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ANALYSIS OF AIR PULSER PERFORMANCE
FOR PULSED EXTRACTION COLUMNS

J. D. Kaser

February 1971

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Chemistry and Metallurgy Division

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ANALYSIS OF AIR PULSER PERFORMANCE FOR PULSED EXTRACTION COLUMNS

J. D. Kaser

INTRODUCTION

The goal of this work was to predict the pulse amplitude in 3A and 3B columns from information on column design, column liquid properties, pulser frequency, and pulser air supply pressure. The 3A column is the extraction column and the 3B column is the stripping column to be used in the third plutonium solvent extraction cycle of Hanford Purex plant. The approach taken was to develop an analytical expression for pulse amplitude and to compare amplitudes predicted by this expression with amplitudes predicted by other methods and with experimentally measured amplitudes.

V. L. Hammond⁽¹⁾ calculated pulse amplitudes by assuming that the air pressure exerted on the liquid in the pulse was a square-wave function of time and by solving the resulting hydraulic differential equation by analog computer. He further developed a simplified expression which agreed well with his analog solution when an arbitrary adjustment was made in the time constant used in the simplified expression. He did not report any experimental data for comparison.

M. E. Weech and B. E. Knight⁽²⁾ analyzed pulser performance. Using few simplifying assumptions, they derived four nonlinear differential equations whose solutions required a fairly involved numerical method performed by digital computer. However, no experimental pulse amplitude data was given to check calculations. In consequence, a review of previous work revealed the need for a simpler, but reasonably accurate

expression for calculating pulse amplitude, and also the need for experimentally checking the calculations.

SUMMARY

An expression was derived for determining the pulse amplitude in air pulsed columns as a function of reservoir air pressure and pulse frequency. Amplitudes calculated by this expression and by V. L. Hammond's simplified equation compare favorably with experimentally measured amplitudes and with amplitudes calculated by a lengthy numerical procedure. Plots of amplitude versus reservoir air pressure were calculated at several pulse frequencies for two-pulse column designs.

EXPERIMENTAL WORK

Column 1 in EDL-102 was used for obtaining experimentally measured amplitudes for checking the accuracy of amplitudes calculated from the derived equations. The general layout of the column and associated pulser system is shown in Figure 1. Air pressure is regulated by a two-mode controller and pressure fluctuations are minimized by the capacitance of the air reservoir. Air is admitted to and from the pulse leg through the three-way solenoid valve. The liquid in the pulse leg oscillates about a mean height, X , above the pulse leg connection while the liquid level in the column is maintained at a height, H , by the organic take-off weir. A small purge of either fresh organic or aqueous solvent may be admitted to the pulse to reduce contamination and fouling.

In order to test the two methods for calculating pulse amplitude, pulse amplitudes were measured with the column both completely filled and partly filled with water. The change in water levels effectively changed the number of plates and the

FIGURE 1. Air Pulsed Extraction Column

length of the pulser leg and column. There was no net flow of water through the column during the experiments. Pulse amplitudes for the column were calculated from the measured amplitude in the pulse leg and the ratio of the cross-sectional areas of pulse leg and column. The pulse leg amplitude was taken to be the difference between the maximum and minimum levels of liquid in the pulse leg as measured with a ruler during steady operation of the pulser.

During measurement, the pulse frequency was held constant at 40, 65, and 90 cycles/min. The pulse frequency is the number of times per minute that air is admitted to the pulse leg or alternatively, the number of times per minute that air is exhausted from the pulse leg.

Reservoir air pressure was measured by a Bourdon gage. Descriptive data for the column are listed in Table 1, while experimentally observed amplitudes are given in Table 2.

TABLE 1. Description of EDL-102 Column 1

Column Height, ft	23.5
Pulse Leg Inside Diameter, ft	0.0833
Column Inside Diameter, ft	0.250
Density of Water in Column, lb/ft ³	62.4
Viscosity of Water, lb/ft-sec	6.72×10^{-4}
Column Plates,	70
57 with 23% free area	
10 with 37% free area	
3 with 25% free area	
Average Free Area, %	24
Equivalent Length of Bends and Horizontal Runs in Pulse Leg, ft	2.0

TABLE 2. Experimentally Measured Pulse Amplitude

Column Partially Filled with Water

Effective Column Height: 15 ft-2 in.

