Pulsation from Positive Displacement Pumps

The acceleration forces created when moving a column of paste in a pipeline

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ABSTRACT

Paste backfill reticulation systems are often designed around steady state friction losses and pressure effects from elevation changes. Most positive displacement pumps do not operate at steady state. The pressure pulse, which results from each pump stroke, is a combination of acceleration forces and friction losses. This paper investigates the magnitude of the acceleration forces, explores the circumstances where these forces could become a fatal design flaw, and possible alternatives which reduce or remove the pulses.

INTRODUCTION

Gravity flow requires no electricity, it does not require maintenance, and it never breaks down, but it is limited by elevation difference. When reticulation distance becomes too great as compared to the elevation difference, or when friction losses become large, pumping is required to convey backfill from the paste plant to the mining stope. The high efficiency and high pressure capabilities of positive displacement pumps make them the preferred choice for pumping paste backfill.

The hydraulically driven piston pump is the industry standard, and has been successfully used to reticulate paste at mines around the world. As paste becomes more prevalent, there are a higher number of reticulation systems being designed with high pressure pumps to push thick paste through the reticulation system.

Some reticulation systems do not achieve the capabilities specified by the design. Peak energy requirements during the pressure pulse of the piston pump is sometimes to blame.

PUMPING CHARACTERISTICS OF PISTON PUMPS

Each piston of a paste pump has a suction stroke, where paste is drawn into the cylinder, a pause for valves to change position, then a pressure stroke to push the paste into the reticulation system. This is followed by another pause for valves to change positions, then the cycle begins again. Generally, two cylinders are installed and they are configured to be out of phase with each other such that each cylinder discharges while the opposite cylinder is filling.

Piston speed and mechanical time for valve switching varies by pump size, model, and manufacturer. Typically, stroke speeds of 8 to 10 strokes per minute are targeted for paste reticulation. Cylinder ramp up times are roughly 0.5 seconds and time required to change valve positions vary from 0.3 to 0.5 seconds depending on valve type. Larger s-tube style valves require the longest time to switch and offer the least flexibility in valve timing adjustment. Figure 1 below shows piston speed for a typical dual piston pump. Both pistons are driven in opposite directions with a pause at each end of the piston stroke before the piston changes direction. The pause is necessary to allow time for valves to switch positions.

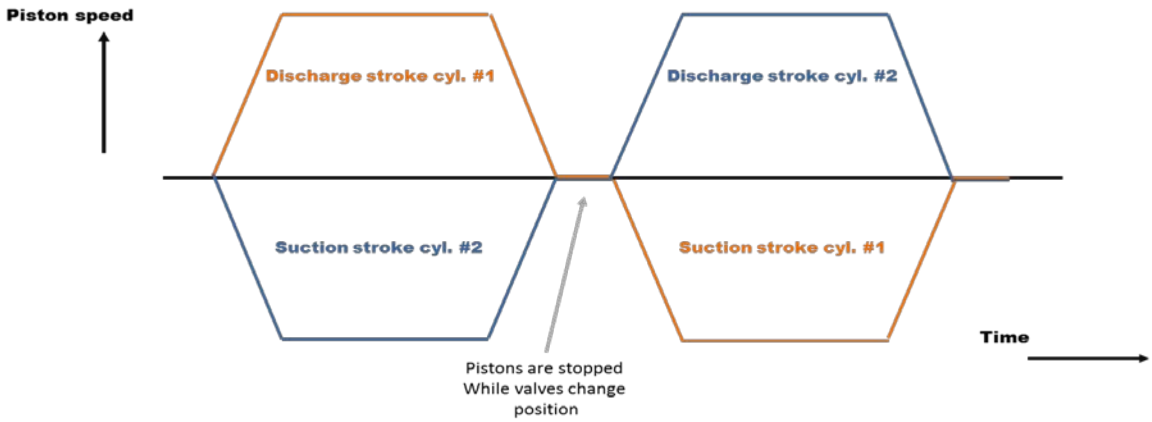

Figure 1. Piston speed of typical dual cylinder piston pump with both cylinders symmetrically opposed

At the start of each stroke, an acceleration occurs. Pump manufacturers extend the time it takes to achieve maximum piston speed in order to minimize acceleration forces and pressure spikes. This acceleration time is programmed into the PLC and generally does not change as a function of pump speed.

