser</td>
<td>lb force/sq in.</td>
</tr>
<tr>
<td>S</td>
<td>Cross-sectional area</td>
<td>sq ft</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>sec</td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
<td>ft/sec</td>
</tr>
<tr>
<td>T</td>
<td>Number of transfer lines in system</td>
<td>--</td>
</tr>
<tr>
<td>$y$</td>
<td>Linear displacement of liquid in column due to pulsing action</td>
<td>ft</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Angular displacement</td>
<td>degrees $(^\circ)$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>lb mass/cu ft</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Frequency of pulse generation</td>
<td>cycles/sec</td>
</tr>
</tbody>
</table>

Subscripts

1. Refers to main contacting column or columns
2. Refers to transfer lines
3. Refers to aqueous side of double-acting pulser
4. Refers to organic side of double-acting pulser
aq. Refers to aqueous phase
org. Refers to organic phase
av. Refers to average value of property in region where two phases are present
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