Effective Number of Plates: 45

<u>Frequency, cycles/min</u>	<u>Air Reservoir Pressure, psig</u>	<u>Column Pulse Amplitude, in.</u>
40	0.5	0.083
40	0.75	0.19
40	1.75	0.89
40	4.5	2.39
65	0.75	0.17
65	3.0	0.56
65	3.75	0.73
65	7.0	1.72
90	2.75	0.19
90	6.0	0.56
90	8.75	1.20
90	10.5	1.50

Column Completely Filled with Water

Column Height: 23.5 ft

Number of Plates: 70

<u>Frequency, Cycles/min</u>	<u>Air Reservoir Pressure, psig</u>	<u>Column Pulse Amplitude, in.</u>
40	1.0	0.25
40	1.75	0.45
40	3.0	0.75
40	4.5	1.44
65	4.5	0.44
65	5.75	0.67
65	7.25	0.89
65	9.0	1.14
90	4.25	0.47
90	7.0	0.78
90	8.25	0.92
90	11.0	1.22

DEVELOPMENT OF EQUATION FOR PREDICTING PULSE AMPLITUDE

The starting point for the development of the pulse amplitude equation is the differential equation for liquid flow as stated by Weech and Knight.⁽²⁾

$$\left[\frac{\rho_m H}{g_c} \left(\frac{A_L}{A_c} \right) + \frac{\rho_L X}{g_c} \right] \frac{d^2 X}{dt^2} + \left[\rho_m \left(\frac{A_L}{A_o} \right)^2 \frac{N}{2g_c C^2} + \frac{2f\rho_L (X_e + X)}{g_c D_L} \right] \left(\frac{dX}{dt} \right)^2 + \frac{g}{g_c} (\rho_L X + \rho_m H) = P_t \quad (1)$$

Equation 1 was linearized by making the following assumptions:

1. That X could be considered constant at its mean value during pulsing;
2. That $\left(\frac{dX}{dt} \right)^2 \approx \left(\frac{dX}{dt} \right)_{\max} \left(\frac{dX}{dt} \right)$ where $\left(\frac{dX}{dt} \right)_{\max}$ = the maximum value of liquid velocity in the pulse leg; and
3. That f , the friction factor, is a function of the average speed of the liquid in the pulse leg taken to be twice the product of the amplitude and frequency.

The expression used to calculate the friction factor is:

$$F = 0.0014 + 0.125 \left(\frac{\mu_L}{D_L^{0.32} 2\omega a_L \rho_L} \right)^{0.32} \quad (2)$$

The air pressure above the liquid in the pulse leg is assumed to be a sinusoidal function of time fluctuating at the pulse frequency between a maximum value equal to the air reservoir pressure and a minimum pressure of zero:

$$P_t = \frac{1}{2} P_r \sin 2\pi\omega t + \frac{1}{2} P_r \quad (3)$$

A further simplification was made that the mean difference in liquid head between the column and pulse leg is equal to the mean air pressure in the pulse leg.

$$\rho_m H - \rho_L X = \frac{1}{2} P_r \quad (4)$$

Linearization of Equation 1 and elimination of P_t and X by use of Equation 4 results in the following second order linear differential equation:

$$\frac{d^2 X}{dt^2} + A_1 \frac{dX}{dt} = B \sin kt$$

$$\text{where, } A_1 = \frac{\left[\rho_m \left(\frac{A_L}{A_O} \right)^2 \frac{N}{2g_c C^2} + \frac{2f\rho_L \left(X_e + \frac{\rho_m H - \frac{1}{2}P_r}{\rho_L} \right)}{g_c D_L} \right] V_{\max}}{\frac{\rho_m H}{g_c} \left(\frac{A_L}{A_c} + 1 \right) - \frac{P_r}{2g_c}}$$