PUMPING PRESSURE

The pressure seen at the start of any pump system is determined by the following equation:

Pressure from friction + Pressure from elevation + Pressure from acceleration = Pump pressure

Most engineering firms simplify this equation by only looking at steady state flow where velocity is constant and pressures from acceleration are equal to zero. This method works well for gravity flow systems and for pumps that produce constant flow velocities, but as discussed earlier, the flow characteristics of a piston pump do not produce constant flow.

In order to quantify the acceleration forces, a 1000m horizontal pipeline was modeled. Acceleration times, flow rates, and pipe diameter were varied to determine the force and pressure required to accelerate the column of paste. Figure 2 presents the results using a constant acceleration time of 0.5 seconds to achieve steady state velocity.

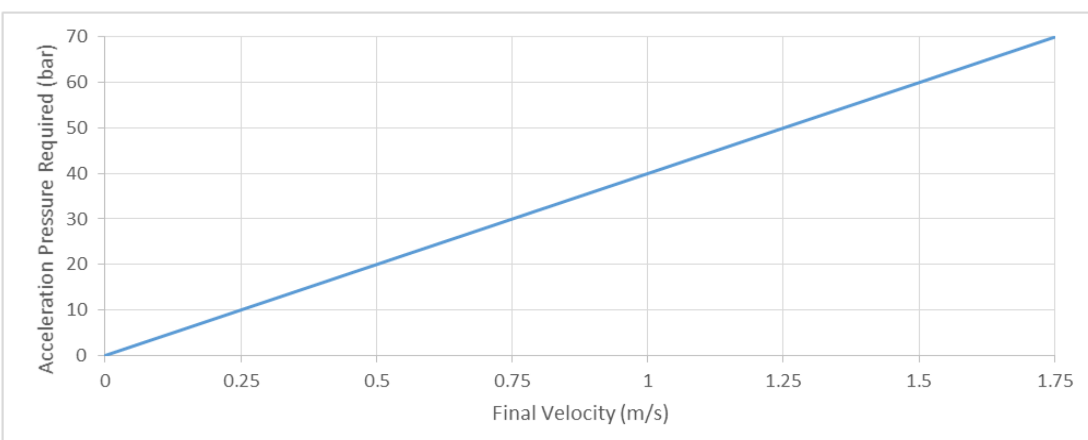

Figure 2. Pressure required to accelerate a 1000m column of paste as a function of final velocity

The model used a specific gravity of 2 for the paste fluid, assumes a non-compressible fluid and calculates only the acceleration forces; friction and gravitational forces are ignored. The pressure required to accelerate the paste column is directly proportional to the final paste velocity and inversely proportional to the time allowed for acceleration. Modeling revealed that the acceleration pressures are not proportional to pipe diameter. The results displayed in Figure 2 are valid for all pipe sizes.

When the acceleration pressure is combined with pressures created by friction losses, the pumping pressure profile looks similar to the idealized version in Figure 3 below.

