1PULSE TRANSMISSION TO A PULSE COLUMN

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ABSTRACT

In the counter-current liquid-liquid extractor of Van Dijck (U.S. 2,011,186) pulses of fluid originate in a pulse pump and pass through a transmission line to the column. The minimum pressure developed in this line by the momentum of the pulsing fluid is

$$P \text{ min.} = \frac{-2\pi^2 k l \rho \omega^2}{A g}$$

where k is the displacement of the pulse pump, l is the length of the transmission line, ω is the pulse frequency, A is the cross-sectional area of the pulse transmission line, and g is the acceleration of gravity. The equation is derived from fundamental consideration and shown to work in practice.

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Liquid-liquid extraction columns have an inherent difficulty. The driving force that moves the solutions past each other is the difference in density of the two phases, and this difference is too small to provide the turbulence and good mixing needed for efficient operation. Energy must be put into the column to get the mixing needed. One way to do this is by the pulse column of Van Dijck (1). Here energy is put in by pulsing the solutions up and down through sieve plates (Figure 1). Such columns are much more efficient than packed columns or unpowered sieve plate columns. They use much less space and head room than packed columns and have much less holdup. In the work of the Atomic Energy Commission, these are very important considerations. Space and headroom in heavily shielded areas are fantastically expensive. High holdups mean high radiation levels. So for atomic energy work, powered extractors are a necessity. The pulse column is particularly attractive in that it is the only power extractor that has no moving parts in the extraction zone. The pulse pump can be on one side of the shielding and the column on the other, provided the cold phase is pulsed.

This leads to certain complications. First, it would be desirable to set the pulse pump at the same height as the liquid in the column, so that if the pump should spring a bad leak, it would not empty the column into the clean zone. This means a long pipe from the pulse pump through the shielding to the column. The liquid in this pipe has momentum, and if it is pulsed too hard, it just won't hold together. Cavitation will occur. The purpose of this paper is to analyze the motion of the liquid in this pipe and see what pipe is needed to transmit a given pulse.

The problem is one of forces due to acceleration, so Newton's first law is used:

$$F = ma = \frac{Wa}{g}$$

F = force

m = mass

a = acceleration

W = weight

g = acceleration of gravity

The acceleration "a" and the weight, "W", can be determined. The acceleration of gravity, "g", is known, so "F", the force, can be computed, divided by "A", the area, to get "P", the pressure. If the sum of this pressure and the hydrostatic head is negative, or even less than the vapor pressure of the solution, cavitation will occur.

Acceleration is the second derivative of space with respect to time. So let us define "s" as the distance a particle travels (in one direction) in the pipe. Then:

$$Y = \frac{s}{2} \sin 2\pi\omega t \quad (\text{Fig. 2})$$

Y = space coordinate of particle

s = "stroke" of particle

ω = cycles per unit time

t = time

FIG. 1

PULSE COLUMN

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FIG 2 SINE WAVE AND CIRCULAR MOTION

$$\frac{dY}{dt} = v = \pi s \omega \cos 2\pi \omega t$$

$$\frac{d^2 Y}{dt^2} = a = -2\pi^2 s \omega^2 \sin 2\pi \omega t$$

The expression for the acceleration "a" can be substituted into Newton's first law, thus:

$$F = \frac{-2\pi^2}{g} W s \omega^2 \sin 2\pi \omega t$$

Now this force is a minimum when $\sin 2\pi \omega t$ is 1, or:

$$F_{\min} = \frac{-2\pi^2}{g} W s \omega^2$$

This formula is exactly the formula for centripetal force. The formula for centrifugal force is usually written as:

$$F = \frac{W}{g} \frac{u^2}{r}$$

where u = peripheral velocity

r = radius

In terms of revolutions per minute, " ω ", and a diameter, " s ", the equation becomes:

$$F = \frac{2}{s} \frac{W}{g} (\pi s \omega)^2$$

$$F = \frac{2\pi^2}{g} W s \omega^2$$

This is the acceleration formula, with " s ", the diameter taking the place of " r ", the stroke of the particle. The sine wave motion of the particle is the projection on the axis of the pipe of the motion of a point traveling in a circle of diameter " s " (Fig. 2). Hence the components of velocity and acceleration along the pipe are the same in the two cases, and when the centrifugal force points along the pipe it is the same as the pulse force. When the centrifugal force points in a different direction, its component along the pipe axis is the sine function:

$$F = \frac{-2\pi^2}{g} W s \omega^2 \sin 2\pi \omega t$$

So whether the basis is Newton's first law or the centrifugal force formula, the same equation is obtained.