$$B = \frac{-\frac{1}{2}P_r}{\frac{\rho_m H}{g_c} \left(\frac{A_L}{A_c} + 1 \right) - \frac{P_r}{2g_c}}$$

$$\text{and } K = 2\pi\omega \quad (5)$$

The following initial conditions were assumed:

$$\frac{d^2 X}{dt^2} = 0$$

$$\frac{dX}{dt} = 0$$

By use of Laplace transforms, the following solution to Equation 5 is obtained:

$$X = X_o + \frac{B}{A_1 K} + \frac{Bk}{A_1(A_1^2 + k^2)} e^{-A_1 t} - \frac{A_1 B}{k(A_1^2 + k^2)} \cos kt - \frac{B}{A_1^2 + k^2} \sin kt. \quad (6)$$

The maximum and minimum velocities and displacements are found by successive differentiation of Equation 6 and by setting the appropriate derivatives equal to zero. The maximum velocity in the pulse leg is:

$$\left(\frac{dX}{dt}\right)_{\max} = \frac{B}{(A_1^2 + k^2)^{1/2}} = V_{\max} \quad (7)$$

The maximum displacement is:

$$X_{\max} = X_0 + \frac{B}{A_1 k} + \frac{B}{k(A_1^2 + k^2)^{1/2}} \quad (8)$$

and the minimum displacement is:

$$X_{\min} = X_0 + \frac{B}{A_1 k} - \frac{B}{k(A_1^2 + k^2)^{1/2}} \quad (9)$$

The pulse amplitude in the pulse leg is the difference between $X_{\max}$ and $X_{\min}$:

$$a_L = \frac{2B}{k(A^2 V_{\max}^2 + k^2)} \quad (10)$$

By comparing Equations 7 and 10, it can be seen that:

$$a_L = \frac{2 V_{\max}}{k} \quad (11)$$

By substituting Equation 11 for $V_{\max}$ in Equation 10 and solving the resulting quadratic equation for a_L , the amplitude, we arrive at the expression for pulse amplitude in the pulse leg:

$$a_L = \frac{2}{Ak} \sqrt{\frac{-k^2 + \sqrt{k^4 + 4A^2 B^2}}{2}} \quad (12)$$

where $A = A_1/V_{\max}$.

Multiplication of Equation 12 by the ratio of pulse leg cross-sectional area to column cross-sectional area and converting from feet to inches, we obtain the final working equation for calculating pulse amplitude in the column:

$$a_c = \frac{24}{AK} \left(\frac{D_L}{D_c} \right)^2 \sqrt{\frac{-k^2 + \sqrt{k^4 + 4A^2B^2}}{2}} \quad (13)$$

METHOD OF CALCULATION

The use of Equation 13 involves a straightforward substitution of numerical values for the quantities indicated. However, two peculiarities of Equation 13 should be explained:

First, an iterative solution for the amplitude is required since the pulse amplitude affects the value of the friction factor f , as shown in Equation 2, which in turn affects the value of A in Equation 13. Therefore, a first guess of the amplitude must be made to obtain a value of f , then the resulting amplitude calculated from Equation 13 is used to calculate an improved value for f and the process is repeated. Satisfactory convergence is usually obtained in two or three iterations.

The second peculiarity involving the evaluation of the term $\frac{A_L}{A_o}$ in Equations 1 and 5 arises from the fact that pulse columns may contain several kinds of plates with different hole areas. Since N is the total number of plates, a properly averaged hole area, A_o , must be used. The resistance of the various kinds of plates is additive. Noting that $A_o = eA_c$, we can write:

$$\left(\frac{A_L}{A_o} \right)^2 N = \left(\frac{A_L}{A_c} \right)^2 \frac{N}{e^2} = \left(\frac{A_L}{A_c} \right)^2 \left(\frac{N_1}{e_1^2} + \frac{N_2}{e_2^2} + \dots \right) \quad (14)$$

Therefore, the average fractional hole is:

$$e^2 = \frac{N}{\frac{N1}{e_1^2} + \frac{N2}{e_2^2} + \dots} \quad (15)$$

where e is the average fractional hole area for all plates in the column.