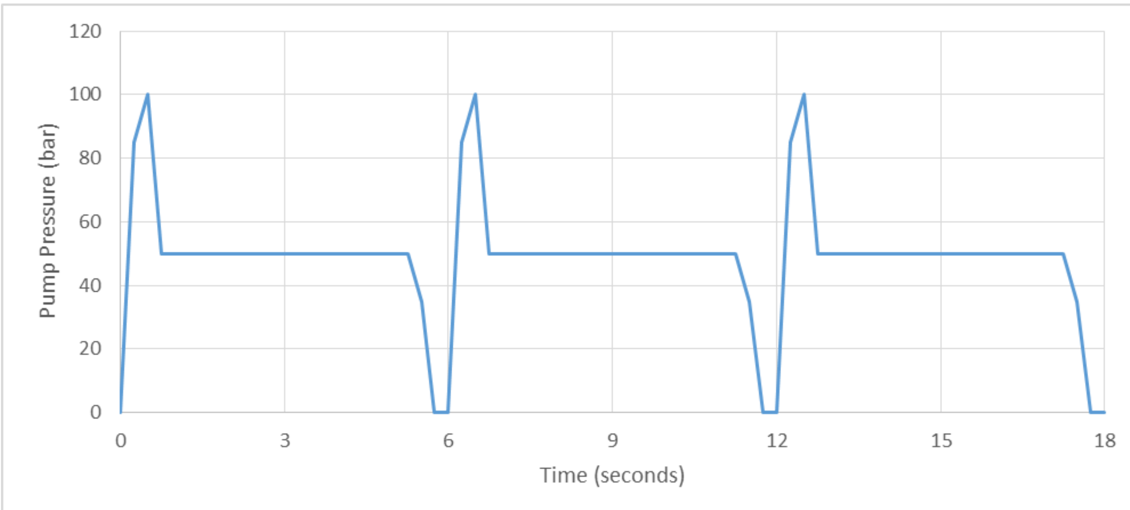

Figure 3. Pressure pulse create with typical hydraulic piston pump

The pressure spike is created by the increase in friction losses combined with the constant pressure required to accelerate the paste column. The steady pressure is observed once the pump piston has reached its steady state speed and no acceleration forces are observed.

The figure above uses the pumping characteristics from Figure 1 combined with 50 bar of pressure during acceleration and a friction loss of 5kPa/m at peak velocity. The figure shows that the peak pressure occurs at the end of acceleration when friction losses build to their peak.

EFFECT OF CAVITATION

In an ideal world, acceleration of the paste column occurs over the same time period as the piston and is set by the manufacturer (typically 0.5 seconds). In reality, some degree of cavitation occurs on the suction stroke and additionally some amount of air enters the system.

Cavitation is often associated with high speed pumps, but it can occur anywhere vacuum occurs. These large piston pumps move slowly in comparison, but the high viscosity and sometimes low suction head pressure available combine to create vacuum in the paste cylinder during the suction stroke. Manufacturers target a cylinder fill efficiency between 90 and 95%, meaning 5 to 10% of the cylinder is filled with something other than paste from the feed hopper. Some of this space is the void created by cavitation.

Cavitation is of particular importance when considering acceleration forces. The cavitation void created during the suction stroke can only exist under vacuum. When the discharge stroke occurs, the initial movement of the piston collapses the cavitation void. When the piston is accelerating and collapsing cavitation void, it is not accelerating the column of paste. Therefore, acceleration time used to collapse cavitation void reduces the acceleration time allocated for acceleration of the paste column.

If we consider an average stroke speed of ten strokes per minute, a complete piston stroke occurs over a period of six seconds. The stroke can be further broken down as follows:

0.5 sec acceleration + 4.5 sec at peak speed + 0.5 sec deceleration + 0.5 sec for valves = 6 sec stroke

Acceleration accounts for 1/12 of the stroke time and roughly 1/24, or roughly 4%, of the stroke volume. Since the stroke volume associated with acceleration is small, any amount of cavitation becomes significant. A cavitation void which occupies 2% of the cylinder volume will reduce the time to accelerate the paste column by 50% and potentially double the force required to accelerate the paste.

AIR IN THE SYSTEM

Air is generally avoided in backfill reticulation systems as it can cause several negative consequences in pipe flow. Air entrainment from the mixing process or from inadequate level control on the pump feed hopper can result in air entering the system. This section discusses the effect that air has on acceleration forces.

Entrained air in the reticulation system acts as a spring or series of springs. It changes the non-compressible paste backfill to a mixture which contains a compressible gas (air). As the discharge stroke occurs, the air is compressed and kinetic energy of the moving paste is stored as potential energy in the compressed air. Later in the stroke, the potential energy is transferred back to the paste into movement. This energy storage within the air partially decouples the pump hydraulics from the paste column and extends the time it takes for the paste column to accelerate/decelerate and lowers the peak acceleration forces. Air pressure being released during piston deceleration can prevent the paste column from coming to a complete stop.

The strategy of using air on the discharge of a pump to dampen pulsations is well known. Air dampeners are common on household plumping systems and industrial pumping applications. They are not commonly used on backfill applications as the cement contained within the backfill causes fouling and failure of the dampener.

FREEFALLS AND THEIR EFFECT

Freefall can occur in a reticulation system when gravity forces pulling in the direction of flow are larger than the frictional forces resisting flow in the opposite direction. The imbalanced force causes that portion of the paste column to accelerate and a gap occurs, generally at the top of a borehole. A column in the borehole will stabilize where the gravitational forces are balanced with the frictional forces. The remainder of the borehole will be partially filled with paste traveling at higher velocities, and pressures in this section are likely to be in vacuum. Due to the flow characteristics in this portion of the flow, it is commonly referred to as freefall or slack flow. Freefalls cause several undesirable consequences in the reticulation system. High velocities occurring in the freefall zone cause accelerated wear in the borehole. Unstable flow can cause surging and pressure fluctuations. Due to this, it is generally recommended that freefalls be avoided.