This equation is correct, but not convenient. It is in terms of quantities we cannot measure or use, such as force. We want quantities we can easily measure, such as pressure. Pressures are obtained by dividing force by "A" the area, to get "P", the force per unit area. The weight of fluid in the pipe, cannot be measured directly, so the substitution is made:

$$W = \rho A l \text{ where}$$

l = length of the pipe

A = cross-sectional area

ρ = density of fluid

The stroke "s" of the particle cannot be measured directly. The displacement, "k", of the pulse pump and the cross section, "A", of the pipe can be measured so:

$$s = \frac{k}{A}$$

There is more to these substitutions than just a change to variables that can be measured. The quantity, "W", in our previous formula strictly speaking is the weight of a particle, "dW", of stroke "s". The work done on the particle is strictly sdW and the total work is proportional to

$$\int s dW.$$

In taking

$$\rho k l = s W$$

it is assumed that

$$\int s dW = s W.$$

This is certainly true if "s", the stroke of a particle, is the same for all particles. This is very nearly true in practice. If the fluid in the pipe is considered as made up to a series of rods or concentric shells, of the same length and density, the force on the end of each rod is PA, and the mass

$\frac{l A \rho}{g}$, so the acceleration of each rod or shell is

$$\frac{F}{m} = a = \frac{PA}{\frac{l A \rho}{g}} = \frac{Pg}{l \rho}$$

In other words, the acceleration of each element of volume is the same and hence, "s", the stroke of each element is the same. This is a plug flow arising because the frictional forces (here neglected) are so small compared to the inertial forces. Making the substitutions

$$p = \frac{-2\pi^2 k \rho l \omega^2 \sin 2\pi \omega t}{Ag}$$

$$p_{\min} = \frac{-2\pi^2 k \rho l \omega^2}{Ag}$$

This formula is developed for the case of a single pipe and a sine wave. If the system consists of several elements in series, the pressures add, thus

$$P_{\min} = \sum P_i \min = \sum \frac{-2\pi^2 k \rho l \omega^2}{A_i g}$$

$$= \frac{-2\pi^2 k \rho \omega^2}{g} \sum \frac{1}{A_i}$$

If the system is not a sine wave but is the type of wave resulting from a crank and connecting rod motion, a correction term is needed thus

$$P_{\min} = \sum \frac{-2\pi^2 k \rho \omega^2}{g} \sum_i \frac{1}{A_i} \left[1 + \frac{R}{L} \right]$$

where R = radius of crank

L = length of connecting rod.

(2)

The deviation of this equation is in a paper by Jealous and Johnson.

At the minimum pressures, flows are zero, hence for computing minimum pressures, friction may be neglected. The relation between acceleration pressures and frictional pressures is given in Fig. 3. The frictional pressures were computed by the method of Jealous and Johnson.(2) The sum of the acceleration pressure plus frictional pressure is the measured pressure and is shown in Fig. 4.

To test this formulation of the problem, the pulse transmission line of a pulse column (Fig. 5) was fitted with pressure transducer. The wave forms recorded were similar to Fig. 3, though an unidentified ripple was superimposed on the basic wave. The basic dimensions of the system were

Density $\rho = 52.3 \text{ lbs. ft.}^{-3}$

Pulse volume $k = 0.281 \text{ ft.}^3$

$$\sum \frac{1}{A} = 32.3 \text{ ft.}^{-1}$$

$$g = 32.2 \text{ ft. sec.}^{-2}$$

$$\frac{R}{L} = 0.091$$

Hence

$$P_{\min} = 317 \omega^2 \text{ lbs. ft.}^{-2} \text{ sec.}^2$$

And for example, at 1 cycle/sec.

$$P_{\min} = -317 \text{ lbs. ft.}^{-2}$$

$$= 2.2 \text{ lbs. in.}$$

The agreement between theory and practice is shown in Fig. 6. Here the observed minimum pressures are plotted against the pressures calculated and excellent agreement is obtained.

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FIGURE 3
PRESSURES IN PULSE COLUMN

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FIGURE 4
 ΔP IN PULSE COLUMN

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FIGURE 5

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FIGURE 6
MINIMUM PRESSURE

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REFERENCES

1. Van Dijck, W. J. D., U.S. Patent 2,011,186, August 13, 1935.
2. Jealous, A. C. and Johnson, H. F., Ind. Eng. Chem. 47, No. 6, June, 1955, pp. 1159-1166.

See also

Williams, J. A. and Little, D. J., Trans. Instu. Chem. Engrs. 32, pp. 174-180, 1954. (Note that while the equations in that article are correct, Fig. 2 b and Fig. 2 c are in error, as they show friction porportional to V instead of V^2 .)