To save time, the curves used in this report were calculated from Equation 13 by digital computer using a BASIC language program listed in Appendix II. BASIC language is a conversational system used with time-sharing teletype terminals provided by Computer Science Corporation.

V. L. Hammond's⁽¹⁾ simplified expression for pulse amplitude, using the nomenclature of the present report is:

$$a_L = -\frac{1}{A} \ln \left\{ 1 - \left[\frac{-1 + \exp\left(\frac{1}{2\omega} \sqrt{-AB}\right)}{1 + \exp\left(\frac{1}{2\omega} \sqrt{-AB}\right)} \right] \right\} \quad (16)$$

This equation includes Hammond's assumption that the amplitude is twice the displacement occurring during the first one-fourth cycle time when the liquid moves upward in the pulse leg from its level of maximum depression.

RESULTS AND DISCUSSIONS

To gain confidence in the accuracy of Equation 13 and 16, calculated pulse amplitudes were compared with measured amplitudes (given in Table 2) for an EDL-102 column filled with water to heights of 15 ft 2 in. and 23 ft and 6 in. The comparisons for the column filled to a height of 15 ft 2 in. are shown in Figure 2 and the comparisons for the column completely filled with water to a height of 23 ft 6 in. are shown in Figure 3. Equation 13 agrees better with the experimental

FIGURE 2. Comparison of Calculated and Experimentally Measured Amplitude for Column Partially Filled with Water

FIGURE 3. Comparison of Calculated and Experimentally Measured Amplitude for Column Completely Filled with Water

data at the higher frequencies of 65 and 90 cycles/min, where the assumption of a sinusoidal variation of air pressure in the pulse leg appears to be more reasonable than the assumption of a square wave air pressure variation. However, at the lowest frequency of 40 cycles/min, Equation 16, which assumes a square wave air pressure function, agrees better with the experimental data.

It may be concluded that either Equations 13 and 16 can be used for rough estimates, while for more accurate predictions Equation 16 should be used for frequencies below about 50 cycles/min and Equation 13 should be used for frequencies higher than 50 cycles/min.

Another test of Equation 13 was made by comparing calculated pulse amplitudes versus pressure curves for the column described in Reference 2 with the curves calculated by Weech and Knight. Again, agreement appears to be satisfactory as shown in Figure 4.

Finally, amplitude-pressure curves were calculated for 3A and 3B Columns and are given in Figures 5 and 6, respectively. These curves can be used to determine the reservoir air pressure required.

The values of the variables used for these columns are listed in Table 3.

FIGURE 4. Comparison of Equation 13 with Numerical Method of Weech and Knight

FIGURE 5. Pulse Amplitude Curves for 3A Column
Calculated from Equation 13

FIGURE 6. Pulse Amplitude Curves for 3B Column
Calculated from Equation 13

TABLE 3. Description of 3A and 3B Columns

	<u>3A Column</u>	<u>3B Column</u>
Column Height, ft	33	25.7
Column Diameter, ft	00.2957	0.2957
Pulse Leg Diameter, ft	0.0874	0.0874
Liquid Density in Pulse Leg, lb mass/ft ³	50.5 53.7	62.4 61.2
Average Liquid Density in Column, lb mass/ft ³		
Equivalent Length of Fittings, Bends, and Horizontal Pipe in Pulse Leg, ft	15.75	11.9
Viscosity of Pulse Leg Liquid, lb mass/ft-sec	0.000941	0.000672
Total Number of Plates	159	122
Average Fractional Hole Area in Plates	0.224	0.229
Orifice Coefficient	0.75	0.75

REFERENCES

1. V. L. Hammond. Hydraulic Characteristics of Air-Pulsed Solvent Extraction Columns, HW-70489. Available from National Technical Information Service, Springfield, Virginia. January 1962.
2. M. E. Weech and B. E. Knight. "Design of Air Pulsers for Pulse Column Application," I&EC Process Design and Development, vol. 6, no. 4, pp. 480-486. 1967.