Freefalls disconnect the paste column and pressure transfer is not possible across a freefall. The flow after a freefall is flowing as a separate gravity flow system, even if a pump is used to push material to the start of the freefall. Therefore, where a freefall occurs in a reticulation system, the pump will only be affected by changes upstream from the freefall. When considering acceleration forces from pulsations, only the paste mass prior to the freefall is accelerated directly by the paste pump. In this manner, freefalls are beneficial for limiting the magnitude of acceleration forces.

The problems occur when paste is progressively made thicker and friction losses increase to the tipping point where freefalls exist in the reticulation system. As freefall zones become smaller and collapse, a step change in pressure will be observed at the pump when the collapse occurs. This step change is a result of two disconnected flows connecting and the pump is now transmitting pressure to the entire paste column. Pressure spikes are also likely to be observed as the freefall collapses.

From an operator's point of view, it will appear as though the reticulation system is more sensitive to slump changes once the freefalls collapse due to the proportionately longer column of paste. Also, if the system is operated near the tipping point of where freefalls exist, it could be possible for the pressures to cross the freefall threshold at every stroke of the pump. This will cause noticeable pressure spikes within the system which can often be heard as hammering within the pipe. These pressure spikes are caused by the two disconnected columns of paste colliding at the collapse of the freefall and the downstream column accelerating to the velocity of the upstream paste column.

Due to the problems these pressure spikes cause, operators often thin out the paste to where the freefalls don't collapse and the pressure spikes seem to go away. Operators are not knowingly creating freefalls, they are simply reverting to a paste density where the problems were not occurring.

Operating at lower paste density is the common consequence of pulsations causing acceleration forces which were not accounted for in the design. Paste density/viscosity is limited, not directly by the steady state friction losses within the reticulation system, but by the acceleration forces causing pressure problems in the system and limiting paste density. The end result is that paste density is limited and paste strength suffers as a result, impacting operating costs.

WHEN IS ACCELERATION LIKELY TO BE A PROBLEM

As discussed earlier in this paper, acceleration forces can limit pumping capability, cause pressure spikes, and consequently limit paste density. The regular change in paste momentum also causes movement of the pipe and fatigue of components at the coupling. Significant bracing is required to resist the movement and prevent pipe failures.

Acceleration forces are likely to become a problem when reticulating thick paste or when pumping up hill. Both factors cause the paste column to decelerate to a stop before the next piston stroke begins its discharge stroke.

Thick paste is more viscous and creates higher friction losses. Higher friction losses increase the likelihood of acceleration issues in the following ways:

- The paste column decelerates more rapidly and is more likely to come to a complete stop between strokes.
- The higher viscosity increases the likelihood and size of cavitation during the suction stroke.
- The likelihood of freefalls within the reticulation system is reduced which can increase the mass being accelerated by each pump stroke.

Pumping up hill is another circumstance which will bring acceleration forces to the foreground. When pumping against gravity, there is a constant force pushing against the pump. This force not only uses up a portion of the pump's capacity, but also rapidly decelerates the fluid column to nearly guarantee it is completely stopped between pump strokes. Since gravity can provide enough deceleration forces to stop the column of fluid, even non-viscous fluids such as water can experience problems.

PULSATION FREE SYSTEMS

Pumping technology has progressed over time and the major suppliers of paste pumps have all developed adaptations to limit pulsations from their piston pumps. These range from clever valve timing to reduce the pause between discharge strokes, to active dampeners that control the pulsations at the pump discharge.

The most innovative systems decouple the two hydraulic cylinders and adapt timing that provides a constant pump discharge with little interruption in flow between discharge cycles of the two cylinders. Figure 4 below is an example of such a system.