APPENDICES

NOMENCLATURE

BASIC LANGUAGE PROGRAM FOR EQUATION 13

APPENDIX I
NOMENCLATURE

<u>Symbol in Report</u>	<u>Symbol in Computer Program</u>	<u>Definition</u>
A	A	$A_1/V_{\max}$, ft^{-1}
A_1		Defined by Equation 5, sec^{-1}
A_c		Cross-sectional area of pulse column, ft^2
A_o		Hole area in column plate, ft^2
A_L		Cross-sectional area of pulse leg, ft^2
a_c	J	Pulse amplitude in column, in.
a_L		Pulse amplitude in pulse leg, ft
B	B	Defined by Equation 5
C	C	Orifice coefficient
D_c	D2	Column diameter, ft
D_L	D1	Pulse leg diameter, ft
e	F1	Fractional hole area in column plate
f	F	Friction factor defined by Equation 2
g	G	Gravitational acceleration, ft/sec^2
g_c	G	Dimensional conversion factor, $32.2 \text{ lb mass}/\text{lb force}\cdot\text{sec}^2$
H	H	Height of liquid in column above pulse leg inlet, ft
k	K	$2\pi\omega$, sec^{-1}
N	N	Number of column plates
Pr	P	Pressure in air reservoir, $\text{lb force}/\text{ft}^2$
Pt		Air pressure in pulse leg, $\text{lb force}/\text{ft}^2$
t		Time, sec
X		Height of liquid in pulse leg above inlet to column, ft
X_e	X	Equivalent length of fittings, bends, and horizontal pipe in pulse leg, ft

<u>Symbol in Report</u>	<u>Symbol in Computer Program</u>	<u>Definition</u>
μ_L	M	Viscosity of liquid in pulse leg, lb mass/ft sec
ρ_m	R2	Average density of liquid in column, lb mass/ft ³
ρ_L	R1	Density of pulse leg liquid, lb mass/ft ³
ω	W	Pulse frequency, sec ⁻¹

APPENDIX II

BASIC LANGUAGE PROGRAM FOR EQUATION 13

```

100 : C=##.### G=##.### F1=##.### H=##.## D1=##.### D2=##.### D1=##.##
101 : R2=##.## X=##.## M=##.####!!!! W=##.### Z=##.###!!!! N=####
110 : P(##)=####.## J(##)=#.###
115 DIM P(50), J(50)
120 OUTPUT "READY FOR DATA"
130 INPUT C,G,F1,H,D1,D2,R1,R2,X,M,E,N
140 OUTPUT
150 OUTPUT
160 OUTPUT
170 OUTPUT "ENTER W,P AND Q1"
180 INPUT W,P,Q1
195 OUTPUT "ENTER FIRST GUESS FOR J"
200 INPUT J2
210 FOR Q=1 TO Q1
220 Y=(R2*H/G)*((D1/D2)^(2+1))-P/(2*G)
235 IF Y<=0 GO TO 420
240 R=C.5*P/Y
250 K=2*&PI*W
260 FOR I=1 TO 100
270 J1=J2
280 F=C.0014+C.125*((12*M*D1)/(D2^(2*R1*2*(W*J1)))^(.32)
290 U=R2*M*(D1/D2)^(4/(2*G*(F1*C)^(2)
300 V=2*R1*F*(X+R2*H/R1-G*P/(2*G*R1))/(G*D1)
310 A=(U+V)/Y
320 J2=(24*(D1/D2)^(2/(A*K)))*(((K^(4+(2*A*B)^(2)^(.5-K^(2)/2)^(.5)
330 Z=ABS(J2-J1)
340 IF Z<E GO TO 380
350 NEXT I
360 PRINT "CONVERGENCE NO GOOD ERROR=",Z
370 J(Q)=J2
380 P(Q)=P
400 P=P+144
410 NEXT Q
420 OUTPUT USING 100,C,G,F1,H,D1,D2,R1
422 OUTPUT USING 101,R2,X,M,W,Z,N
425 FOR Q=1 TO Q1
430 OUTPUT USING 110,Q,P(Q),Q,J(Q)
440 NEXT Q
450 GO TO 140

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