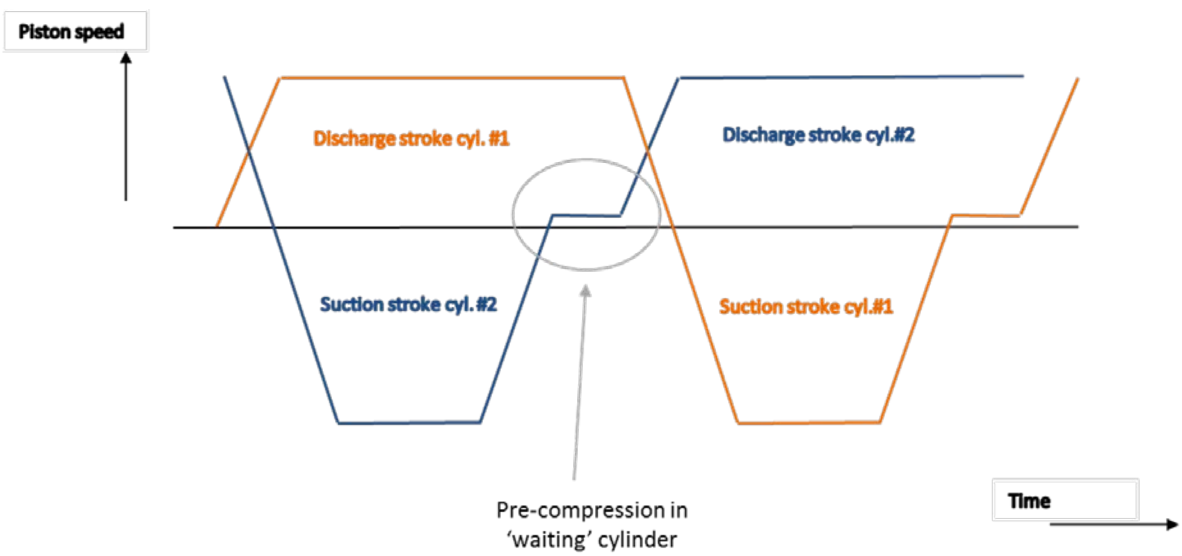

Figure 4. Piston speed of GEHO® VZ Pulsation Free system

These new control systems have asymmetry between the velocities of the suction and discharge strokes and allow for pre-compression of the paste to collapse any cavitation voids. The discharge of the two cylinders are overlapped such that the flow in the pipeline does not significantly change velocity and therefore acceleration forces are nearly eliminated. This type of pulsation free system is only available on pumps equipped with poppet style valves, where valves can act independently of each other.

These changes to the flow characteristics of the pump provide the following benefits:

- Pressure capacity of pump is entirely available for friction losses and elevation pressures.
- Removal of pulsations reduces maintenance of pumps and pipeline components.
- Peak velocities in the system are lower and therefore have lower friction losses.
- Energy consumption is lower due to lower friction losses.
- Pre-compression of cylinder eliminates effects of cavitation in pump.

EXISTING SYSTEMS

There are many reticulation systems currently installed around the world which are experiencing pumping limitations due to the pulsating nature of the pumps installed. This section discusses what options are available to help resolve the issues.

If a system is experiencing problems due to acceleration from pump pulsations, there are variables which can be adjusted to reduce acceleration forces; how quickly the acceleration occurs, and how much mass is being accelerated.

Possible methods for reducing acceleration issues within a pumping system include:

- Eliminate cavitation within the pump by ensuring the suction pipework is free of obstructions and an adequate level is maintained in the feed hopper.
- Request the pump supplier lengthen the “ramp up time” in the pump PLC to allow the acceleration of the piston to occur over a longer period.
- Introduce air or another dampening method to buffer the acceleration forces.
- Operate a thinner paste with lower friction losses in order to:
    - Increase occurrences of freefall and limit mass being accelerated by pump.
    - Allow more pump capacity to be used for acceleration.
- Retrofit or replace the existing pump to a pulsation free system.

Pumping limitation can increase operating costs by millions of dollars per year. The primary component of the additional cost is binder. Reducing paste density to allow pumping also reduces paste strength. Additional binder must be added to compensate for the lower density. The additional cost of binder can be an order of magnitude higher than the cost of a new pump. Any operation experiencing pumping limitation should consider purchasing a new pump and moving to a pulsation free system.

CONCLUSIONS

Acceleration forces can account for more than 50% of the peak pressure delivered by paste pumps. Acceleration forces will become most noticeable when reticulating thick paste or when pumping up hill. The consequences of high acceleration forces can limit functionality of a pumping system and lead to increased operating costs. Acceleration forces should be considered for every design that includes pumps. Selection of pumps that eliminate pulsations can resolve the problem.